

published in the literature [50,51]. The main advantage of EESM over MIESM is that the nonlinear weighting function $\Phi(\cdot)$ and its inverse function used to calculate the effective SINR are closed-form and easy to compute. The performance of EESM to predict the BLER in the MIMO high-correlation scenarios can be tested in two ways, that is, using a single parameter (one-dimension minimization) or using two different parameters. The advantage of using a single parameter is that minimization effort is simple and there is a single minimum. This is the reason that there are two sets of parameters for EESM shown in Table 11.3. The values of the EESM parameters in Table 11.3 are in good agreement with those published in the literature for QPSK and 16QAM and deviate for 64QAM [28,34,50,51]. Comparing the MSEs corresponding to MIESM and EESM in the table suggests that MIESM outperforms EESM and provides more accurate link-abstraction relative to reference link-level curves at the expense of more complexity.

The accuracy of a mutual information-based metric depends on the equivalent channel over which this metric is defined. The capacity is defined as the mutual information based on a Gaussian channel with Gaussian distributed inputs. The modulation constrained capacity is the mutual information of a symbol channel, that is, constrained by the input symbols drawn from a complex set. The computation of the mutual information per coded bit can be derived from the received symbol-level mutual information which is regarded as received bit mutual information rate (RBIR) link-to-system mapping. An alternative approach directly arrives at the bit-level mutual information and is known as the mean mutual information per bit (MMIB) PHY abstraction method. The procedure of the MIESM approach is illustrated in Figure 11.6. Given a set of N received encoder symbol SINRs from the system-level simulation, denoted as $\{\text{SINR}_1, \text{SINR}_2, \text{SINR}_3, \dots, \text{SINR}_N\}$; a mutual-information metric is calculated. Based on the computed MI metric, an equivalent SINR is obtained and used to look-up the BLER value [34,50,51].

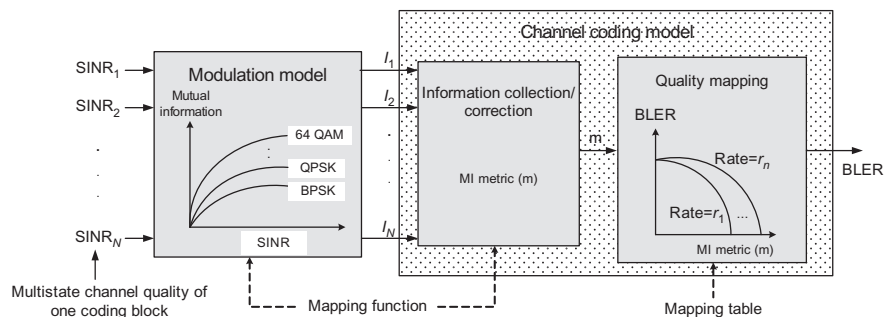


FIGURE 11.6

Procedure for MIESM link-to-system mapping method [26].

11.5 IMT-Advanced test environments

For evaluation of the IMT-Advanced candidates, the ITU-R WP 5D defined several test environments where each test environment is characterized with certain user mobility, path loss and channel models, and system configuration parameters. The evaluation of candidate radio access technologies was performed in selected scenarios of the following test environments [12–14]:

- Indoor test environment models isolated cells at offices and/or in hotspots comprising stationary and pedestrian users. In this model, the emphasis is on very small cells, very high user throughputs, and high user density inside buildings.
- Urban micro-cellular test environment with higher user density was defined to model pedestrian and slow vehicular users. The micro-cellular test environment's focus is on small cells and high user densities which demonstrates typical traffic load in city centers and dense urban areas. The key characteristic of this test environment is high traffic loads as well as outdoor and outdoor-to-indoor coverage. This scenario is interference-limited. A continuous cellular layout and the associated interference are assumed and radio access points are located below rooftop level.
- Urban macro-cellular environment (base coverage urban) was defined to model coverage for pedestrian users up to fast-moving vehicular users. The base coverage urban test environment focuses on large cells and continuous coverage. The main characteristics of this test environment are continuous and ubiquitous coverage in urban areas. This scenario is interference-limited, using macro-cells with radio access points above rooftop level. In an urban macro-cell test environment, mobile stations are located outdoor at street level and fixed base station antennas are located clearly above surrounding building heights. Therefore, NLoS or obstructed sight can be considered in this scenario.
- High-speed or rural test environment models high-speed vehicular and trains. The high-speed test environment focuses on larger cells and continuous coverage. The key characteristics of this test environment are continuous wide area coverage supporting high-speed vehicles. This scenario will therefore be noise-limited and/or interference-limited and uses macro-sized cells.

11.6 Network layout for system-level simulations

In the rural or high-speed, macro- and micro-cellular environments, no specific topographical details are taken into consideration. Base stations are placed in regular grids conforming to a hexagonal layout. A basic hexagonal layout with three cells/sectors per site is shown in Figure 11.7 where antenna bore-sight, cell range, and inter-site distance are also illustrated. The system-level simulations use a wrap-around model with 19 sites each comprising 3 cells. The users are dropped

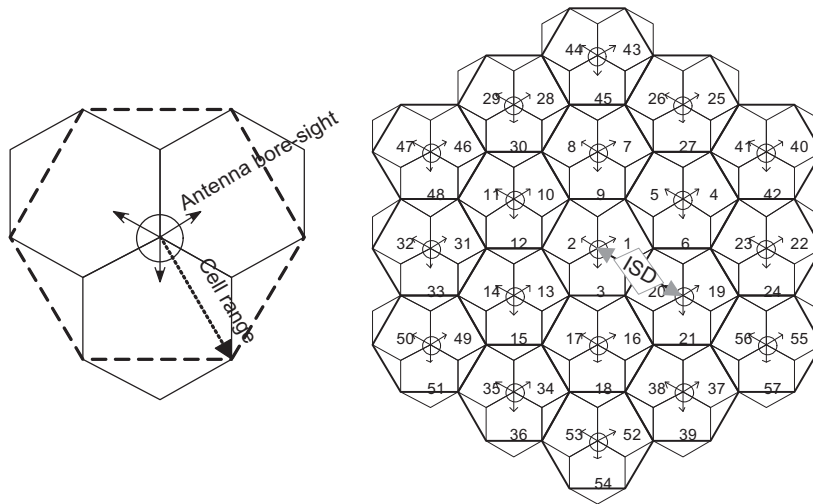
**FIGURE 11.7**

Illustration of a hexagonal cellular network layout [14].

uniformly over the entire coverage area (Monte Carlo method⁴) in order to model the inter-cell interference. Depending on the configuration being simulated and required output, the effect of the surrounding outer cells may be disregarded. In such cases, only 19 cells of the center cluster may be modeled. For the cases where modeling of the interfering outer cells is necessary for accuracy of the results, the wrap-around structure with the seven cluster network can be used. A cluster is defined as six displacements of the center hexagon. In the wrap-around inter-cell interference model, the network is extended to a cluster of networks consisting of seven replicas of the original hexagonal network, with the original hexagonal network in the middle while the other six copies are attached to it symmetrically on six sides. The number of mobile stations is predetermined for each sector/cell, where each MS location is randomly distributed with uniform distribution (see Figure 11.7).

The serving cell of each MS is determined in two steps due to the wrap-around nature of the cell layout. The first step is to determine the 19 shortest-distanced cells for each MS from all seven logical cell clusters, and the second step is to determine the serving cell/sector among the nearest 19 cells for each MS based on the strongest link according to the path loss and shadowing. To determine the shortest-distanced cell for each MS, the distances between the MS

⁴Monte Carlo methods are a class of computational algorithms that rely on repeated random sampling to compute their results. Monte Carlo methods are often used in simulating physical and mathematical systems. Because of their reliance on repeated computation of random or pseudorandom quantities, these methods are most suited to calculation by a computer and tend to be used when it is unfeasible or impossible to find a closed-form result with a deterministic algorithm [56].

and all logical cell clusters are calculated and the 19 cells with a shortest distance in all seven cell clusters are selected. The serving cell for each MS provides the strongest link with a strongest received long-term signal power. It should be noted that the shadowing experienced on the link between MS and cells located in different clusters is the same.

11.7 IMT-Advanced evaluation methodology and baseline configurations

The IMT-Advanced candidate technologies were required to be evaluated under at least three test environments. ITU-R WP 5D specified a common evaluation methodology based on which the candidates were required to be configured and assessed against the IMT-Advanced minimum system requirements. Table 11.4 provides the common parameters for evaluation of radio access technologies as specified by ITU-R recommendations [6,12–14].

The BS antennas in each sector are assumed to have antenna patterns in azimuth and elevation directions that are given by:

$$\begin{aligned} A_e(\phi) &= -\min \left[12 \left(\frac{\phi - \phi_{\text{tilt}}}{\phi_{3\text{dB}}} \right)^2, A_m \right] \text{ Elevation direction} \\ A(\theta) &= -\min \left[12 \left(\frac{\theta}{\theta_{3\text{dB}}} \right)^2, A_m \right] \text{ Azimuth direction} \end{aligned} \quad (11.24)$$

where $A(\theta)$ is the relative antenna gain (in dB) in the direction of $-180^\circ \leq \theta \leq 180^\circ$, $\theta_{3\text{dB}}$ is the 3 dB beam-width ($\theta_{3\text{dB}} = 70^\circ$), $A_m = 20$ dB is the maximum attenuation, $A_e(\phi)$ is the relative antenna gain (in dB) in the elevation direction $-90^\circ \leq \phi \leq 90^\circ$, $\phi_{3\text{dB}}$ is the elevation 3 dB beam-width ($\phi_{3\text{dB}} = 15^\circ$), and ϕ_{tilt} is the tilt angle. The value of the antenna tilt angle is assumed to be $\phi_{\text{tilt}} = 0^\circ$ for InH, $\phi_{\text{tilt}} = 12^\circ$ for UMi, $\phi_{\text{tilt}} = 12^\circ$ for UMa, and $\phi_{\text{tilt}} = 6^\circ$ for RMa test environments.

The combined antenna pattern at angles off the cardinal axes is computed as $-\min[-(A(\theta) + A_e(\phi)), A_m]$. The antenna bearing is defined as the angle between the main antenna lobe center and a line directed due east given in degrees. The bearing angle increases in a clockwise direction. The center directions of the main antenna lobe in each sector point to the corresponding side of the hexagon. For an indoor test environment, the BS is assumed to have an omni-directional antenna pattern. The mobile station is assumed to have omni-directional antennas.

11.8 Link-level and system-level channel models

The channel behavior is described by its long- and short-term fading characteristics where the former often depends on the geometrical location of a user in a wireless network and the latter defines the time-variant spatial channels.

In general, there are two ways of modeling a channel, deterministic and stochastic. The deterministic category encompasses all models that describe the propagation channel for a specific transmitter location, receiver location, and environment. Deterministic channel models are site-specific, as they clearly depend on the location of transmitter, receiver, and the properties of the environment. They are therefore most suitable for network planning and deployment. In many cases, it is not possible or desirable to model the propagation channel in a specific environment. Especially for system testing and evaluation, it is more appropriate to consider channels that reflect “typical,” “best case,” and “worst case” propagation scenarios. A stochastic channel model thus reflects the statistics of the channel impulse responses and during the actual simulation; impulse responses are generated as realizations according to those statistics[18–22,29–33,35–43].

Essential to the evaluation of multiple-antenna techniques, which are the key enabling technology for IMT-Advanced systems, is the modeling of MIMO channels that can be represented as double-directional channels or as vector (or matrix) channels. The former representation is more related to the physical propagation effects, while the latter is more focused on the mathematical effect of the channel on the system. The double-directional model is a physical model in which the channel is constructed from summing over multiple waves or rays. Thus, it can also be referred to as a “ray-based model.” The vector or matrix channel is a mathematical or analytical model in which the space-time channel as seen by the receiver is constructed mathematically, assuming certain system and antenna parameters. In this approach, the channel coefficients are correlated random processes in both space and time, where the correlation is defined mathematically.

The ITU-R WP 5D specified channel models for the evaluation of IMT-Advanced candidate technologies which consisted of primary and extension modules. The framework of the primary module is based on the WINNER II channel model,⁵ which applies the same approach as the 3GPP/3GPP2 spatial channel model (SCM).⁶ The extension module extends the capabilities of the IMT-Advanced channel model to cover additional deployment scenarios beyond that of IMT-Advanced candidate technology evaluations, allowing the use of modified parameters to generate large-scale parameters. The ITU-R WP 5D specified channel model is a geometric stochastic model. It does not explicitly specify the locations of the scatterers, rather the directions of the rays generated as a result of scattering objects. The geometric modeling of the radio channel enables separation of propagation parameters and antennas. The channel parameters for individual snapshots are determined stochastically based on statistical distributions extracted from channel measurements. Antenna geometries and radiation patterns

⁵Information on WINNER II channel models can be found at <http://www.ist-winner.org/deliverables.html>.

⁶Information on the 3GPP/3GPP2 spatial channel model can be found in 3GPP TR 25.996 *spatial channel model for multiple input multiple output (MIMO)*, September 2003.

complex-valued gains of vertical-to-vertical and horizontal-to-vertical polarizations of ray n, m , respectively, λ_0 represents the wave length of the RF carrier, $\bar{\varphi}_{n,m}$ AoD unit vector, $\bar{\phi}_{n,m}$ is the AoA unit vector, $\bar{r}_{TX,s}$ and $\bar{r}_{RX,u}$ are the location vectors of element s and u , respectively, and $v_{n,m}$ denotes the Doppler frequency component of ray n, m [1,14,26]. If the radio channel is dynamically modeled, the above-mentioned small-scale parameters are going to be time-variant.

In Figure 11.8, the placement of the MS with respect to each BS is to be determined according to the cell layout. From this placement, the distance between the MS and the BS d and the LoS directions with respect to the BS and MS, θ_{BS} and θ_{MS} can be determined. Note that θ_{BS} and θ_{MS} are defined relative to the broadside directions. The MS antenna array orientations Ω_{MS} are independent and identically distributed and are obtained from a uniform $0-360^\circ$ distribution.

The generic MIMO channel model is a stochastic model with two levels of unpredictability: large-scale parameters, such as shadow fading, delay, and angular spreads that are drawn randomly from tabulated distribution functions; and small-scale parameters, such as delay, power, and direction of arrival and departure that are selected randomly according to tabulated distribution functions and large-scale parameters. An infinite number of different realizations of the channel model can be generated randomly selecting different initial phases for the scattering objects.

The general approach in the SCM is based on the geometry of a network layout. The large-scale parameters, such as path loss and shadowing factor, are generated according to the geometric positions of the BS and MS. Then the statistical channel behavior is defined using distribution functions of delay and angle, and also by the power delay and angular profiles. Typically, an exponential power delay profile and Laplacian power angular profile are assumed with the function completely defined once the root mean-square (RMS) delay spread and angular spread are specified. The RMS delay and angular spread parameters can be random variables with a mean and standard deviation. The RMS delay and angular spread can be mutually correlated, together with other large-scale parameters, such as shadowing factors. According to the exact profile and distribution functions defined by the particular RMS delay and angular spread values, a finite number of channel taps are randomly generated with a per-tap delay, mean power, mean AoA and AoD, and RMS angular spread. They are defined in a way such that the overall power profile and distribution function are satisfied. Each tap is the contribution of a number of rays (plane waves) arriving at the same time, with each ray having its own amplitude, AoA, and AoD. The number of taps and their delay and angles may be randomly defined, but a reduced-complexity model can specify the delays, mean powers, and angles of the channel taps in a predetermined manner when typical values are often chosen. Similar to the well-known tapped-delay-line version of the wide-sense stationary uncorrelated scattering model, where the power delay profile is fixed, a spatial tapped-delay-line reduced-complexity model additionally defines the spatial information, such as per-tap mean AoA, AoD, and per-tap angular spread, and the power angular

profile. Spatial tapped-delay-line models are also referred to as cluster-delay-line models as each tap is modeled as the effect of a cluster of rays arriving at the same time. Each tap suffers from fading in space and over time. The spatial fading process will satisfy a predetermined power angular profile.

The realization of a time-varying spatial channel can be performed in two ways:

- Ray-based: The channel coefficient between each transmit and receive antenna pair is the summation of all rays at each tap and at each time instant, according to the antenna configuration, gain pattern, AoA, AoD of each ray. The temporal channel variation depends on the traveling speed and direction relative to the AoA/AoD of each ray.
- Correlation-based: The antenna correlation for each tap is computed first according the per-tap mean AoA/AoD, per-tap power angular profile, and antenna configuration parameters (e.g., spacing and polarization). The per-tap Doppler spectrum depends on the traveling speed and direction relative to the mean per-tap AoA/AoD, as well as the per-tap power angular profile. The MIMO channel coefficients at each tap can then be generated mathematically by transforming typically the independent and identically distributed Gaussian random variables according to the antenna correlation and the temporal correlation (correspondingly the particular Doppler spectrum).

The generic channel model is based on the drop concept. The system-level simulation is performed in a sequence of “drops,” where a “drop” is defined as one simulation run over a certain time period when using the generic model. A drop (or snapshot of a channel segment) is a simulation instance where the random properties of the channel remain constant except for the fast fading caused by the changing phases of the rays. The constant properties during a single drop are the power, delay, and direction of the rays. In a simulation, the number and the length of drops are selected based on the evaluation requirements and the deployment scenario. The generic channel model allows simulation of several statistically independent drops in order to obtain a statistical representation of system performance. The channel model parameters for evaluation of IMT-Advanced technologies in various test environments are shown in Table 11.5. In Table 11.5, DS is the RMS delay spread, ASD is the RMS azimuth spread of departure angles, ASA denotes the RMS azimuth spread of arrival angles, SF represents the shadow fading, and parameter K denotes the Rician K -factor. IMT-Advanced primary module path loss model parameters for a hexagonal cell layout are summarized in Table 11.6.

The break point distance in the above table is defined as $d'_{BP} = 4h'_{BS}h'_{MS}f_c/c$ where f_c is the center frequency (Hz), $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space, h'_{BS} and h'_{MS} are the effective antenna heights at the BS and the MS, respectively. The effective antenna heights h'_{BS} and h'_{MS} are computed as follows: $h'_{BS} = h_{BS} - 1$ and $h'_{MS} = h_{MS} - 1$ where h_{BS} and h_{MS} are the actual antenna heights. The effective height in urban environments is assumed to be equal to 1.0m. In the above table, PL_b denotes basic path loss, PL_{B1} is loss of UMi

Table 11.5 Channel Model Parameters for IMT-Advanced Test Environments [4,14]

Channel Model Parameters		InH		UMi			UMa		RMa	
		LoS	NLoS	LoS	NLoS	Outdoor-to-Indoor	LoS	NLoS	LoS	NLoS
Delay spread	μ	− 7.70	− 7.41	− 7.19	− 6.89	− 6.62	− 7.03	− 6.44	− 7.49	− 7.43
(DS) $\log_{10}(\text{s})$	σ	0.18	0.14	0.40	0.54	0.32	0.66	0.39	0.55	0.48
AoD spread	μ	1.60	1.62	1.20	1.41	1.25	1.15	1.41	0.90	0.95
(ASD)	σ	0.18	0.25	0.43	0.17	0.42	0.28	0.28	0.38	0.45
$\log_{10}(\text{degrees})$										
AoA spread	μ	1.62	1.77	1.75	1.84	1.76	1.81	1.87	1.52	1.52
(ASA)	σ	0.22	0.16	0.19	0.15	0.16	0.20	0.11	0.24	0.13
$\log_{10}(\text{degrees})$										
Shadow fading	σ	3	4	3	4	7	4	6	4	8
(SF) (dB)										
K -factor (K) (dB)	μ	7	N/A	9	N/A	N/A	9	N/A	7	N/A
	σ	4	N/A	5	N/A	N/A	3.5	N/A	4	N/A
Cross-	ASD vs. DS	0.6	0.4	0.5	0	0.4	0.4	0.4	0	− 0.4
correlations	ASA vs. DS	0.8	0	0.8	0.4	0.4	0.8	0.6	0	0
	ASA vs. SF	− 0.5	− 0.4	− 0.4	− 0.4	0	− 0.5	0	0	0
	ASD vs. SF	− 0.4	0	− 0.5	0	0.2	− 0.5	− 0.6	0	0.6
	DS vs. SF	− 0.8	− 0.5	− 0.4	− 0.7	− 0.5	− 0.4	− 0.4	− 0.5	− 0.5
	ASD vs. ASA	0.4	0	0.4	0	0	0	0.4	0	0
	ASD vs. K	0	N/A	− 0.2	N/A	N/A	0	N/A	0	N/A
	ASA vs. K	0	N/A	− 0.3	N/A	N/A	− 0.2	N/A	0	N/A
	DS vs. K	− 0.5	N/A	− 0.7	N/A	N/A	− 0.4	N/A	0	N/A
	SF vs. K	0.5	N/A	0.5	N/A	N/A	0	N/A	0	N/A

(Continued)

Table 11.5 (Continued)

Channel Model Parameters	InH		UMi			UMa		RMa	
	LoS	NLoS	LoS	NLoS	Outdoor-to-Indoor	LoS	NLoS	LoS	NLoS
Delay distribution	Exponential	Exponential	Exponential	Exponential	Exponential	Exponential	Exponential	Exponential	Exponential
AoD and AoA distribution	Laplacian		Wrapped Gaussian			Wrapped Gaussian		Wrapped Gaussian	
Delay scaling parameter r_τ	3.6	3	3.2	3	2.2	2.5	2.3	3.8	1.7
Cross-polarization ratio μ (dB)	11	10	9	8.0	9	8	7	12	7
Number of clusters	15	19	12	19	12	12	20	11	10
Number of rays per cluster	20	20	20	20	20	20	20	20	20
Cluster ASD	5	5	3	10	5	5	2	2	2
Cluster ASA	8	11	17	22	8	11	15	3	3
Per cluster shadowing standard deviation ζ (dB)	6	3	3	3	4	3	3	3	3
Correlation distance (m)	DS	5	7	10	10	30	40	50	36
	ASD	3	8	10	11	18	50	25	30
	ASA	3	8	9	17	15	50	35	40
	SF	6	10	13	7	37	50	37	120
	K	N/A	15	N/A	N/A	12	N/A	40	N/A

Table 11.6 IMT-Advanced Primary Module Path Loss Models (f_c Is in GHz, All Distances Are in Meters, and a Hexagonal Cell Layout Is Assumed) [14]

Scenario		Path Loss PL (dB)	Shadow Fading Standard Deviation (dB)	Applicability Range (m)/Antenna Height (m)
InH	LoS	$16.9 \log_{10}(d) + 32.8 + 20 \log_{10}(f_c)$	$\sigma = 3$	$3 < d < 100$ $h_{BS} = 3 - 6$ $h_{MS} = 1 - 2.5$
	NLoS	$43.3 \log_{10}(d) + 11.5 + 20 \log_{10}(f_c)$	$\sigma = 4$	$10 < d < 150$ $h_{BS} = 3 - 6$ $h_{MS} = 1 - 2.5$
UMi	LoS	$22.0 \log_{10}(d) + 28.0 + 20 \log_{10}(f_c)$ $40 \log_{10}(d_1) + 7.8 - 18 \log_{10}(h'_{BS}) - 18 \log_{10}(h'_{MS}) + 2 \log_{10}(f_c)$	$\sigma = 3$	$10 < d_1 < d'_{BP}$ $d'_{BP} < d_1 < 5000$ $h_{BS} = 10; h_{MS} = 1.5$
	NLoS	$36.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c)$	$\sigma = 4$	$10 < d < 2000$ $h_{BS} = 3$ $h_{MS} = 1 - 2.5$
UMa	Outdoor-to-indoor	$PL_b + PL_{tw} + PL_{in}$ $PL_b = PL_{B1}(d_{out} + d_{in}); PL_{tw} = 20; PL_{in} = 0.5d_{in}$	$\sigma = 7$	$10 < d_{out} + d_{in} < 1000$ $0 < d_{in} < 25$
	LoS	$22.0 \log_{10}(d) + 28.0 + 20 \log_{10}(f_c)$ $40.0 \log_{10}(d_1) + 7.8 - 18.0 \log_{10}(h'_{BS}) - 18.0 \log_{10}(h'_{MS}) + 2.0 \log_{10}(f_c)$	$\sigma = 4$	$10 < d_1 < d'_{BP}$ $d'_{BP} < d_1 < 5000$ $h_{BS} = 25; h_{MS} = 1.5$
	NLoS	$161.04 - 7.1 \log_{10}(W) + 7.5 \log_{10}(h)$ $- (24.37 - 3.7(h/h_{BS})^2) \log_{10}(h_{BS})$ $+ (43.42 - 3.1 \log_{10}(h_{BS})) (\log_{10}(d) - 3)$ $+ 20 \log_{10}(f_c) - (3.2 (\log_{10}(11.75h_{MS}))^2 - 4.97$	$\sigma = 6$	$10 < d < 5000$ $h_{BS} = 25; h_{MS} = 1.5;$ $W = 20; h = 205 < h < 50;$ $5 < W < 50$ $10 < h_{BS} < 150;$ $1 < h_{MS} < 10$

(Continued)

Table 11.6 (Continued)

Scenario		Path Loss PL (dB)	Shadow Fading Standard Deviation (dB)	Applicability Range (m)/Antenna Height (m)
RMa	LoS	$PL_1 = 20 \log_{10}(40\pi df_c/3) + \min(0.03h^{1.72}, 10)$ $\log_{10}(d) - \min(0.044h^{1.72}, 14.77) + 0.002\log_{10}(h)d$ $PL_2 = PL_1(d_{BP}) + 40 \log_{10}(d/d_{BP})$	$\sigma = 4$ $\sigma = 6$	$10 < d < d_{BP}$ $d_{BP} < d < 10000$ $h_{BS} = 35; h_{MS} = 1.5$ $W = 20; h = 5$
	NLoS	$161.04 - 7.1 \log_{10}(W) + 7.5 \log_{10}(h)$ $-(24.37 - 3.7(h/h_{BS})^2)\log_{10}(h_{BS})$ $+ (43.42 - 3.1 \log_{10}(h_{BS}))(\log_{10}(d) - 3)$ $+ 20 \log_{10}(f_c) - (3.2 (\log_{10}(11.75 h_{MS}))^2 - 4.97)$	$\sigma = 8$	$10 < d < 5000$ $h_{BS} = 35;$ $h_{MS} = 1.5$ $W = 20; h = 5$

outdoor scenario, PL_{tw} is penetration loss through the wall, PL_{in} denotes the loss inside, d_{out} is the distance from the BS to the wall next to the MS location, d_{in} denotes the perpendicular distance from the wall to the MS which is evenly distributed between 0 and 25 m, and the break point distance is defined as $d_{BP} = 2\pi h_{BS}h_{MS}f_c/c$.

Spatial correlation is often said to degrade the performance of multi-antenna systems and impose a limit on the number of antennas that can effectively fit in a small mobile device. This seems intuitive as the spatial correlation decreases the number of independent channels that can be created by precoding. When modeling spatial correlation, it is useful to employ the Kronecker model, where the correlation between transmit and receive antennas are assumed independent and separable. This model is reasonable when the main scattering appears close to the antenna arrays and has been validated by outdoor and indoor measurements. Assuming Rayleigh fading, the Kronecker model means that the channel matrix can be represented as $\mathbf{H} = \mathbf{R}_{RX}^{1/2} \mathbf{H}_{channel} (\mathbf{R}_{TX}^{1/2})^T$ where the elements of $\mathbf{H}_{channel}$ are independent and identically distributed as circular symmetric complex Gaussian with zero-mean and unit variance. The important part of the model is that $\mathbf{H}_{channel}$ is pre-multiplied by the receive-side spatial correlation matrix $\mathbf{R}_{RX}$ and post-multiplied by the transmit-side spatial correlation matrix $\mathbf{R}_{TX}$. Equivalently, the channel matrix can be expressed as $\mathbf{H} \sim Z(0, \mathbf{R}_{TX} \otimes \mathbf{R}_{RX})$ where $\otimes$ denotes the Kronecker product.

Using the Kronecker model, the spatial correlation depends directly on the eigenvalue distributions of the correlation matrices $\mathbf{R}_{RX}$ and $\mathbf{R}_{TX}$. Each eigenvector represents a spatial direction of the channel and its corresponding eigenvalue describes the average channel/signal gain in this direction. For the transmit-side, the correlation matrix $\mathbf{R}_{TX}$ describes the average gain in a spatial transmit direction, while the receive-side correlation matrix $\mathbf{R}_{RX}$ describes a spatial receive direction. High spatial correlation is represented by a large eigenvalue spread in $\mathbf{R}_{TX}$ or $\mathbf{R}_{RX}$, implying that some spatial directions are statistically stronger than the others. On the other hand, low spatial correlation is represented by a small eigenvalue spread in $\mathbf{R}_{TX}$ or $\mathbf{R}_{RX}$, which implies that almost the same signal gain can be expected from all spatial directions [57].

Let us now focus on a specific case of downlink transmission from a base station to a mobile station. Denoting the n th snapshot of the spatial correlation matrices at the BS and the MS by $\mathbf{R}_{BS,n}$ and $\mathbf{R}_{MS,n}$, the per-tap spatial correlation is determined as the Kronecker product⁷ of the BS and MS's antenna correlation matrices:

⁷Given an $m \times n$ matrix $\mathbf{A}$ and a $p \times q$ matrix $\mathbf{B}$, the Kronecker product $\mathbf{C} = \mathbf{A} \otimes \mathbf{B}$, also called the matrix direct product, is an $mp \times nq$ matrix with elements defined by $c_{\alpha\beta} = a_{ij}b_{kl}$, where $\alpha \equiv p(i-1) + k$ and $\beta \equiv q(j-1) + l$. The matrix direct product provides the matrix of the linear transformation induced by the vector space tensor product of the original vector spaces. More precisely, suppose that operators $S:V_1 \rightarrow W_1$ and $T:V_2 \rightarrow W_2$ are given by $S(x) = Ax$ and $T(y) = By$. Then $S \otimes T:V_1 \otimes V_2 \rightarrow W_1 \otimes W_2$ is determined by $S \otimes T(x \otimes y) = (Ax) \otimes (By) = (A \otimes B)(x \otimes y)$ [57].

$$\mathbf{R}_n = \mathbf{R}_{\text{BS},n} \otimes \mathbf{R}_{\text{MS},n} \quad (11.27)$$

We denote the number of receive antennas by N_{RX} and the number of transmit antennas by the N_{TX} . If cross-polarized antennas are present at the receiver, it is assumed that $N_{\text{RX}}/2$ receive antennas have the same polarization, while the remaining $N_{\text{RX}}/2$ receive antennas have orthogonal polarization. Likewise, if cross-polarized antennas are present at the transmitter, it is assumed that the $N_{\text{TX}}/2$ transmit antennas have the same polarization; while the remaining $N_{\text{TX}}/2$ transmit antennas have orthogonal polarization. It is further assumed that the antenna arrays are composed of pairs of colocated antennas with orthogonal polarization. With these assumptions, the per-tap channel correlation is determined as follows:

$$\mathbf{R}_n = \mathbf{R}_{\text{BS},n} \otimes \mathbf{\Gamma} \otimes \mathbf{R}_{\text{MS},n} \quad (11.28)$$

Where $\mathbf{R}_{\text{MS},n}$ is an $N_{\text{RX}} \times N_{\text{RX}}$ matrix if all receive antennas have the same polarization, or an $N_{\text{RX}}/2 \times N_{\text{RX}}/2$ matrix if the receive antennas are cross-polarized. Likewise, $\mathbf{R}_{\text{BS},n}$ is an $N_{\text{TX}} \times N_{\text{TX}}$ matrix if all the transmit antennas have the same polarization, or an $N_{\text{TX}}/2 \times N_{\text{TX}}/2$ matrix if the transmit antennas are cross-polarized. Matrix $\mathbf{\Gamma}$ is a cross-polarization matrix based on the cross-polarization defined in the cluster-delay-line models. Matrix $\mathbf{\Gamma}$ is a 2×2 matrix if cross-polarized antennas are used at the transmitter or at the receiver. It is a 4×4 matrix if cross-polarized antennas are used at both the transmitter and the receiver.

Table 11.7 defines the correlation matrices for the eNB and UE in E-UTRA with a different number of transmit/receive antennas at each entity [4].

For the scenarios with more antennas at either eNB, UE, or both, the channel spatial correlation matrix can be expressed as the Kronecker product of $\mathbf{R}_{\text{eNB}}$ and $\mathbf{R}_{\text{UE}}$ according to $\mathbf{R}_{\text{spatial}} = \mathbf{R}_{\text{eNB}} \otimes \mathbf{R}_{\text{UE}}$. The parameters α and β for different antenna correlation types are given in Table 11.8.

Table 11.7 eNB/UE Correlation Matrix [4,58]				
Entity	Number of Antennas			
	1	2	4	
eNB	$\mathbf{R}_{\text{eNB}} = 1$	$\mathbf{R}_{\text{eNB}} = \begin{pmatrix} 1 & \alpha \\ \alpha^* & 1 \end{pmatrix}$	$\mathbf{R}_{\text{eNB}} = \begin{pmatrix} 1 & \alpha^{1/9} & \alpha^{4/9} & \alpha \\ \alpha^{1/9*} & 1 & \alpha^{1/9} & \alpha^{4/9} \\ \alpha^{4/9*} & \alpha^{1/9*} & 1 & \alpha^{1/9} \\ \alpha^* & \alpha^{4/9*} & \alpha^{1/9*} & 1 \end{pmatrix}$	
UE	$\mathbf{R}_{\text{UE}} = 1$	$\mathbf{R}_{\text{UE}} = \begin{pmatrix} 1 & \beta \\ \beta^* & 1 \end{pmatrix}$	$\mathbf{R}_{\text{UE}} = \begin{pmatrix} 1 & \beta^{1/9} & \beta^{4/9} & \beta \\ \beta^{1/9*} & 1 & \beta^{1/9} & \beta^{4/9} \\ \beta^{4/9*} & \beta^{1/9*} & 1 & \beta^{1/9} \\ \beta^* & \beta^{4/9*} & \beta^{1/9*} & 1 \end{pmatrix}$	

Table 11.8 Values of α and β for Different Antenna Correlations [4]

Low Correlation		Medium Correlation		High Correlation	
α	β	α	β	α	β
0	0	0.3	0.9	0.9	0.9

Table 11.9 EPA/EVA/ETA Multipath Power Delay Profiles [4,58]

Tap Excess Delay (ns)	Relative Power (dB)	Tap Excess Delay (ns)	Relative Power (dB)	Tap Excess Delay (ns)	Relative Power (dB)
EPA		EVA		ETU	
0	0.0	0	0.0	0	-1.0
30	-1.0	30	-1.5	50	-1.0
70	-2.0	150	-1.4	120	-1.0
90	-3.0	310	-3.6	200	0.0
110	-8.0	370	-0.6	230	0.0
190	-17.2	710	-9.1	500	0.0
410	-20.8	1090	-7.0	1600	-3.0
—	—	1730	-12.0	2300	-5.0
—	—	2510	-16.9	5000	-7.0

Table 11.10 Delay Profiles of LTE Channel Models [4,58]

Model	Number of Channel Taps	RMS Delay Spread (ns)	Maximum Tap Excess Delay (ns)
EPA	7	45	410
EVA	9	357	2510
ETU	9	991	5000

The multipath fading channel model specifies three different delay profiles which are representative of low, medium, and high delay spread environments, that is, extended pedestrian A (EPA) model, extended vehicular A (EVA) model, and extended typical urban (ETU) model [52]. The multipath delay profiles for these channels are shown in Table 11.9 and the associated number of channel taps, RMS delay spread, and maximum tap excess delays are provided in Table 11.10. In addition to a multipath delay profile, a maximum Doppler frequency is specified for each multipath fading propagation condition as follows: EPA 5 Hz ($\nu_{\max} = 5$ Hz), EVA 70 Hz ($\nu_{\max} = 70$ Hz), and ETU 300 Hz ($\nu_{\max} = 300$ Hz).

11.9 LTE-Advanced link-level and system-level performance

The 3GPP LTE-Advanced was a candidate for IMT-Advanced whose performance was fully characterized based on the ITU-R defined evaluation methodology. The following sections summarize the performance characterization of the 3GPP LTE-Advanced as part of the IMT-Advanced submission.

11.9.1 Cell spectral efficiency and cell-edge spectral efficiency

Cell spectral and cell-edge spectral efficiencies were evaluated through extensive simulations conducted by a number of 3GPP member companies. The simulation results were reported based on specific 3GPP LTE-Advanced configurations, that is, downlink and uplink MU-MIMO, downlink and uplink CoMP, and uplink SU-MIMO, for both FDD and TDD duplex schemes in various test scenarios. It must be noted that during LTE Rel-10 development and prior to IMT-Advanced submission, CoMP was an incomplete study item in 3GPP and no standard technique was specified for CoMP at that time; therefore, CoMP simulation results presented in this chapter, which were provided by a number of 3GPP member companies, did not use standard techniques and may not agree with each other in various conditions. Nevertheless, the CoMP study item was later completed and CoMP was specified as a feature in LTE Rel-11 specifications that will be discussed in the next chapter [11].

The performance differences among contributing sources can be explained by implementation-specific functionalities at the transmitter and the receiver that are not explicitly specified by the standard, such as receiver type, scheduling algorithms, and error modeling. In the results reported for the downlink, the size of the control channel (L OFDM symbols) and the number of the MBSFN subframes are the factors that affect the overhead. Note that in 3GPP submission, the control channel overhead is statically modeled, that is, the downlink control channels occupy a fixed number of OFDM symbols irrespective of the number of users, although it is expected that the size of the physical downlink control channel dynamically varies with the number of active users in the cell. In the MBSFN subframes and in the MBSFN region, there are no cell-specific reference signals (CRS), which effectively reduces the overhead.

Channel estimation and receiver types are the factors that affect the demodulation performance. Availability of CSI at the eNB is the assumption that impacts the transmit signal processing at the eNB for MU-MIMO and CoMP schemes. In the tables for the uplink, physical uplink control channel bandwidth is the factor that affects the overhead. Each value in Tables 11.11 and 11.12 is obtained as an average of all samples provided by different companies. The results suggest that the requirements are fulfilled with $L = 3$ corresponding to the largest overhead except for the system bandwidth of 1.4 MHz where the requirements cannot be met. If the control overhead

Table 11.11 LTE-Advanced Downlink Cell Spectral and Cell-Edge Spectral Efficiencies [2,6]									
Scheme and Antenna Configuration	Test Environment	Duplex Scheme	ITU-R Requirement Cell Spectral Efficiency/Cell-Edge Spectral Efficiency	Cell Spectral Efficiency (bits/s/Hz/cell)			Cell-Edge Spectral Efficiency (bits/s/Hz)		
				L = 1	L = 2	L = 3	L = 1	L = 2	L = 3
Rel-8 SU-MIMO 4 × 2(A)	InH	FDD	3/0.1	4.8	4.5	4.1	0.23	0.21	0.19
MU-MIMO 4 × 2 (C)			3/0.1	6.6	6.1	5.5	0.26	0.24	0.22
Rel-8 SU-MIMO 4 × 2 (A)		TDD	3/0.1	4.7	4.4	4.1	0.22	0.20	0.19
MU-MIMO 4 × 2 (C)			3/0.1	6.7	6.1	5.6	0.24	0.22	0.20
MU-MIMO 4 × 2 (C)	UMi	FDD	2.6/0.075	3.5	3.2	2.9	0.10	0.096	0.087
MU-MIMO 4 × 2 (A)			2.6/0.075	3.4	3.1	2.8	0.12	0.11	0.099
CS/CB-CoMP 4 × 2 (C)			2.6/0.075	3.6	3.3	3.0	0.11	0.099	0.089
JP-CoMP 4 × 2 (C)			2.6/0.075	4.5	4.1	3.7	0.14	0.13	0.12
MU-MIMO 8 × 2 (C/E)		TDD	2.6/0.075	4.2	3.8	3.5	0.15	0.14	0.13
MU-MIMO 4 × 2 (C)			2.6/0.075	3.5	3.2	3.0	0.11	0.096	0.089
MU-MIMO 4 × 2 (A)			2.6/0.075	3.2	2.9	2.7	0.11	0.10	0.095

(Continued)

Scheme and Antenna Configuration	Test Environment	Duplex Scheme	ITU-R Requirement Cell Spectral Efficiency/Cell-Edge Spectral Efficiency	Cell Spectral Efficiency (bits/s/Hz/cell)			Cell-Edge Spectral Efficiency (bits/s/Hz)		
				L = 1	L = 2	L = 3	L = 1	L = 2	L = 3
CS/CB-CoMP 4 × 2 (C)	UMa	FDD	2.6/0.075	3.6	3.3	3.1	0.10	0.092	0.086
JP-CoMP 4 × 2 (C)			2.6/0.075	4.6	4.2	3.9	0.10	0.092	0.085
MU-MIMO 8 × 2 (C/E)			2.6/0.075	4.2	3.9	3.6	0.12	0.11	0.099
MU-MIMO 4 × 2 (C)			2.2/0.06	2.8	2.6	2.4	0.079	0.073	0.066
CS/CB-CoMP 4 × 2 (C)			2.2/0.06	2.9	2.6	2.4	0.081	0.074	0.067
JP-CoMP 4 × 2 (A)			2.2/0.06	3.0	2.7	2.5	0.080	0.073	0.066
CS/CB-CoMP 8 × 2 (C)		TDD	2.2/0.06	3.8	3.5	3.2	0.10	0.093	0.084
MU-MIMO 4 × 2 (C)			2.2/0.06	2.9	2.6	2.4	0.079	0.071	0.067
CS/CB-CoMP 4 × 2 (C)			2.2/0.06	2.9	2.6	2.4	0.083	0.075	0.070
JP-CoMP 4 × 2 (C)			2.2/0.06	3.6	3.3	3.1	0.090	0.082	0.076
CS/CB-CoMP 8 × 2 (C/E)			2.2/0.06	3.7	3.3	3.1	0.10	0.093	0.087

Rel-8 SU-MIMO 4 × 2 (C)	RMa	FDD	1.1/0.04	2.3	2.1	1.9	0.081	0.076	0.069
Rel-8 SU-MIMO 4 × 2 (A)			1.1/0.04	2.1	2.0	1.8	0.067	0.063	0.057
MU-MIMO 4 × 2 (C)			1.1/0.04	3.9	3.5	3.2	0.11	0.099	0.090
MU-MIMO 8 × 2 (C)			1.1/0.04	4.1	3.7	3.4	0.13	0.12	0.11
Rel-8 SU-MIMO 4 × 2 (C)		TDD	1.1/0.04	2.0	1.9	1.8	0.072	0.067	0.063
Rel-8 SU-MIMO 4 × 2 (A)			1.1/0.04	1.9	1.7	1.6	0.057	0.053	0.049
MU-MIMO 4 × 2 (C)			1.1/0.04	3.5	3.2	3.0	0.098	0.089	0.083
MU-MIMO 8 × 2 (C/E)			1.1/0.04	4.0	3.6	3.4	0.12	0.11	0.10
Rel-8 Single- Layer BF 8 × 2 (E)			1.1/0.04	2.5	2.3	2.1	0.11	0.10	0.093

Table 11.12 3GPP LTE-Advanced Uplink Cell Spectral and Cell-Edge Spectral Efficiencies [2,6]

Scheme and Antenna Configuration	Test Environment	Duplex Scheme	ITU-R Requirement Cell Spectral Efficiency/Cell-Edge Spectral Efficiency	Cell Spectral Efficiency (bits/s/Hz/cell)	Cell-edge Spectral Efficiency (bits/s/Hz)
Rel-8 SIMO 1 × 4 (A)	InH	FDD	2.25/0.07	3.3	0.23
Rel-8 SIMO 1 × 4 (C)			2.25/0.07	3.3	0.24
Rel-8 MU-MIMO 1 × 4 (A)			2.25/0.07	5.8	0.42
SU-MIMO 2 × 4 (A)			2.25/0.07	4.3	0.25
Rel-8 SIMO 1 × 4 (A)		TDD	2.25/0.07	3.1	0.22
Rel-8 SIMO 1 × 4 (C)			2.25/0.07	3.1	0.23
Rel-8 MU-MIMO 1 × 4 (A)			2.25/0.07	5.5	0.39
SU-MIMO 2 × 4 (A)			2.25/0.07	3.9	0.25
Rel-8 SIMO 1 × 4 (C)	UMi	FDD	1.8/0.05	1.9	0.073
Rel-8 MU-MIMO 1 × 4 (A)			1.8/0.05	2.5	0.077
MU-MIMO 2 × 4 (A)			1.8/0.05	2.5	0.086
Rel-8 SIMO 1 × 4 (C)		TDD	1.8/0.05	1.9	0.070
Rel-8 MU-MIMO 1 × 4 (A)			1.8/0.05	2.3	0.071
MU-MIMO 2 × 4 (A)			1.8/0.05	2.8	0.068
MU-MIMO 1 × 8 (E)			1.8/0.05	3.0	0.079

Rel-8 SIMO 1 × 4 (C)	UMa	FDD	1.4/0.03	1.5	0.062
CoMP 1 × 4 (A)			1.4/0.03	1.7	0.086
CoMP 2 × 4 (C)			1.4/0.03	2.1	0.099
Rel-8 SIMO 1 × 4 (C)		TDD	1.4/0.03	1.5	0.062
CoMP 1 × 4 (C)			1.4/0.03	1.9	0.090
CoMP 2 × 4 (C)			1.4/0.03	2.0	0.097
MU-MIMO 1 × 8 (E)			1.4/0.03	2.7	0.076
Rel-8 SIMO 1 × 4 (C)	RMa	FDD	0.7/0.015	1.8	0.082
Rel-8 MU-MIMO 1 × 4 (A)			0.7/0.015	2.2	0.097
CoMP 2 × 4 (A)			0.7/0.015	2.3	0.13
Rel-8 SIMO 1 × 4 (C)		TDD	0.7/0.015	1.8	0.080
Rel-8 MU-MIMO 1 × 4 (A)			0.7/0.015	2.1	0.093
CoMP 2 × 4 (A)			0.7/0.015	2.5	0.15
MU-MIMO 1 × 8 (E)			0.7/0.015	2.6	0.10

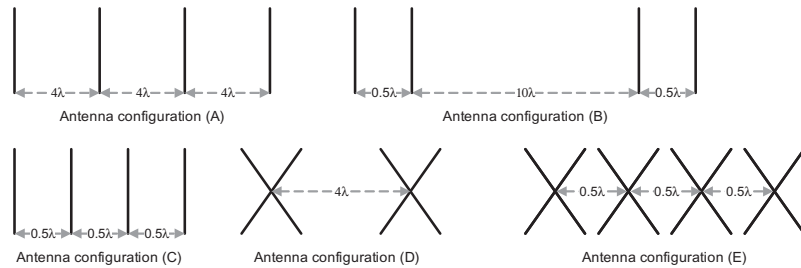
**FIGURE 11.9**

Illustration of antenna configurations used in LTE evaluations.

assumption is relaxed, that is the number of active users decreases, $L = 1, 2$ can be considered and thereby the performance can be further improved. The tables show that LTE Rel-8 with SU-MIMO 4×2 configuration can already fulfill the ITU-R requirements. The tables also show that further performance improvements can be achieved using additional technical features.

In the following tables, various antenna configurations have been utilized. There are four or eight transmit antennas with the following configurations: (A) uncorrelated co-polarized, that is, co-polarized antennas are four-wavelength apart; (B) grouped co-polarized, that is, two groups of co-polarized antennas where there is a 10-wavelength distance between the center of each group and 0.5-wavelength separation between antennas within each group; (C) correlated and co-polarized, that is, 0.5-wavelength between antennas; (D) uncorrelated and cross-polarized, that is, columns with $\pm 45^\circ$ linearly polarized antennas and separated by four wavelengths; and (E) correlated and cross-polarized, that is, columns with $\pm 45^\circ$ linearly polarized antennas and separated by 0.5-wavelengths. These configurations are illustrated in Figure 11.9.

The downlink and uplink cell spectral and cell-edge spectral efficiencies in various test environments for the TDD and FDD duplex schemes are shown in Tables 11.11 and 11.12, respectively. In these tables, the acronyms “JP-CoMP,” “CS-CoMP,” and “CB-CoMP” refer to joint processing, coordinated scheduling, and coordinated beamforming multi-point transmission schemes, respectively. The joint processing refers to a CoMP scheme where data is available at each of the geographically separated transmission points and physical downlink shared channel (PDSCH) transmission occurs from multiple points, whereas coordinated scheduling/beamforming is an alternative CoMP technique where data is only available at serving cell and data transmission is from that point, but user scheduling/beamforming decisions are made with coordination among different cells.

11.9.2 VoIP capacity

While most of the modern packet-switched air-interfaces do not specify voice codecs, calculation of the VoIP capacity requires explicit assumptions about a particular voice codec and its parameters, such as the frame rate, real-time

transport protocol (RTP) payload size, and discontinuous transmission (DTX) capability. The VoIP capacity of LTE-Advanced was calculated assuming use of AMR 12.2 kbps codec with a 50% speech activity factor. It was further assumed that the percentage of users in outage is less than 2% where a user is defined to have experienced outage if less than 98% of the VoIP packets have been delivered successfully to the user within a one-way radio access delay bound of 50 ms. The assumptions and the configuration parameters used in the system-level simulations for VoIP are as described in Table 11.13. The number of active VoIP users was calculated through extensive system-level simulations that were conducted by a number of 3GPP member companies. Table 11.14 shows the VoIP capacity results in the indoor, micro-cellular, macro-cellular, and high-speed test environments for FDD and TDD duplex schemes. The results suggest that LTE-Advanced satisfies the ITU-R requirements in various deployment scenarios. The antenna configurations are illustrated in Figure 11.9.

11.9.3 Mobility

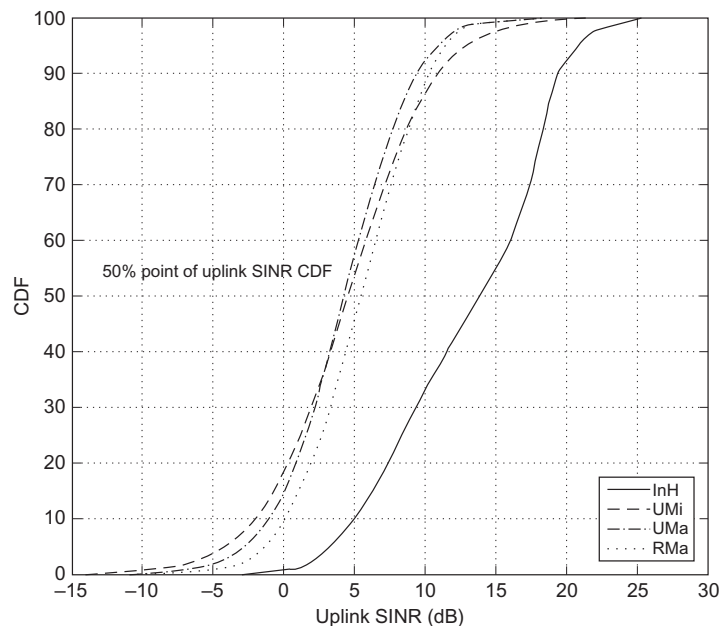
IMT-Advanced specified four mobility classes based on UE speeds as follows: Stationary (0 km/h); Pedestrian (0 to 10 km/h); Vehicular (10 to 120 km/h); and High-speed vehicular (120 to 350 km/h). In order to evaluate LTE-Advanced against mobility requirement, the methodology that is set forth in Report ITU-R M.2135-1 [14] is followed, where in the first step the system-level simulation is performed for each test environment in the uplink to obtain the uplink SINR distribution (see Figure 11.10). From the uplink SINR distribution the 50% point of CDF is obtained for each test environment. In the second step, link-level simulation is conducted to generate the spectral efficiency versus SINR curves for each test environment. The spectral efficiency values include the effect of control channel overhead from the uplink system-level simulations for each test scenario. The mobility requirement in each mobility class is satisfied, if the uplink traffic channel

Table 11.13 Assumptions for VoIP Capacity Calculation [14,26]

Parameter	Value
Codec	AMR12.2 kbps mode
Encoder frame length	20 ms
VAF	50%
Payload	Active: 33 bytes (octet-aligned mode) Inactive: 7 bytes SID packet is sent every 160 ms during silence intervals
Protocol overhead with compressed header	10 bits + padding (RTP-pre-header) 4 bytes (RTP/UDP/IP) 2 bytes (radio link control (RLC)/ security) 16 bits (CRC)

Table 11.14 LTE-Advanced VoIP Capacity [6]

Antenna Configuration	Duplex Scheme	Test Environment	ITU-R Requirement	VoIP Capacity (Active Users/MHz/Cell)
Antenna configuration (A)	FDD	InH	50	140
		UMi	40	80
		UMa	40	68
		RMa	30	91
Antenna configuration (C)	FDD	InH	50	131
		UMi	40	75
		UMa	40	69
		RMa	30	94
Antenna configuration (A)	TDD	InH	50	137
		UMi	40	74
		UMa	40	65
		RMa	30	86
Antenna configuration (C)	TDD	InH	50	130
		UMi	40	74
		UMa	40	67
		RMa	30	92

**FIGURE 11.10**

Statistical distribution of the uplink SINR in various test environments [6].

link-level data rate, normalized by bandwidth, is greater than the minimum requirements shown in Table 11.15, when the user is moving at the maximum speed in that mobility class in each of the test environments [14].

It can be concluded from Table 11.15 that the evaluated LTE-Advanced configurations can fulfill the ITU-R requirements concerning the mobility in all test environments.

11.9.4 Peak spectral efficiency

The peak spectral efficiency of LTE-Advanced is calculated based on the following assumptions: 20 MHz bandwidth; one OFDM symbol for downlink control signaling; CRS corresponding to one and four antenna ports; UE-specific reference signals corresponding to 24 and zero resource elements per resource-block pair. It was further assumed that physical broadcast channel and synchronization sequences occupy a total of 564 (Rel-10 MU-MIMO/CoMP with six MBSFN subframes per 10 ms) and 528 (Rel-8 downlink SU-MIMO) resource elements per radio frame for downlink eight- and four-layer spatial multiplexing, respectively. In addition, DL/UL configuration 1 (2 DL subframes, 1 special subframe, 2 uplink subframes) and special-subframe configuration 4 (12 DwPTS, 1 GP, 1 UpPTS, UpPTS is used for sounding reference signal transmission) are assumed for the TDD mode. The results shown in Table 11.16 suggest that LTE Rel-8 already fulfills the ITU-R requirements for downlink peak spectral efficiency. The table also shows the additional performance improvement that can be achieved using advanced features, for example, downlink eight-layer spatial multiplexing.

The uplink peak spectral efficiency is calculated assuming 20 MHz bandwidth, PUCCH occupying two pairs of resource blocks per subframe, and physical random access channel consuming six resource-block pairs per radio frame. The same TDDDL/UL and special-subframe configurations are assumed as for the downlink peak spectral efficiency calculation. Table 11.16 shows that the extension of LTE Rel-8 with two-layer spatial multiplexing can fulfill the ITU-R requirement in the uplink.

11.9.5 User-plane/control-plane latency and handover interruption time

The LTE user-plane one-way access latency for a scheduled UE consists of fixed node-processing delays, which include radio frame alignment and 1 ms transmission time interval (TTI) duration. Using the latency calculation model shown in Figure 11.11, and assuming that the number of HARQ processes is 8 for the FDD mode, the one-way latency is given as $T_{\text{USER-PLANE}} = 4 + 8p$ where p is the probability of HARQ retransmissions or the error probability of the first HARQ retransmission. While the minimum latency of $T_{\text{USER-PLANE}} = 4$ ms is achieved for $p = 0$, a more realistic value of $T_{\text{USER-PLANE}} = 4.8$ ms is obtained for $p = 0.1$.

Table 11.15 3GPP LTE Uplink Link-Level Simulation Results for the Mobility Requirements [2,6,14]					
Path Loss Model (LoS/NLoS)	Duplex Scheme	Test Environment	ITU-R Requirements	Median SINR (dB)	Uplink Spectral Efficiency (bits/s/Hz)
Antenna configuration 1 × 4 (NLoS)	FDD	InH	1.0	13.89	2.56
		UMi	0.75	4.54	1.21
		UMa	0.55	4.30	1.08
		RMa	0.25	5.42	1.22
Antenna configuration 1 × 4 (LoS)	FDD	InH	1.0	13.89	3.15
		UMi	0.75	4.54	1.42
		UMa	0.55	4.30	1.36
		RMa	0.25	5.42	1.45
Antenna configuration 1 × 4 (NLoS)	TDD	InH	1.0	13.89	2.63
		UMi	0.75	4.54	1.14
		UMa	0.55	4.30	0.95
		RMa	0.25	5.42	1.03
Antenna configuration 1 × 4 (LoS)	TDD	InH	1.0	13.89	3.11
		UMi	0.75	4.54	1.48
		UMa	0.55	4.30	1.36
		RMa	0.25	5.42	1.38

Table 11.16 3GPP LTE-Advanced Peak Spectral Efficiency [2]

Scheme	Duplex Scheme	Direction	Spectral Efficiency (bits/s/Hz)
ITU-R requirement	FDD	Downlink	15
Rel-8 four-layer spatial multiplexing			16.3
Eight-layer spatial multiplexing		Uplink	30.6
ITU-R requirement			6.75
Two-Layer spatial multiplexing	TDD	Downlink	8.4
Four-Layer spatial multiplexing			16.8
ITU-R requirement			15
Rel-8 four-layer spatial multiplexing			16.0
Eight-Layer spatial multiplexing		Uplink	30.0
ITU-R requirement			6.75
Two-Layer spatial multiplexing			8.1
Four-Layer spatial multiplexing			16.1

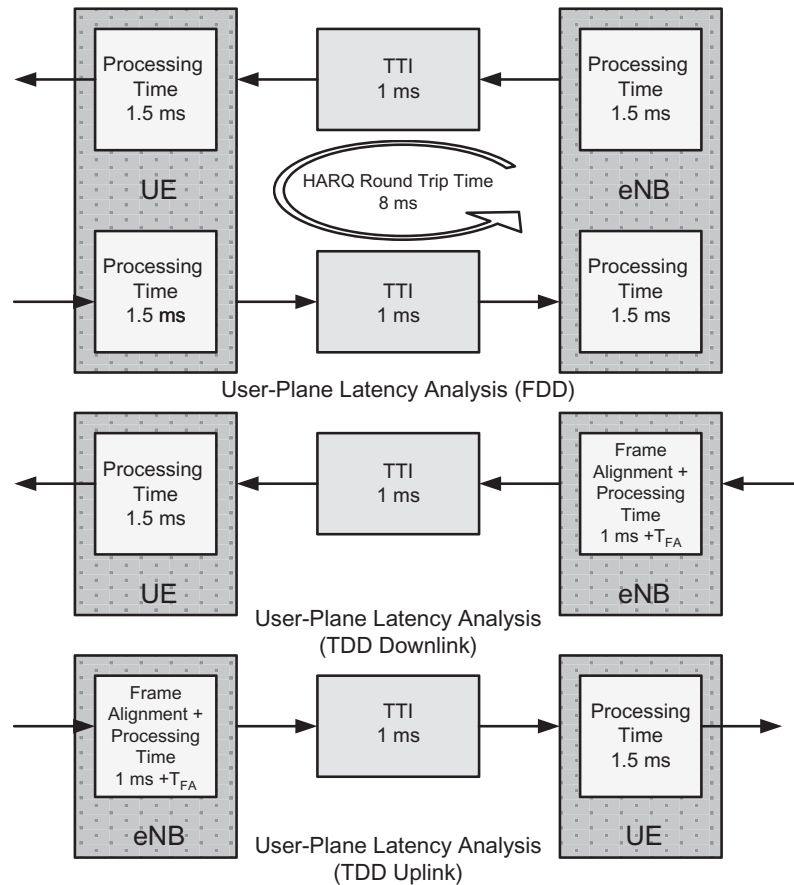
The user-plane one-way latency for a scheduled UE in the TDD mode consists of fixed node-processing delays, radio frame alignment, and TTI duration. The latency component can be seen in Figure 11.11 for the downlink and uplink. Using the latency model shown in Figure 11.11, the total one-way processing time is 2.5 ms, T_{FA} is the radio frame alignment which depends on various configurations of the TDD frame structure, and the TTI duration is 1 ms, hence, the user-plane latency of the TDD mode can be written as $T_{USER-PLANE} = 3.5 + T_{FA} + pT_{RTT}$ where T_{RTT} is the average HARQ round-trip time and p is the error probability of the first HARQ transmission.

Table 11.17 shows the user-plane latency component breakdown in downlink and uplink for different TDD DL/UL configurations when $p = 0.1$ is assumed. It is shown that in all cases, LTE can meet the ITU-R requirements for user-plane latency.

The above analysis further shows that the 5 ms user-plane latency requirement can be satisfied in the TDD mode in uplink and downlink using the DL/UL configuration 6 only when $p = 0$ is assumed.

In order to calculate the control-plane latency, the model shown in Figure 11.12 is used. The transition from the RRC_IDLE to the RRC_CONNECTED state in LTE comprises several steps that are shown in sequential order in Table 11.18.

While the results of the analysis suggest that LTE Rel-8 satisfies the ITU-R requirements, using the improved features and protocols introduced in later releases would allow reduction of the control-plane latency to 50 ms. Note that since the non-access stratum (NAS) setup process can be executed in parallel with the RRC connection setup, it does not appear in the total latency calculation.

**FIGURE 11.11**

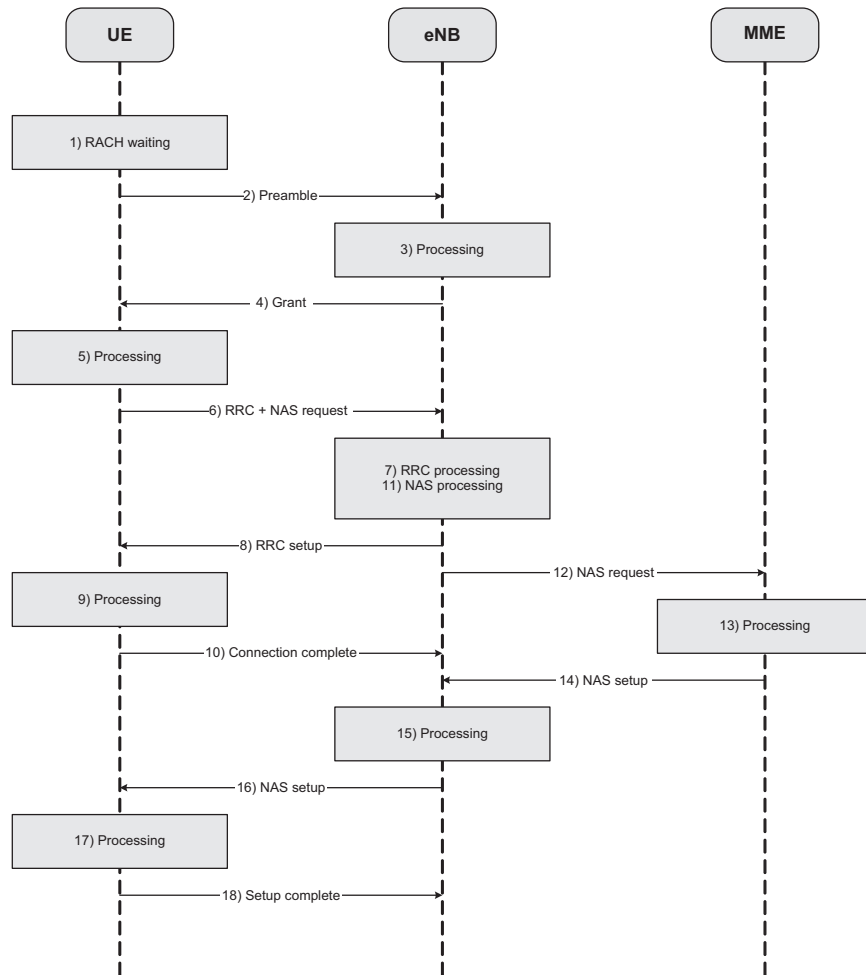
LTE user-plane latency calculation model [2].

The analysis shown in Table 11.18 shows that any of the LTE configurations can fulfill the ITU-R requirements related to control-plane latency.

The calculation of the user-plane latency was carried out for synchronized (or prescheduled) UEs. In the case where the UE is not prescheduled or when the UE is required to synchronize in order to be allocated uplink resources, reduced RACH scheduling period, shorter PUCCH cycle, and reduced processing delays can be applied to satisfy the control-plane latency requirements.

The LTE-Advanced general handover procedure is based on that of LTE Rel-8, which was described in Chapter 4, and is illustrated in Figure 11.13. The model shown in the figure has been used for calculation of the handover interruption time. As shown in the figure, once the handover command has been processed by

Table 11.17 TDD Mode User-Plane Latency Analysis with 10% HARQ Retransmission Probability [2]									
Step	Procedure	Direction	DL/UL Configuration						
			0	1	2	3	4	5	6
1	eNB processing delay (ms)	Downlink	1	1	1	1	1	1	1
2	Frame alignment (ms)		1.7	1.1	0.7	1.1	0.8	0.6	1.4
3	TTI duration (ms)		1	1	1	1	1	1	1
4	UE processing delay (ms)		1.5	1.5	1.5	1.5	1.5	1.5	1.5
5	HARQ retransmission (ms)		0.1×10	0.1×10.2	0.1×9.8	0.1×10.5	0.1×11.6	0.1×12.4	0.1×11.2
	Total one-way delay (ms)		6.2	5.62	5.18	5.65	5.46	5.34	6.02
1	UE processing delay (ms)	Uplink	1	1	1	1	1	1	1
2	Frame alignment (ms)		1.1	1.7	2.5	3.3	4.1	5	1.4
3	TTI duration (ms)		1	1	1	1	1	1	1
4	eNB processing delay (ms)		1.5	1.5	1.5	1.5	1.5	1.5	1.5
5	HARQ retransmission (ms)		0.1×11.6	0.1×10	0.1×10	0.1×10	0.1×10	0.1×10	0.1×11.5
	Total one-way delay (ms)		5.76	6.2	7	7.8	8.6	9.5	6.05

**FIGURE 11.12**

Analysis of RRC_IDLE to RRC_CONNECTED state transition in 3GPP LTE [2].

the UE, the UE detaches from the source eNB and stops receiving data. This marks a point in time where the user-plane connectivity is interrupted. The UE then performs frequency synchronization with the target eNB depending on whether the target cell is operating on the same carrier frequency as the current serving cell. Since the UE has already identified and measured the target cell, the corresponding delay will be negligible. The UE then performs downlink synchronization. Although baseband and RF timing alignments are part of the delay budget, since the UE has already acquired downlink synchronization with the target

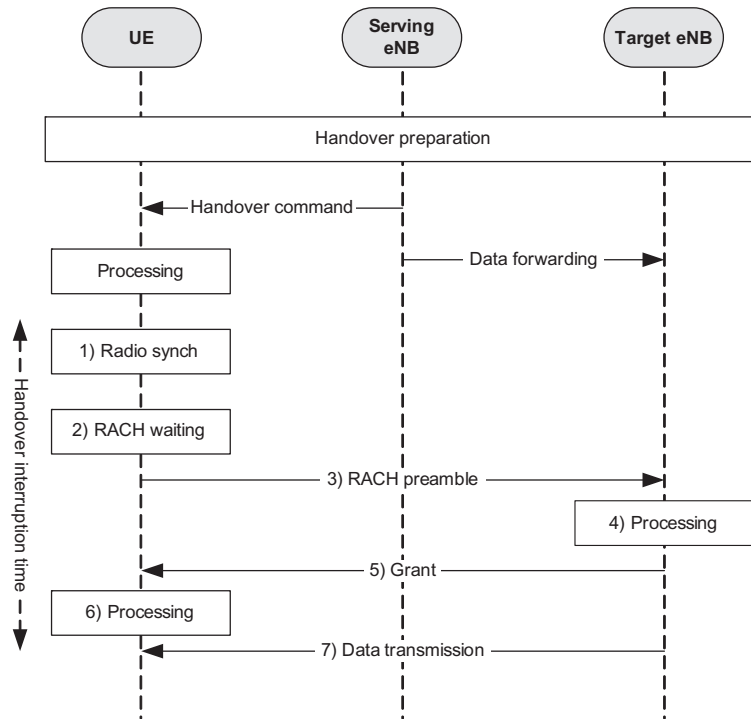
Table 11.18 Analysis of Control-Plane Latency Components [2]

Step	Procedure	Processing Time (ms)
1	Average delay due to RACH scheduling period (1 ms RACH cycle)	0.5
2	RACH preamble	1
3–4	Preamble detection and transmission of random access response (time between the end RACH transmission and UE's reception of scheduling grant and timing adjustment)	3
5	UE processing delay (decoding of scheduling grant, timing alignment, and C-RNTI assignment + L1 encoding of RRC connection request)	5
6	Transmission of RRC and NAS request	1
7	Processing delay in eNB (L2 and RRC)	4
8	Transmission of RRC connection setup and UL grant	1
9	Processing delay in the UE (L2 and RRC)	12
10	Transmission of RRC connection setup complete	1
11	Processing delay in eNB (Uu→S1-C)	—
12	S1-C transfer delay	—
13	MME Processing Delay (including UE context retrieval of 10 ms)	—
14	S1-C transfer delay	—
15	Processing delay in eNB (S1-C→Uu)	4
16	Transmission of RRC security mode command and connection reconfiguration + TTI alignment	1.5
17	Processing delay in UE (L2 and RRC)	16
	Control-plane delay	50

cell in conjunction with previous measurements and can relate the target cell downlink timing to the source cell downlink timing with a time offset, the corresponding delay is going to be less than 1 ms. The data forwarding between the two eNBs is initiated before the UE moves and establishes connection to the target cell, and because the backhaul is faster than the radio interface, forwarded data is already awaiting transmission in the target cell when the user-plane with the target cell is reestablished. The latter delay component thereby does not affect the overall delay.

Based on the analysis shown in Table 11.19, the minimum handover interruption time is 10.5 ms for the FDD mode and 12.5 ms for the TDD mode. Note that this delay does not depend on the frequency of the target cell as long as the cell frequency has already been measured by the UE during the measurement gap.

As explained earlier, the minimum handover interruption time is 10.5 ms for FDD and 12.5 ms for TDD regardless of the frequency of the target cell and

**FIGURE 11.13**

Model for calculation of handover interruption time [2,10].

measurements. Note that in the FDD mode, the average delay due to RACH scheduling is 0.5 ms assuming 1 ms RACH periodicity, whereas in the TDD mode, the minimum delay is obtained with configuration 0 (i.e., six normal uplink subframes); however, when taking into account the average waiting time for a downlink subframe to receive the random access response and to initiate transmission of downlink data, TDD configuration 1 (with random access preambles in special subframes) offers the shortest handover interruption time.

11.9.6 Estimation of the L1/L2 overhead

The downlink L1/L2 overhead of the LTE-Advanced includes different types of reference signals, that is, CRS transmitted within each resource block, UE-specific demodulation reference signals (DM-RS), and the reference signals that are specifically utilized in the estimation of CSI (CSI-RS). The overhead channels further include control signaling channels that are transmitted in the first L OFDM symbols ($L = 1, 2$, or 3) of each subframe ($L = 4$ in the case of 1.4 MHz bandwidth system bandwidth) and the synchronization signals, as

Table 11.19 Breakdown of Handover Interruption Time [2]

Step	Procedure	FDD Mode Processing Time (ms)	TDD Mode Processing Time (ms)
1	Radio synchronization to the target cell	1	1
2	Average delay due to RACH scheduling period assuming 1 ms periodicity	0.5	2.5
3	RACH preamble	1	1
4–5	Preamble detection and transmission of random access response (time between the end RACH transmission and UE's reception of scheduling grant and timing adjustment)	5	5
6	Decoding of scheduling grant and timing alignment	2	2
7	Transmission of downlink data	1	1
	Handover interruption time	10.5	12.5

well as physical broadcast control channel. The protocol headers corresponding to layer-2 sub-layers (MAC/RLC/PDCP) were also included in the self-evaluation results. The overhead due to CRS and L1/L2 control signaling depend on the number of antenna ports and the number of OFDM symbols used for the control region. The number of overhead resource elements per resource-block pair (168 resource elements in total) and the corresponding relative overhead is shown in Table 11.20 for non-MBSFN and MBSFN subframes. The overhead (due to L1/L2 control signaling and CRS) in Table 11.20 is shown in terms of the number of resource elements per resource-block pair and in percentages.

In the case of MBSFN subframes, the overhead is reduced. All subframes in a radio frame are assumed to be either regular or MBSFN type in overhead estimation. The total overhead depends on the fraction of MBSFN subframes. In the self-evaluation results, a fraction of 0% and 60% was assumed. The overhead due to UE-specific reference signals depends on the number of UE-specific antenna-ports and is 12 resource elements (7.1%) for one and two antenna ports, and 24 resource elements (14.3%) for three to eight antenna ports. Note that the overhead due to UE-specific reference signals is only present in resource blocks in which UE-specific reference signals are transmitted.

The relative overhead due to synchronization signals and physical broadcast channel depends on the operation bandwidth. A total of 528 resource elements per 10 ms radio frame are used for the synchronization signals and physical broadcast channel for four CRS antenna ports, corresponding to approximately 0.6% and 0.3% overhead for 10 and 20 MHz operating bandwidth, respectively.

Table 11.20 LTE-Advanced L1/L2 Overhead [2,6]							
Control-Region Size	Subframe Type	FDD Duplex Scheme			TDD Duplex Scheme		
		Number of Cell-Specific Antenna Ports			Number of Cell-Specific Antenna Ports		
		1	2	4	1	2	4
$L = 1$	Regular subframes	18 (10.7%)	24 (14.3%)	32 (19.0%)	18 (10.7%)	24 (14.3%)	32 (19.0%)
$L = 2$		30 (17.9%)	36 (21.4%)	40 (23.9%)	30 (17.9%)	36 (21.4%)	40 (23.9%)
$L = 3$		42 (25%)	48 (28.6%)	52 (31.0%)	42 (25%)	48 (28.6%)	52 (31.0%)
$L = 1$	MBSFN subframes	12 (7.1%)	12 (7.1%)	12 (7.1%)	12 (7.1%)	12 (7.1%)	12 (7.1%)
$L = 2$		24 (14.2%)	24 (14.2%)	24 (14.2%)	24 (14.2%)	24 (14.2%)	24 (14.2%)
$L = 3$		36 (21.4%)	36 (21.4%)	36 (21.4%)	36 (21.4%)	36 (21.4%)	36 (21.4%)

The overhead due to protocol headers is proportional to data packet size and is approximately 2.7%, 0.51%, and 0.32% for physical-layer data rates of 1, 10, and 100 Mbps, respectively. This overhead was not included in the self-evaluation results. The relative overhead due to CSI-RS depends on the number of antennas and periodicity. In a typical case, it is about 0.12% per antenna port (0.48% for four antenna ports and 0.96% for eight antenna ports). The relative overhead due to UE-specific reference signals is estimated at approximately 7% in case of rank 1 and rank 2 transmission, and 14% for rank 3 to rank 8 transmission.

In the uplink, the L1/L2 overhead includes the demodulation reference symbols that are used in uplink channel estimation for coherent demodulation and are transmitted once every 0.5 ms. It further includes the sounding reference signal used for uplink channel state estimation at the eNB and the L1/L2 control signaling transmitted on configurable amount of resource blocks, as well as L2 control overhead due to random access, uplink time-alignment control, power headroom reports, and buffer-status reports. The L2 overhead associated with the PDU headers (MAC/RLC/PDCP) is further taken into consideration in the total overhead calculation. The amount of overhead due to DM-RS is approximately 14%, corresponding to one SC-FDMA symbol in each slot. The relative overhead is estimated independent of the rank of the transmission. The amount of SRS overhead depends on the sounding reference signal transmission interval and the bandwidth. Using a 10 ms SRS transmission interval and full-band SRS, the relative overhead is approximately 0.7%. The amount of uplink resources reserved for random access depends on the PRACH configuration, for example, a typical case with PRACH preamble format 0 is six resource blocks per radio frame, resulting in a relative overhead of 0.6%, 1.2%, and 2.4% for a channel bandwidth of 20, 10, and 5 MHz, respectively.

The relative overhead due to uplink timing-alignment control depends on the configuration and the number of active UEs within a cell. The absolute overhead is typically less than 32 bits/s per UE. The amount of overhead for buffer-status reports depends on the configuration; assuming a continuous data and reporting interval of 10–20 ms, the absolute overhead is 0.8–3.2 kbps. The amount of overhead due to protocol headers depends on the data packet size and is approximately 2.7%, 0.51%, and 0.32% for L1 data rates of 1, 10, and 100 Mbps, respectively. The above overhead calculations are based on a normal cyclic prefix length. In the case of MBSFN subframes in the TDD mode, all the subframes are assumed to be of MBSFN type in the overhead estimation. The total overhead depends on the fraction of MBSFN subframes. In self-evaluation results, a fraction of 0% and 33% has been assumed for a TDDDL:UL ratio of 3:2 (i.e., TDDDL:UL configuration 1).

In the TDD mode, the relative overhead due to synchronization signals and physical broadcast channel depends on the operation bandwidth and DL/UL configuration. A total of 528 resource elements per 10 ms radio frame are used for the synchronization signals and the broadcast channel when using four CRS antenna ports. For a DL:UL ratio of 3:2, the latter overhead translates into

approximately 1.0% and 0.5%, for 10 and 20 MHz operation bandwidth, respectively. The amount of SRS overhead depends on the SRS transmission interval and bandwidth as well as the usage of UpPTS in the special subframe. For a DL:UL ratio of 3:2 with four DL/UL switching points per 10 ms radio frame, the SRS transmission interval of 5 ms and full-band SRS within UpPTS, the relative overhead is approximately 3.45%. The amount of uplink resources reserved for random access depends on the configuration of the random access channel. In a typical case with a DL:UL ratio of 3:2 and PRACH preamble format 0, i.e., six resource blocks per radio frame are used for the PRACH, resulting in a relative overhead of 1.4%, 2.8%, and 5.6% for channel bandwidth of 20, 10, and 5 MHz, respectively.

11.9.7 Link budget

The LTE-Advanced link budget under various deployment scenarios specified by ITU-R was evaluated as part of the IMT-Advanced submission (Table 11.21). Table 11.21 summarizes the link budget of the TDD mode. It is shown that LTE-Advanced control and data channel coverage meets the IMT-Advanced link budget requirements.

11.9.8 Evaluation of LTE-Advanced against LTE Rel-10 requirements

This section provides the self-evaluation results of LTE-Advanced against LTE Rel-10 requirements [3], where the target values for cell spectral efficiency and cell-edge spectral efficiency are specified for 3GPP case 1 channel model [4] with 2×2 , 4×2 , and 4×4 antenna configurations in the downlink, and 1×2 and 2×4 antenna configurations in the uplink. Table 11.22 shows the downlink/uplink cell and cell-edge spectral efficiency results under 3GPP Case 1 configuration for the FDD and TDD modes. The results suggest that, if LTE Rel-8 is extended with MU-MIMO 4×2 in the downlink, the LTE Rel-10 performance targets can be fulfilled. The table also includes the advanced features by which the performance can be further improved. The uplink performance results indicate that LTE Rel-8 SIMO and LTE-Advanced CoMP, SU-MIMO, and MU-MIMO schemes can fulfill the LTE Rel-10 requirements. In 3GPP case 1 scenario, the center frequency is 2.0 GHz, the transmission bandwidth is 2×10 MHz for the FDD mode and 20 MHz for the TDD mode, inter-site distance is 500 m, the penetration loss is 20 dB, and all users are assumed moving at 3 km/h.

11.10 Miscellaneous evaluations

In order to investigate the usage and advantages of various LTE downlink MIMO schemes in realistic deployment scenarios, link-level and system-level simulations were performed under certain assumptions [47–49]. In order to

Table 11.21 LTE-Advanced Link Budget in Various Deployment Scenarios for the TDD Mode [2,6,15]								
Parameter	InH		UMi		UMa		RMa	
	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink
System Configuration								
Carrier frequency (GHz)	3.4	3.4	2.5	2.5	2.0	2.0	0.8	0.8
BS antenna heights (m)	6	6	10	10	25	25	35	35
MS antenna heights (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Cell area reliability for control channels	95%	95%	95%	95%	95%	95%	95%	95%
Cell area reliability for control channels	90%	90%	90%	90%	90%	90%	90%	90%
Transmission bit rate for control channel (kbps)	46.93	1.60	44.80	1.60	44.80	1.60	44.80	1.60
Transmission bit rate for data channel (Mbps)	4.65	0.37	2.25	0.074	2.25	0.074	2.25	0.074
Target packet error rate for control channels	1%	1%	1%	1%	1%	1%	1%	1%
Target packet error rate for data channels	10%	10%	10%	10%	10%	10%	10%	10%
Spectral efficiency (bits/s/Hz) for data	0.23	0.52	0.22	0.21	0.22	0.21	0.22	0.21
Path loss model	NLoS	NLoS	NLoS	NLoS	NLoS	NLoS	NLoS	NLoS
Mobile speed (km/h)	3	3	3	3	30	30	120	120
Feeder loss (dB)	2	2	2	2	2	2	2	2
Transmitter								
Number of transmit antennas	2	1	2	1	2	1	2	1
Maximum transmit power per antenna (dBm)	21	21	41	24	46	24	46	24
Total transmit power (dBm)	24	21	44	24	49	24	49	24
Transmitter antenna gain (dBi)	0	0	17	0	17	0	17	0

(Continued)

Table 11.21 (Continued)								
Parameter	InH		UMi		UMa		RMa	
	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink
Transmitter array gain (dB)	0	0	0	0	0	0	0	0
Control channel power boosting gain (dB)	0	0	0	0	0	0	0	0
Data channel power loss due to pilot/control boosting (dB)	0	0	0	0	0	0	0	0
Cable, connector, combiner, body losses, etc. (dB)	3	1	3	1	3	1	3	1
Control channel EIRP (dBm)	21	20	58	23	63	23	63	23
Data channel EIRP (dBm)	21	20	58	23	63	23	63	23
Receiver								
Number of receive antennas	2	4	2	4	2	4	2	4
Receiver antenna gain (dBi)	0	0	0	17	0	17	0	17
Cable, connector, combiner, body losses, etc. (dB)	1	3	1	3	1	3	1	3
Receiver noise figure (dB)	7	5	7	5	7	5	7	5
Thermal noise density (dBm/Hz)	− 174	− 174	− 174	− 174	− 174	− 174	− 174	− 174
Receiver interference density for control channels (dBm/Hz)	− 174	− 174.9	− 169.3	− 161.7	− 169.3	− 161.7	− 169.3	− 161.7
Receiver interference density for data channels (dBm/Hz)	− 174	− 174.9	− 169.3	− 165.7	− 169.3	− 165.7	− 169.3	− 165.7
Total noise plus interference density for control channels (dBm/Hz)	− 167	− 168	− 165	− 161	− 165	− 161	− 165	− 161
Total noise plus interference density for data channels (dBm/Hz)	− 167	− 168	− 165	− 164	− 165	− 164	− 165	− 164

Occupied channel bandwidth for control channels (MHz)	36	0.18	18	0.18	18	0.18	18	0.18
Occupied channel bandwidth for data channels (MHz)	36	1.8	18	0.90	18	0.9	18	0.90
Effective noise power for control channels (dBm)	-91	-115	-92	-108	-92	-108	-92	-108
Effective noise power for control channels (dBm)	-91	-105	-92	-104	-92	-104	-92	-104
Required SNR for the control channel (dB)	-4.2	-10.6	-4.2	-10.5	-4.2	-10.1	-4.2	-9.9
Required SNR for the data channel (dB)	-1.6	-2.3	-1.7	-5.5	-1.7	-5.1	-1.7	-4.8
Receiver implementation margin (dB)	2	2	2	2	2	2	2	2
HARQ gain for control channel (dB)	0	0	0	0	0	0	0	0
HARQ gain for data channel (dB)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Receiver sensitivity for control channel (dBm)	-94	-124	-95	-117	-95	-117	-95	-116
Receiver sensitivity for data channel (dBm)	-91	-106	-93	-108	-93	-108	-93	-108
Hardware link budget for control channel (dB)	115	144	153	157	158	157	158	156
Hardware link budget for data channel (dB)	113	126	151	148	156	148	156	148
Calculation of Available Path Loss								
Lognormal shadow fading standard deviation (dB)	4	4	4	4	6	6	8	8
Shadow fading margin for control channels (dB)	2.8	2.8	3.1	3.1	5	5	5	5
Shadow fading margin for data channels (dB)	0.9	0.9	1.3	1.3	8.1	8.1	10.5	10.5
BS selection/macro-diversity gain (dB)	0	0	0	0	4.9	4.9	6.7	6.7

(Continued)

Table 11.21 (Continued)								
Parameter	InH		UMi		UMa		RMa	
	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink
Penetration loss (dB)	0	0	0	0	0	0	0	0
Other gains (dB)	0	0	0	0	9	9	9	9
Available path loss for control channel (dB)	111	138	149	151	0	0	0	0
Available path loss for data channel (dB)	111	122	148	144	140	136	137	134
Range/Coverage Efficiency Calculation								
Maximum range for control channel (m)	100.0	100.0	1405.2	1621.2	1175.6	978.0	3210.9	2634.3
Maximum range for data channel (m)	100.0	100.0	1383.9	1062.7	1258.4	714.4	3565.5	1975.1
Coverage area for control channel (km ² /site)	0.031	0.031	6.20	8.26	4.34	3.01	32.4	21.8
Coverage area for data channel (km ² /site)	0.031	0.031	6.02	3.55	4.97	1.60	39.9	12.3

Table 11.22 Self-Evaluation of LTE-Advanced Against LTE Rel-10 Requirements [4]

Scheme and Antenna Configuration	Direction	Duplex Scheme	Rel-10 Requirements (Cell Spectral Efficiency/Cell-Edge Spectral Efficiency)	Cell Spectral Efficiency (bits/s/Hz/cell)	Cell-Edge Spectral Efficiency (bits/s/Hz)
				$L = 3$	$L = 3$
MU-MIMO 2 × 2 (C)	Downlink	FDD	2.4/0.07	2.69	0.090
JP-CoMP 2 × 2 (C)			2.4/0.07	2.70	0.104
MU-MIMO 4 × 2 (C)			2.6/0.09	3.43	0.118
CS/CB-CoMP 4 × 2 (C)			2.6/0.09	3.34	0.129
JP-CoMP 4 × 2 (C)			2.6/0.09	3.87	0.162
MU-MIMO 4 × 4 (C)			3.7/0.12	4.69	0.203
CS/CB-CoMP 4 × 4 (C)			3.7/0.12	4.66	0.205
JP-CoMP 4 × 4 (C)			3.7/0.12	5.19	0.269
MU-MIMO 2 × 2 (C)		TDD	2.4/0.07	2.88	0.113
JP-CoMP 2 × 2 (C)			2.4/0.07	3.15	0.130
MU-MIMO 4 × 2 (C)			2.6/0.09	3.76	0.151
JP-CoMP 4 × 2 (C)			2.6/0.09	4.64	0.199
MU-MIMO 4 × 4 (C)			3.7/0.12	4.97	0.209

(Continued)

Table 11.22 (Continued)					
Scheme and Antenna Configuration	Direction	Duplex Scheme	Rel-10 Requirements (Cell Spectral Efficiency/Cell-Edge Spectral Efficiency)	Cell Spectral Efficiency (bits/s/Hz/cell) <i>L</i> = 3	Cell-Edge Spectral Efficiency (bits/s/Hz) <i>L</i> = 3
CS/CB-CoMP 4 × 4 (C)	Uplink	FDD	3.7/0.12	5.06	0.244
JP-CoMP 4 × 4 (C)			3.7/0.12	6.61	0.330
Rel-8 SIMO 1 × 2 (C)			1.2/0.04	1.33	0.047
CoMP 1 × 2 (C)		TDD	1.2/0.04	1.40	0.051
SU-MIMO 2 × 4 (C)			2.0/0.07	2.27	0.091
Rel-8 SIMO 1 × 2 (C)			1.2/0.04	1.24	0.045
CoMP 1 × 2 (C)			1.2/0.04	1.51	0.051
SU-MIMO 2 × 4 (C)			2.0/0.07	2.15	0.090
MU-MIMO 2 × 4 (C)			2.0/0.07	2.59	0.079

Table 11.23 System-Level Simulation Parameters (Other Parameters Same as [4] Case 1 Scenario)	
Parameter/Feature	Value/Configuration
Bandwidth	1.4 MHz
Frequency	2.1 GHz
Network layout	19-cell wrap-around (tri-sector with 3D antenna models)
Scheduler algorithm	Proportional fair
Channel model	WINNER +
Receiver type	Zero-forcing
Simulation length	5000 subframes
Number of UEs/Cell	10
Path loss model	$PL = 128.1 + 37.6 \log_{10} R$
Feedback delay	Modeled

reduce the simulation run time, a 1.4 MHz system bandwidth was assumed. Figures 11.14–11.19 show snapshots of the simulation results. Table 11.23 provides the assumptions that were made in addition to baseline configuration for 3GPP case 1 that is included in 3GPP TR 36.814 [4]. The UEs are randomly dropped in the cell, but all UEs are assumed to be in the outdoor area. MIESM link-to-system mapping scheme is used in the simulations.

Figure 11.14 shows the LTE-Advanced downlink throughput versus SNR, as well as downlink spectral efficiency CDF for SISO and closed-loop spatial multiplexing (CLSM) transmission mode 4 with various antenna configurations.

The CDF of wideband SINR (geometry) with macroscopic path loss with and without additional lognormal-distributed space-correlated shadow fading is illustrated in Figure 11.15. The downlink spectral efficiency (bits/s/Hz) for various MIMO configurations with lognormal-distributed space-correlated shadow fading effect is shown in Figure 11.16. This figure shows how spectral efficiency is distributed geographically across the cells and the network. In particular, the cell-edges and the effect of MIMO to improve cell-edge performance must be noted. Figure 11.17 illustrates the sector SINR calculated with distance-dependent macroscopic path loss and additional lognormal-distributed space-correlated shadow fading. In this case we assume a SISO configuration. Figure 11.18 depicts downlink spectral efficiency (bits/s/Hz) without the effect of shadow fading. The geographical distribution of sector SINR calculated with distance-dependent macro-scale path loss is shown in Figure 11.19. Figure 11.19 further shows CQI mapping across the cell. As expected, the lower modulation order and coding rates are used near cell-edges, and as we move toward the eNB, higher CQI values are reported by the UEs. The results closely correlate with the expectations of the system behavior as well as those published in the literature under given assumptions.

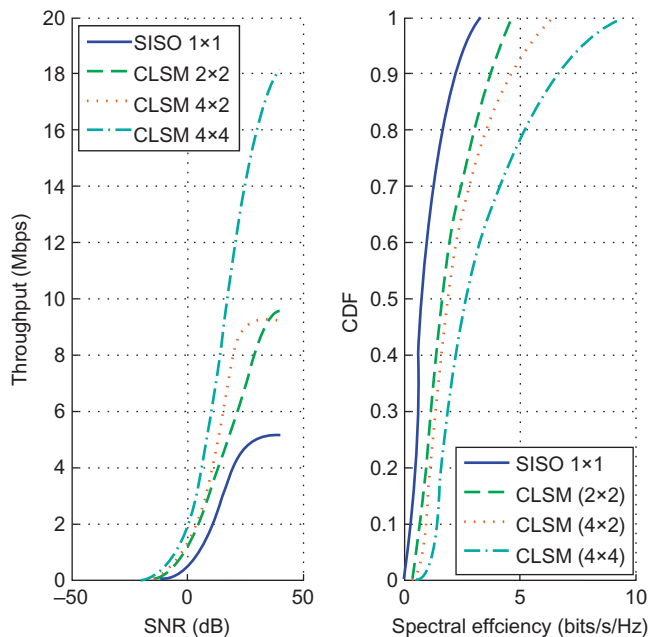


FIGURE 11.14

LTE-Advanced downlink throughput versus SNR and spectral efficiency CDF for various MIMO modes (1.4 MHz bandwidth) [45].

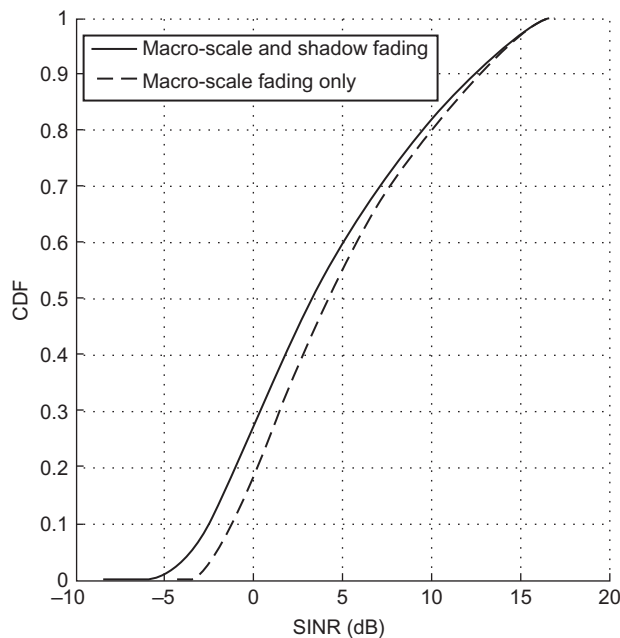


FIGURE 11.15

Distribution of downlink wideband SINR [45].

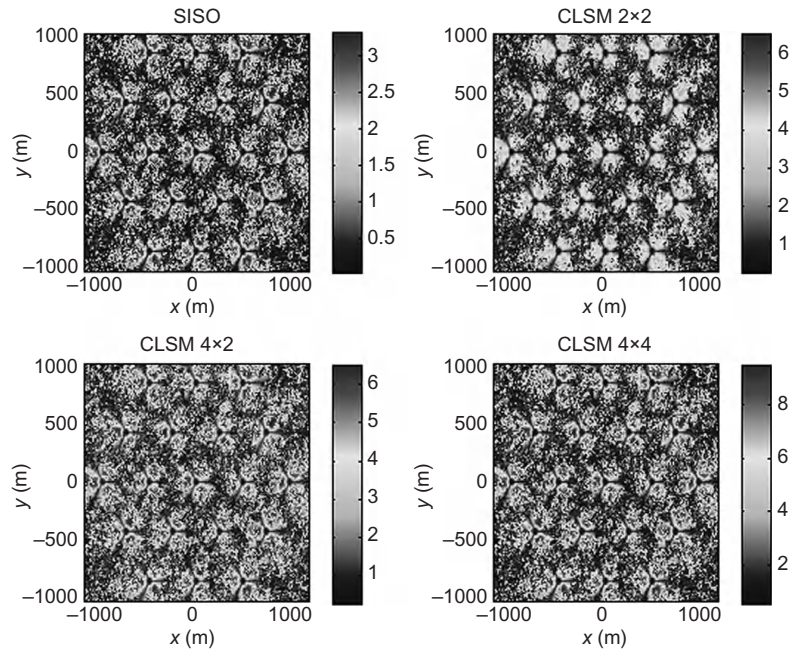


FIGURE 11.16

Spectral efficiency (bits/s/Hz) for various MIMO configurations (1.4 MHz bandwidth, with shadow fading) [45]

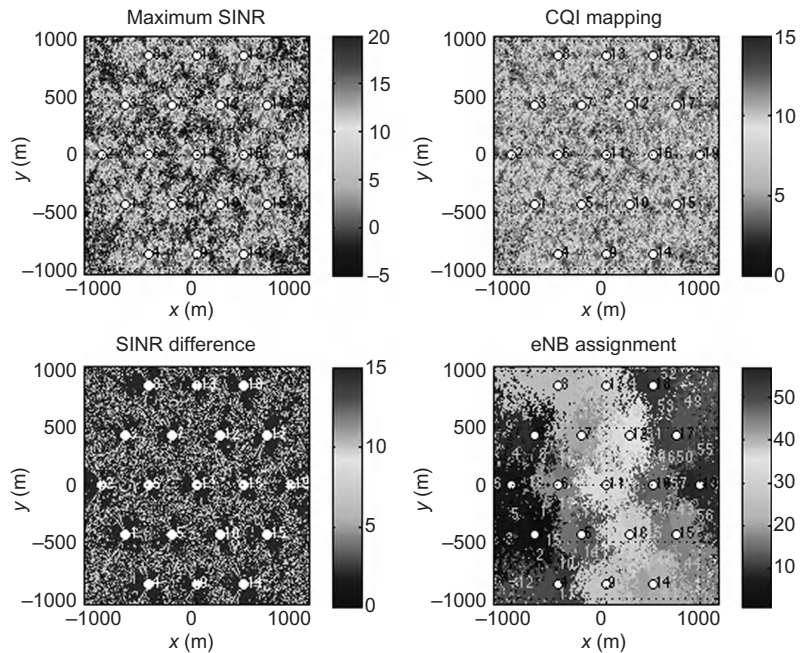


FIGURE 11.17

Sector SINR calculated with distance-dependent macroscopic path loss and additional lognormal-distributed space-correlated shadow fading (1.4 MHz bandwidth, SISO) [45]

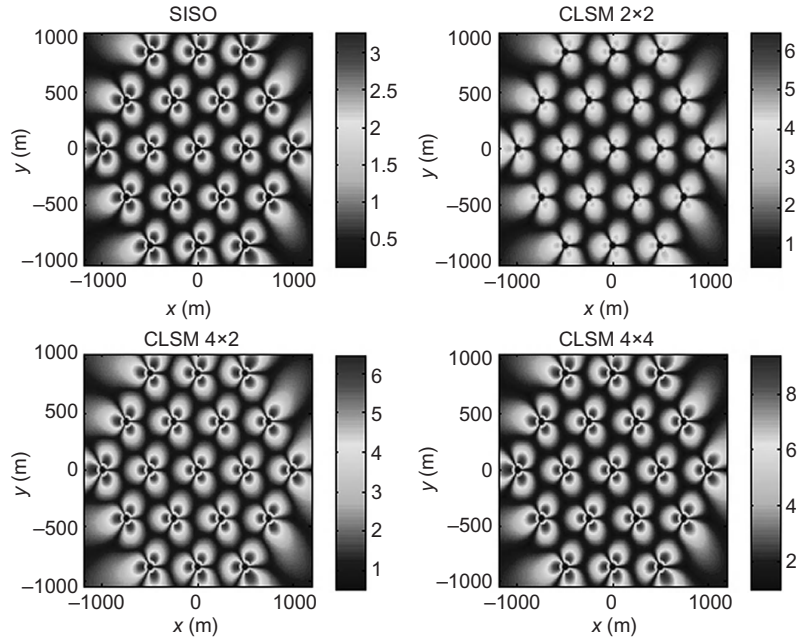


FIGURE 11.18

Spectral efficiency (bits/s/Hz) (1.4 MHz bandwidth and no shadow fading) [45]

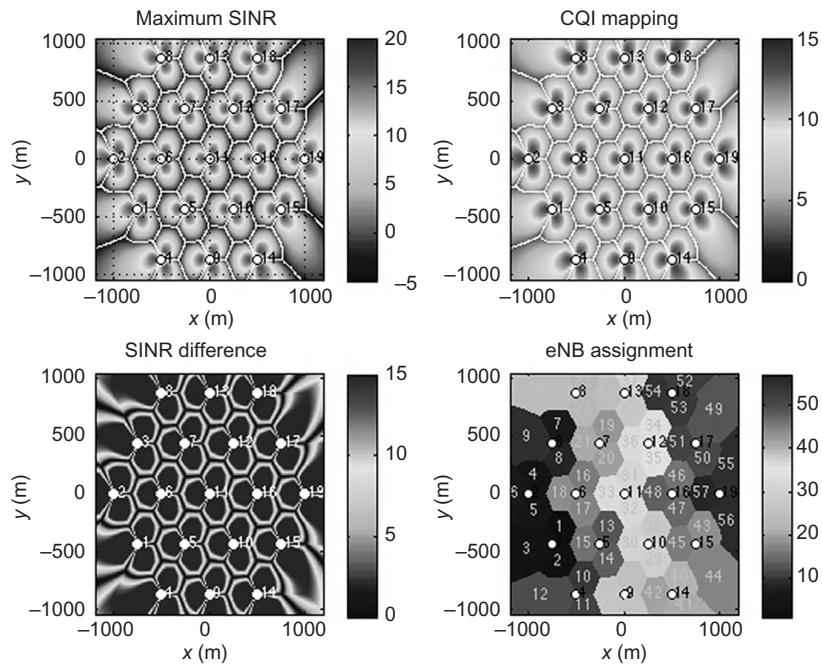


FIGURE 11.19

Sector SINR calculated with distance-dependent macro-scale path loss and CQI mapping (1.4 MHz bandwidth, SISO) [45]

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Coordinated Multipoint Transmission and Reception (CoMP)

12

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The MIMO or network MIMO techniques are used for improving sector throughput and cell-edge throughput through multi-cell collaborative precoding, network coordinated beamforming, or inter-cell interference nulling. When a mobile station is at the cell-edge, it may be able to receive signals from multiple cell sites, and the mobile station's transmission may also be received at multiple cell sites. If the data transmission and signaling from multiple cell sites can be coordinated, the downlink performance can be significantly improved. This coordination can be similar to the interference avoidance techniques or the case where the same data is transmitted from multiple cell sites. In the uplink, since the signal can be received by multiple cell sites, the system can take advantage of coordinated multi-point reception to significantly improve the link performance. The coordinated multi-point (CoMP) transmission/reception specified in long-term evolution (LTE) Rel-11 is a method of MIMO transmission for interference reduction, which enables features such as network synchronization, cell- and user-specific reference signals, feedback of

multi-cell channel state information (CSI), and synchronous data transfer between the base stations that can be used for interference mitigation and to achieve macro-diversity gain [23–26].

The LTE Rel-11 specifications provide support for coordinated transmission in the downlink and coordinated reception in the uplink. The use cases include homogeneous configurations, where the points are different cells, as well as heterogeneous configurations, where a set of low-power nodes (e.g., remote radio heads (RRH) or pico-cells) are located in the geographical area served by a macro-cell. For coordinated transmission in the downlink, the signals transmitted from multiple transmission points are coordinated to improve the received strength of the desired signal at the UE or to reduce the co-channel interference. The main advantage of coordinated reception in the uplink is to ensure that the uplink signal from the UE is reliably received by the network while limiting uplink interference, taking into account the existence of multiple reception points. Note that the mechanisms discussed in this chapter apply to both FDD and TDD modes of operation [5].

In this chapter, we will discuss the theoretical and practical aspects of coordinated multipoint transmission/reception not only from the radio access network perspective, but also from the core network and backhaul point of view and will investigate whether some of the proposed schemes would realistically offer any gains when their backhaul implications and cost of implementation and operation are considered.

12.1 Interference cancellation in cellular networks

In the downlink of an LTE system, the UE often suffers from different types of interference. In the case of single-user MIMO (SU-MIMO), the signal received by the UE includes a linear combination of multiple streams, which causes inter-stream interference. On the other hand, in a multi-user MIMO (MU-MIMO) scenario, where a single cell communicates with many UEs simultaneously using the same time–frequency resources, the signal received by each UE suffers from interference caused by the signals intended for other UEs served by the same cell. This interference is known as inter-user interference. A UE at the cell-edge suffers from inter-cell interference, i.e., interference caused by the signals sent from a neighbor cell to its UEs. The neighbor cell might belong to the same site as the serving cell (intra-site) or to a different site (inter-site). Different interference cancellation schemes are applied at the receiver to mitigate the interference in the above cases. While the inter-stream interference cancellation can be performed at the UE without requiring any additional information, inter-user interference cancellation may require knowledge of the precoding matrices of the other UEs that one wishes to cancel. Moreover, the inter-cell interference cancellation needs an estimate of the channels seen between the neighbor interfering cells and the UE. The above interference models are illustrated in Figure 12.1 [26].

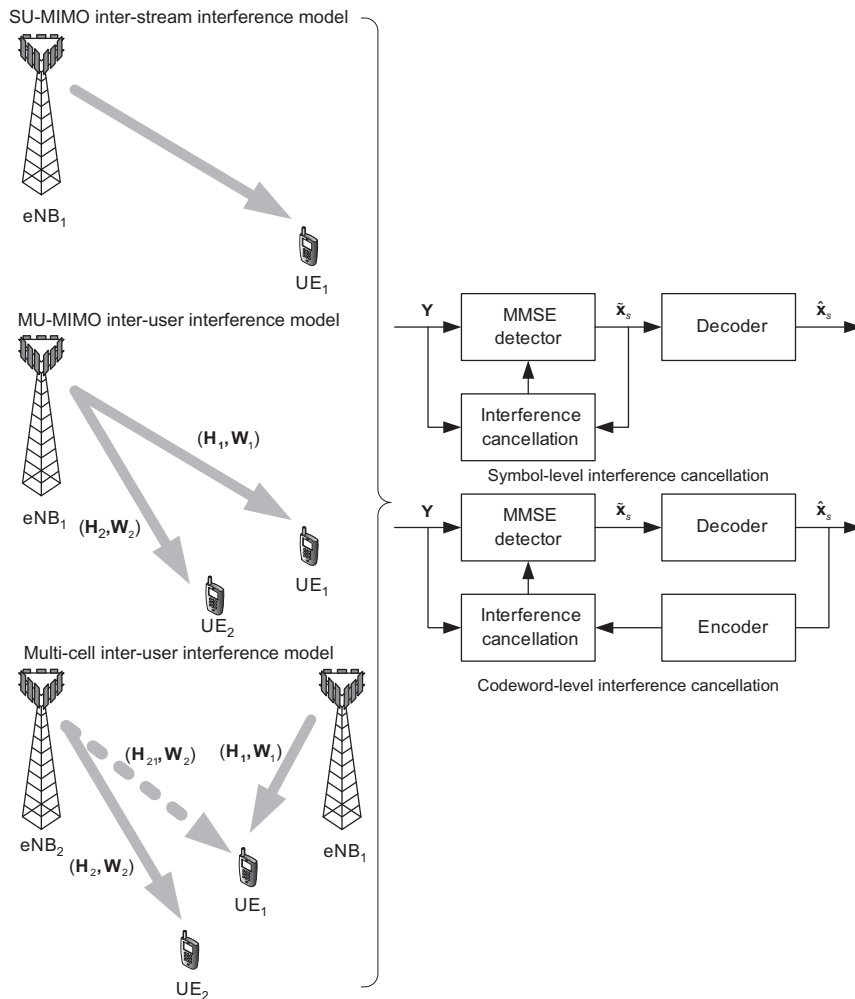
**FIGURE 12.1**

Illustration of interference models and cancellation at symbol and codeword level [26].
MMSE, minimum mean square error.

Let us consider a scenario where eNBs and UEs have multiple transmit/receive antennas (i.e., a MIMO channel). As shown in Figure 12.1 and in the case of a SU-MIMO inter-stream interference model, the signal received at the UE includes, in addition to noise, a linear combination of multiple streams. The beam is generated by using a non-identity precoding matrix. For simplicity, we assume that the channel is flat. In order to mitigate the inter-stream interference at the

UE, interference cancellation can be applied either at the modulated symbol level, where we cancel the estimated interfering stream before decoding, or at the code-word level where we cancel the interfering decoded codeword (see Figure 12.1).

Interference cancellation techniques have been widely studied in the literature [23–26]. While successive interference cancellation scheme processes each stream successively by canceling the previously decoded streams, parallel interference cancellation scheme processes all stream in parallel and cancel their interference after they have all been decoded independently. In order to avoid the propagation of interference cancellation error, each stream can be canceled only if it was correctly decoded by checking the corresponding decoded packet cyclic redundancy check (CRC). Successive interference cancellation can also be done iteratively, i.e., after the first iteration over all streams; we can further improve the quality of the decoded streams by canceling the residual errors estimated in the first iteration, and so on. There are methods proposed in the literature for reducing the complexity of iterative interference cancellation algorithms. In Figure 12.1, and in the case of the MU-MIMO inter-user interference model, the cell serves both UEs simultaneously using the same time–frequency resources. The first user UE_1 receives, in addition to its own data, interference due to data intended for the second user UE_2 , i.e., inter-user interference. In order to cancel the inter-user interference, UE_1 needs to know the precoding matrix $\mathbf{W}_2$ that was used for UE_2 . In general, $\mathbf{W}_2$ is not known by UE_1 , and some additional signaling would be required in order to make $\mathbf{W}_2$ available at UE_1 .

In Figure 12.1 and in the case of the multi-cell MU-MIMO interference model, UE_1 at the cell-edge is served by the eNB_1 through channel $\mathbf{H}_1$ and with the precoding matrix $\mathbf{W}_1$, and suffers from inter-cell interference, i.e., interference from the neighbor cell which serves another user UE_2 with the precoding matrix $\mathbf{W}_2$. In order to cancel the inter-cell interference, UE_1 needs an estimate of the channel $\mathbf{H}_{21}$ and the precoding matrix $\mathbf{W}_2$ intended for UE_2 . The channel $\mathbf{H}_{21}$ can be estimated by UE_1 based on some reference signals sent from the neighbor cell. The precoding matrix $\mathbf{W}_2$ is in general not known by UE_1 and would require some additional signaling from eNB_2 .

Let us consider the case of multi-cell inter-user interference shown in Figure 12.1. It can be shown that the signal to interference plus noise ratio (SINR) at UE_1 can be formulated as follows:

$$\text{SINR}_1(\mathbf{W}_1, \mathbf{W}_2) = \frac{|\mathbf{H}_1 \mathbf{W}_1|^2}{\sigma_n^2 + \sigma_f^2 + |\mathbf{H}_{21} \mathbf{W}_2|^2} \quad (12.1)$$

In Eq. (12.1), $\mathbf{W}_1$ and $\mathbf{W}_2$ represent the beamforming optimization matrices/vectors at the eNBs; $\mathbf{H}_1$ and $\mathbf{H}_{21}$ denote information that is not typically available at the CoMP scheduling unit, but measurable at the UEs; σ_n^2 denotes the receiver noise variance; and σ_f^2 indicates the interference from eNBs outside the coordinated set. Thus, the inter-cell interference propagated through channels $\mathbf{H}_{21}$ and $\mathbf{H}_{12}$ results in degradation of SINR measured at UE_1 and UE_2 , respectively.

As mentioned above, the UE in the downlink of an LTE system can suffer from inter-stream, inter-user, and/or intra-site/inter-cell interference. While the UE is able to perform inter-stream interference cancellation without any additional information, it needs the precoding matrices of other UEs served by the same cell in an MU-MIMO system in order to cancel the interuser interference, and it additionally requires an estimate of the channels of the interfering neighboring cells in order to be able to cancel the inter-cell interference. An important use case for successive interference cancellation is MU-MIMO, but the principles can also be generalized to CoMP schemes. Multi-user MIMO is well known to improve the spectral efficiency by allowing a group of users to simultaneously share the same radio resources. In addition, MIMO provides antenna gain that improves the overall performance. The capacity region of the multi-user channel can be theoretically increased by MIMO through the so-called multiplexing gain. For the spatially separated (uncorrelated) users, the multiplexing gain can be achieved if CSI is available at the base station.

12.2 Distributed antenna systems

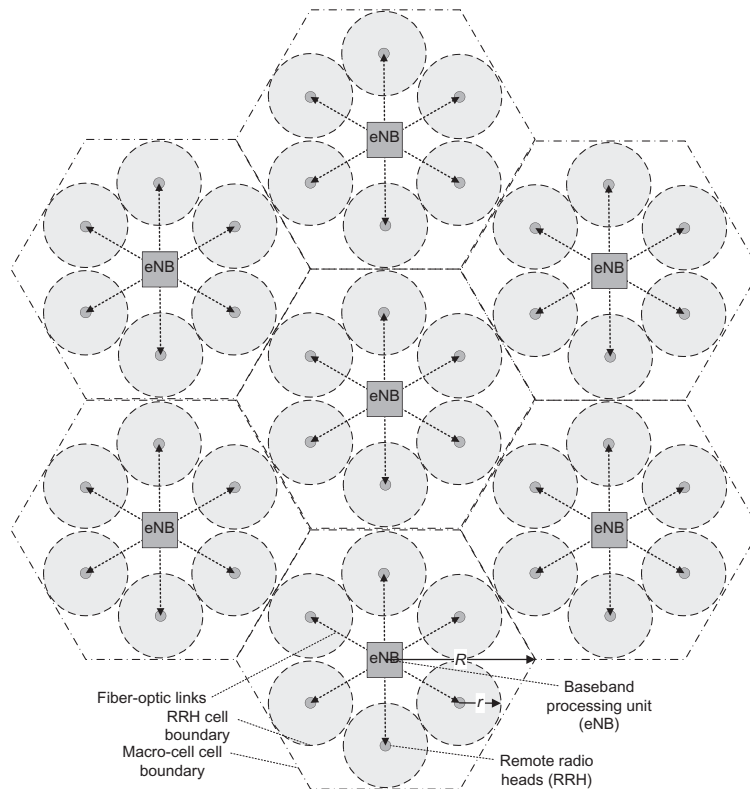
A distributed antenna system (DAS) is a network of spatially separated antennas connected to a common source via a transport medium that provides wireless service within a geographic area (cell) or a structure (indoor coverage). The basic notion of DAS was to split the transmit power among several antenna elements which are geographically separated, in order to provide coverage over the same area as a centralized antenna system, but with reduced total power and improved reliability. Thus, a set of centralized antennas radiating at high power are replaced by a group of low-power antenna elements to cover the same area. This concept was initially described in a paper by Saleh et al. [9]. Different variants of DAS have recently been deployed by selected network operators worldwide [10,16]. Examples include systems comprising RRH which consist of multiple outdoor units in which only the radio frequency (RF) front-end functionalities are implemented. The RRHs are connected to the baseband processing part of the base station through a bi-directional high-capacity/low-latency link. The DAS scheme can be implemented as a multi-airlink/multi-frequency/multi-wireless network, or a fiber-optic-based network. While the basic DAS concept is very similar to RRH, it can be differentiated with the latter features based on its greater flexibility and capacity that can be dynamically adapted to and optimized for varying traffic and user mobility conditions. The DAS enables independent operation of multiple frequency bands and multiple protocols across a single access network; consequently, multiple operator network sharing can be supported by a DAS [8,10–14,18]. Recent studies have shown that in addition to coverage improvements, a DAS can also provide other advantages such as reduced power and increased system capacity in a single-cell environment. Each distributed antenna module is connected to a home base station (or central unit) via dedicated wires,

fiber optics, or an exclusive RF link. Although the connections via the same RF link used in a cell are possible, the connections with the same RF link construct information-theoretic relay channels are categorized as another research area called cooperative communications. Since the distributed antenna modules and the home base station together construct a macroscopic multiple-input single-output (MISO) vector channel, the DAS can be also interpreted as a macroscopic multiple-antenna system [19].

The advantage of the DAS scheme is that less power is consumed in overcoming penetration and shadowing losses, since a line-of-sight channel is often present, leading to reduced fading depths and reduced delay spread. A DAS can be implemented using passive splitters and feeders, and active repeater amplifiers can be included to overcome the feeder loss. If a given area is covered by N distributed antenna elements rather than a single antenna, then the total radiated power is reduced by approximately a factor of $N^{1-n/2}$, and the power per antenna is reduced by a factor of $N^{n/2}$, where a path loss model with path loss exponent n^1 is assumed. As an alternative, the total area covered could be extended for a given limit of effective radiated power, which may be important to ensure compliance with regulatory limits. In other words, for a given target radiated power, an N -element antenna system will have increased coverage area over a single-antenna system by a factor of $N^{1-2/n}$. Given the same coverage area, the maximum path loss for an N -element distributed antenna system is reduced by a factor of $N^{n/2}$. The transmit power of user devices can then be reduced by a factor of $N^{n/2}$, resulting in a more energy-efficient uplink and lower battery consumption. The use of distributed antenna systems is expected to reduce inter-cell interference and to improve SINR especially for users near cell boundaries, which are often performance limiting users, compared to conventional cellular systems in an interference-limited multi-cell environment. As a result, distributed antenna systems achieve lower symbol error probability and higher capacity than conventional cellular systems. Recent studies suggest that distributed antenna architectures could be an effective solution for reducing inter-cell interference in an interference-limited cellular environment.

Let us look at a distributed antenna system from mathematical point of view. As shown in Figure 12.2, in a distributed antenna system the main baseband processing modules such as channel cards are centralized at a location (central processing unit), and are connected with distributed antenna modules. Each distributed antenna module is physically connected with a home base station via a dedicated link. The general architecture of a DAS in a multi-cell environment is illustrated in Figure 12.2, where a cell is covered by a small base station and six

¹In the study of wireless communications, path loss can be represented by the path loss exponent, whose value is normally in the range of 2–4, where 2 is for propagation in free space and 4 is for a relatively lossy environment and for the case of full specular reflection from the earth's surface. In some environments, such as buildings, stadiums, and other indoor environments, the path loss exponent can reach values in the range of 4–6. On the other hand, a tunnel may act as a waveguide, resulting in a path loss exponent of less than 2.

**FIGURE 12.2**

Example of the architecture of a distributed antenna system with one-tier interference model.

distributed antenna modules. In contrast, the same area is covered by only a single high-power base station in traditional cellular systems. The actual number of distributed antenna modules would be determined by coverage, user densities, and other deployment/economic/environmental factors. Let $P_i^{(j)}$ denote the total transmit power of the i th distributed antenna module of the j th cell, where the small base station of each cell and home cell are indexed by $i = 0$ and $j = 0$, respectively. Let us further assume that $\sum_{i=1}^{N_{\text{unit}}} P_i^{(j)} = P \forall j$, where P is the total transmit power of the conventional base station for a fair comparison. The radius of a cell is R , and the coverage radius of a distributed antenna module is r . We further assume a seven cell cellular structure with universal frequency reuse, where a given cell is surrounded by one continuous tier of six cells, as shown in Figure 12.2.

Let us assume (without loss of generality) that there are six RRHs in each cell, and further in each site, downlink signals are transmitted through all the

distributed antenna modules and the home base station. In this case, the multiple distributed antenna modules and the home base station together construct a macroscopic MISO vector channel given by [19]:

$$\mathbf{h} = \begin{pmatrix} \sqrt{PL_0^{(0)}}h_0^{(0)} & \sqrt{PL_1^{(0)}}h_1^{(0)} & \sqrt{PL_2^{(0)}}h_2^{(0)} & \sqrt{PL_3^{(0)}}h_3^{(0)} \\ \sqrt{PL_4^{(0)}}h_4^{(0)} & \sqrt{PL_5^{(0)}}h_5^{(0)} & \sqrt{PL_6^{(0)}}h_6^{(0)} \end{pmatrix} \quad (12.2)$$

In Eq. (12.2), $h_i^{(j)}$ denotes short-term fading channel from the i th distributed antenna module in the j th cell which is an independent and identically distributed complex Gaussian random variable $h_i^{(j)} \sim C(0, 1)$. The fading channel is assumed to be static during orthogonal frequency division multiplexing (OFDM) symbol duration. The coefficient $PL_i^{(j)}$ denotes path loss and shadow fading from the i th distributed antenna module in the j th cell. The transmitted signal vector is represented as $\mathbf{x} = (x_0^{(0)}, x_1^{(0)}, \dots, x_6^{(0)})^T$, where each entry $x_i^{(j)}$ represents the transmitted signal from the i th distributed antenna module in the j th cell with $\mathcal{E}\{|x_i^{(j)}|^2\} = P_i^{(j)}$. Under these conditions, the received signal at a mobile station in a given OFDM symbol duration is given by [19]:

$$y = \underbrace{\mathbf{h}\mathbf{x}}_{\text{Desired signal}} + \underbrace{\sum_{j=1}^6 \sum_{i=0}^6 h_i^{(j)} \sqrt{PL_i^{(j)}} x_i^{(j)}}_{\text{Inter-cell interference}} + \underbrace{n}_{\text{Receiver noise}} \quad (12.3)$$

where n is an additive white Gaussian noise with normal distribution $n \sim \mathcal{N}(0, \sigma_n^2)$. Since the number of interfering sources is sufficiently large and the interfering sources are independent of each other, the interference plus noise can be assumed to be a complex Gaussian random variable z with variance $\sigma_z^2 = \sum_{j=1}^6 \sum_{i=0}^6 PL_i^{(j)} P_i^{(j)} + \sigma_n^2$ according to the central limit theorem², whereas the interference plus noise power of the conventional cellular system is given by $\sigma_c^2 = \sum_{j=1}^6 PL_0^{(j)} P_0^{(j)} + \sigma_n^2$. When only a single distributed antenna module or the

²In probability theory, the central limit theorem states that, given certain conditions, the mean of a sufficiently large number of independent random variables, each with finite mean and variance, will be approximately normally distributed. Let $X_1, X_2, \dots, X_n$ be a set of n independent random variables and let each X_i have an arbitrary probability distribution $p(x_1, x_2, \dots, x_N)$ with mean μ_i

and a finite variance σ_i^2 . Then, the normal form variable $X_{\text{normal}} = \left(\sum_{i=1}^N (x_i - \mu_i) \right) / \sqrt{\sum_{i=1}^N \sigma_i^2}$ has a limiting cumulative distribution function which approaches a normal distribution. Under additional conditions on the distribution of the addend, the probability density itself is also normal with mean $\mu = 0$ and variance $\sigma^2 = 1$. If conversion to normal form is not performed, then the random variable $X = \left(\sum_{i=1}^N x_i \right) / N$ is normally distributed with $\mu_X = \mu_x$ and $\sigma_X = \sigma_x / \sqrt{N}$ [28].

home base station is selected for transmission (based on the criterion of minimizing propagation path loss), the received signal is given by [19]:

$$y = \underbrace{h_m^{(0)} \sqrt{PL_m^{(0)}} x_m^{(0)}}_{\text{Desired signal}} + \underbrace{\sum_{j=1}^6 h_i^{(j)} \sqrt{PL_i^{(j)}} x_i^{(j)}}_{\text{Inter-cell interference}} + \underbrace{n}_{\text{Receiver noise}} \quad (12.4)$$

where $m = \arg \min_{k=0,1,\dots,6} (PL_0^{(j)}, PL_1^{(j)}, \dots, PL_6^{(j)})$ and qj is randomly selected from the set $\{0, 1, \dots, 6\}$. The interference plus noise can be shown to be a complex Gaussian random variable u with variance $\sigma_u^2 = \sum_{j=1}^6 PL_{qj}^{(j)} P_{qj}^{(j)} + \sigma_n^2$. Since other cells adopt the same transmission scheme as the home cell, only one of the interfering sources in the other cells can be randomly selected in a dynamic point switching scheme. If the CSI is known only at the receiver and the channel is ergodic, the ergodic capacity at a given location of the mobile station under study can be written as follows:

$$C_{\text{ergodic}} = \mathcal{E}_{\mathbf{h}} \left\{ \log_2 \left(1 + \frac{1}{\sigma_z^2} \mathbf{h} \Phi \mathbf{h}^H \right) \right\} \quad (12.5)$$

where Φ is the covariance matrix of the transmitted signal vector $\mathbf{x}$ given by $\Phi = \text{diag}(P_0^{(0)}, P_1^{(0)}, \dots, P_6^{(0)})$. When the channel is known in the transmitter side, the ergodic capacity at a given location of the mobile station is given by:

$$C_{\text{ergodic}} = \mathcal{E}_{\mathbf{h}} \left\{ \max_{\varphi_{ii} \leq P_i^{(0)} \forall i} \log_2 \left(1 + \frac{1}{\sigma_z^2} \mathbf{h} \Phi \mathbf{h}^H \right) \right\} \quad (12.6)$$

where φ_{ii} is the i th diagonal element of matrix Φ . The maximum capacity is achieved by proper design of the transmit power spectrum matrix Φ under individual power constraints of the distributed antenna modules and the home base station. If power cooperation among the distributed antenna modules and the home base station is allowed, this problem reduces to a standard water-filling problem in a macroscopic MISO vector channel [19].

The above study suggests that the distributed antenna systems effectively reduce inter-cell interference and improve SINR especially for the cell-edge users, which are typically performance limiting users, compared to conventional cellular systems in an interference-limited multi-cell environment. As a result, distributed antenna systems achieve lower symbol error probability and higher capacity than conventional cellular systems; thus, distributed antenna architectures appear to be an effective solution for reducing inter-cell interference in an interference-limited cellular environment.

12.3 Theory of CoMP operation

Future cellular networks are required to provide high-data-rate services to a large number of users, which necessitates high spectral efficiency over the entire cell

coverage area. In order to address this problem, it is important to ensure robustness of the radio interface to interference, in particular inter-cell interference, which appears when the same radio resources are reused in different cells in an uncoordinated manner. The inter-cell interference particularly degrades the performance of users located in the cell-edge areas, which causes an inconsistent level of performance among cell-edge and inner-cell users. One possible solution to alleviate this performance discrepancy is to employ coordinated multi-point transmission and reception, which refers to a system where the transmission or reception at multiple, geographically separated antenna sites is dynamically coordinated in order to improve system performance. The coordination can be distributed either by means of direct communication between different sites, or by means of a central coordinating node [34–47].

The notion of clustering (grouping of the cooperating cells) is essential to coordinated beamforming and relaxed coherent joint processing. Indeed, the term CoMP suggests that a number of base stations share some knowledge about users. However, as the number of users and eNBs increases, the signaling overhead required for the inter-eNB information exchange and the amount of feedback needed from the users dramatically increase. Therefore, cooperation should be limited to a small number of cells/sites. To achieve this goal, the network is divided into clusters of cooperating cells. Cluster selection is important to the performance of cooperation strategies. Cluster formation may be static, if the clusters remain fixed in time, or dynamic (see Figures 12.7 and 12.8). Selection may be performed in a network-centric or in a user-centric manner. The network-centric clustering typically divides the network into a set of disjoint clusters of eNBs such that one eNB can belong only to one cluster. In contrast, in the user-centric clustering approach, one eNB may belong to more than one cluster, depending on the parameter under consideration. From the user point of view, this means that, in a given cell, each user may have a different set of cooperating eNBs. The concept of clustering is similar to cooperative sets and/or measurement sets, which will be defined later.

CoMP architectures may include centrally located or distributed processing among the collaborating nodes. The use of geographically distributed antennas in CoMP and the introduction of multiple transmission nodes is conceptually similar to the distributed antenna systems. In particular, in a CoMP scheme exploiting DAS principles, there are several possible transmission strategies including the power-weighted transmission scheme and the single transmit-selection scheme.

Assuming linear transceiver processing, a CoMP system with N antennas is ideally able to accommodate up to N streams without becoming interference limited. The inter-stream interference can be controlled or even completely eliminated by proper precoder selection. This is especially true in the coherent joint processing case, where user data is conveyed from multiple base station antenna nodes over a large virtual MIMO channel. The coherent multi-user multi-cell precoding techniques have strict requirements in terms of signaling and measurements. In addition to the complete channel knowledge of all jointly processed links, a stringent

synchronization across the transmitting nodes and centralized entities performing scheduling and computation of joint precoding weights is required in order to avoid carrier phase drifting at different transmit nodes. A large amount of data needs to be exchanged between the network nodes. Therefore, broadband links, such as optical fibers or dedicated radio links, are needed.

Another form of coordinated transmission is dynamic multi-cell scheduling and interference avoidance, where the network nodes coordinate their transmissions (precoder design, scheduling) in order to minimize the inter-cell interference. Carrier phase coherence between the transmit nodes is not required, since each data stream is transmitted from a single transmission point. As a result, the non-coherent coordinated multi-cell transmission approaches have somewhat looser requirements on the coordination and the backhaul, but could potentially need centralized resource management mechanisms.

In order to understand how the above coordinated transmission schemes are mathematically formulated, consider an example of a centralized non-codebook-based coordinated beamforming scenario with static cooperating clusters. Let us assume a general downlink system model for the network consisting of N_{cell} cells and N_{user} single-antenna UEs per cell. This scenario can be considered a traditional cellular network, in which only one transmitter per cell is used, or a CoMP network, in which more than one transmitter per cell is used. We refer to this model as a CoMP system made of N_{unit} single-antenna remote units per cell. In general, the downlink system model of a CoMP cellular network can be expressed as $\mathbf{y} = \mathbf{H}\mathbf{W}\mathbf{x} + \mathbf{n}$, where $\mathbf{H} \in \mathbb{C}^{N_{\text{user}} \times N_{\text{cell}}N_{\text{unit}}}$, and $\mathbf{W} \in \mathbb{C}^{N_{\text{cell}}N_{\text{unit}} \times N_{\text{user}}}$ are the CoMP processing matrices, which depend on the particular CoMP configuration, $\mathbf{x} = (x_1, x_2, \dots, x_{N_{\text{user}}})^T \in \mathbb{C}^{N_{\text{user}} \times 1}$ is a complex vector that contains the transmitted signal, $\mathbf{y} = (y_1, y_2, \dots, y_{N_{\text{user}}})^T \in \mathbb{C}^{N_{\text{user}} \times 1}$ is a complex vector containing N_{user} signals received by N_{user} UEs, and $\mathbf{n} \in \mathbb{C}^{N_{\text{user}} \times 1}$ is the noise vector. The ij th entry $\{h_{ij}^{(k)}\}$ of matrix $\mathbf{H}$ represents the complex-valued channel gain between the i th UE ($1 \leq i \leq N_{\text{user}}$) and the j th remote unit ($1 \leq j \leq N_{\text{unit}}$) belonging to the k th cell ($1 \leq k \leq N_{\text{cell}}$). The ji th element $\{w_{ji}^{(k)}\}$ of the matrix $\mathbf{W}$ is the square root of the transmission power applied at the j th remote unit ($1 \leq j \leq N_{\text{unit}}$), transmitting toward the i th UE ($1 \leq i \leq N_{\text{user}}$), belonging to the k th cell ($1 \leq k \leq N_{\text{cell}}$). In this model, we assume a flat fading channel as typically observed at each subcarrier in an OFDM system. The above model can be extended to the case of remote units and mobile terminals equipped with multiple antennas. In the following, we assume that there are two cells in the network, and there are three remote units per cell, and further there are two users in each cell, thus $N_{\text{cell}} = 2$, $N_{\text{unit}} = 3$, and $N_{\text{user}} = 2$. Using the above hypotheses, one can rewrite the received signal equation as follows [24]:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = (\mathbf{H}^{(1)} \quad \mathbf{H}^{(2)}) \begin{pmatrix} \mathbf{W}^{(1)} \\ \mathbf{W}^{(2)} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \quad (12.7)$$

which can be further expanded as follows:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} h_{11}^{(1)} & h_{12}^{(1)} & h_{13}^{(1)} & h_{11}^{(2)} & h_{12}^{(2)} & h_{13}^{(2)} \\ h_{21}^{(1)} & h_{22}^{(1)} & h_{23}^{(1)} & h_{21}^{(2)} & h_{22}^{(2)} & h_{23}^{(2)} \end{pmatrix} \begin{pmatrix} w_{11}^{(1)} & w_{12}^{(1)} \\ w_{21}^{(1)} & w_{22}^{(1)} \\ w_{31}^{(1)} & w_{32}^{(1)} \\ w_{11}^{(2)} & w_{12}^{(2)} \\ w_{21}^{(2)} & w_{22}^{(2)} \\ w_{31}^{(2)} & w_{32}^{(2)} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \quad (12.8)$$

where y_i is the signal received by the i th UE and x_j denotes the signal transmitted by the j th remote unit. The particular expressions of $\mathbf{W} \in \mathbb{C}^{N_{\text{cell}}N_{\text{unit}} \times N_{\text{user}}}$ for CoMP transmit-selection and power-weighted schemes when only one user per cell is considered are as follows:

$$\mathbf{W}_{\text{transmit-selection}} = \begin{pmatrix} 0 & 0 \\ w_{ji}^{(1)} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & w_{ji}^{(2)} \\ 0 & 0 \end{pmatrix} \mathbf{W}_{\text{weighted-power}} = \begin{pmatrix} w_{11}^{(1)} & 0 \\ w_{21}^{(1)} & 0 \\ w_{31}^{(1)} & 0 \\ 0 & w_{12}^{(2)} \\ 0 & w_{22}^{(2)} \\ 0 & w_{32}^{(2)} \end{pmatrix} \quad (12.9)$$

In the above expressions, and for the CoMP transmit-selection scheme, the only non-zero term $w_{ji}^{(k)}$ for $k = 1, 2$ is selected by a certain criterion such as minimizing the path loss between any of the remote units transmitting toward the mobile user which is being served, i.e., $w_{ji}^{(k)} = \min_j \{PL(j, i)\}_{k=1,2}$ for the i th mobile user. In the CoMP power-weighted scheme $\sum_{j=1}^{N_{\text{unit}}} w_{ji}^{(k)} = P_{\text{total}}$ for $k = 1, 2$ where P_{total} is the total transmit power of the conventional base station, for the i th mobile user.

Consider a coordination cluster with N_{TP} transmission points, each equipped with an antenna array comprising N_{TX} antenna elements, and N_{user} UEs equipped with N_{RX} receive antennas. Assuming an OFDM transmission, the baseband signal received by the i th UE at the k th subcarrier in the downlink is given by:

$$\mathbf{y}_i(k) = \mathbf{H}_i(k)\mathbf{x}(k) + \mathbf{n}_i(k) \quad (12.10)$$

where the $N_{\text{RX}} \times N_{\text{unit}}N_{\text{TX}}$ matrix $\mathbf{H}_i(k)$ is the composite channel between all transmission points and the i th UE; $\mathbf{n}_i(k)$ represents thermal noise vector including inter-cluster interference which is assumed to be white Gaussian distributed with

covariance matrix $\mathcal{E}\{\mathbf{n}_i(k)\mathbf{n}_i^H(k)\} = \sigma_i^2 \mathbf{I}$; $\mathbf{x}$ is an $N_{\text{unit}}N_{\text{TX}} \times 1$ vector representing the sum signal transmitted from all transmission points, given by:

$$\mathbf{x}(k) = \sum_{i=1}^{N_{\text{user}}} \mathbf{x}_i(k) = \sum_{i=1}^{N_{\text{user}}} \sqrt{p_i} \mathbf{u}_i s_i(k) \quad (12.11)$$

where $s_i(k)$ is a modulation symbol drawn from a unit-variance symbol alphabet, which is transmitted to the i th UE using the transmit power p_i and beamforming vector $\mathbf{u}_i$, respectively. The beamforming vectors are normalized to have unit power $\mathcal{E}(\mathbf{u}_i^H \mathbf{u}_i) = 1$ for $i = 1, 2, \dots, N_{\text{user}}$. The average SINR for the i th UE, assuming an MRC receiver type, is given by [24]:

$$\text{SINR}_i(\mathbf{U}, \mathbf{p}) = \frac{\mathbf{p}_i \mathbf{u}_i^H \mathbf{R}_i \mathbf{u}_i}{\sum_{j \neq i} \mathbf{p}_j \mathbf{u}_j^H \mathbf{R}_i \mathbf{u}_j + \sigma_i^2} \quad (12.12)$$

where $\mathbf{U}$ is the transmit beamforming matrix given by $\mathbf{U} = (\mathbf{u}_1 \ \mathbf{u}_2 \ \dots \ \mathbf{u}_{N_{\text{user}}})$, $\mathbf{p}_i$ is the vector of transmit powers, and $\mathbf{R}_i$ is the transmit correlation matrix for the i th UE, given by $\mathbf{R}_i = \mathcal{E}\{\mathbf{H}_i^H(k)\mathbf{H}_i(k)\} = \text{diag}(R_{i1}, R_{i2}, \dots, R_{iN_{\text{unit}}})$. Since the transmission points are separated by large distances, their antennas are mutually uncorrelated. The considered coordinated beamforming scheme is a modified form of the multi-user beamforming algorithm, in which the beamforming vectors and power allocations are obtained by maximizing the jointly achievable SINR margin as follows [24]:

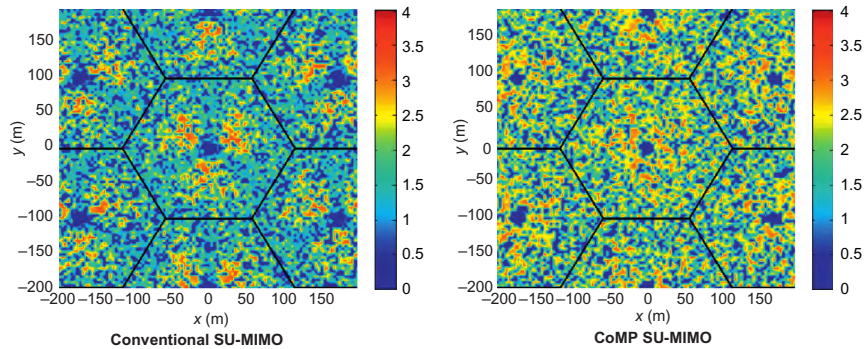
$$C = \max_{\mathbf{U}, \mathbf{p}} \min_{i \in \{1, 2, \dots, N_{\text{user}}\}} \frac{\text{SINR}_i(\mathbf{U}, \mathbf{p}_i)}{\gamma_i} \quad (12.13)$$

The above optimization is performed under per-transmitter power constraint:

$$\sum_{i \in S_n} p_i \leq P_{\max} \quad n \in \{1, 2, \dots, N_{\text{unit}}\} \quad (12.14)$$

where γ_i is the target SINR for the i th UE, S_n is the set of UEs connected to the n th transmission point, and $P_{\max}$ is the maximum transmission point transmit power. The beamforming vectors and downlink power allocations are found iteratively using the uplink–downlink duality theorem, which states that the downlink broadcast channel has a virtual dual uplink multiple access channel which has the same SINR achievable regions as the downlink, and the same beamforming vectors to achieve the SINRs in both links [24].

It can be expected that the most appropriate scenarios for coordinated beamforming have low angular spreads which are found in the urban, suburban, and rural environments with above-rooftop antenna deployment. Due to low feedback requirements, coordinated beamforming is especially of interest in the FDD mode. The joint processing might be difficult to realize in a practical system due to the stringent feedback requirements. It can also be expected that coordinated beamforming is robust to user mobility, hence making it an attractive alternative

**FIGURE 12.3**

Performance of intra-eNB CoMP with SU-MIMO and implicit feedback relative to conventional SU-MIMO.

both in low and high mobility scenarios [24]. The performance (cell spectral efficiency) of an intra-eNB CoMP with SU-MIMO and implicit feedback relative to a conventional SU-MIMO scheme have been simulated and are shown in Figure 12.3. The improvement of cell spectral efficiency due to use of CoMP in different areas of the cell and in particular the cell-edge areas can be seen in Figure 12.3. The simulation assumptions are consistent with those recommended in 3GPP TR 36.814 [4].

12.4 CoMP architectures

In LTE Rel-8, MIMO transmission in each cell is controlled independent of that of the neighbor cells. Inter-cell interference coordination (ICIC) was supported by means of coordination message exchanges between base stations via a standardized inter-eNB interface known as X2 [6,7]. The goal of ICIC is to provide the scheduler at one cell with information about the current or prospective interference condition at its neighbors. However, in reality, the transfer latency of these coordination messages depends on the backhaul technology and is not negligible. While ICIC techniques are primarily designed for semi-static coordination, CoMP techniques target more dynamic coordination and may require much lower latency. The macro-cells constitute the basis of a mobile network's coverage; the deployment of low-power nodes (e.g., pico- or femto-cells or relay nodes) within the macro-cell is expected to be an effective solution in the future to address ever-increasing mobile traffic demands. Such networks, referred to as heterogeneous networks, are characterized by severe inter-cell interference between the macro and the low-power nodes due to their proximity and different transmit power classes. The inter-cell interference effect is even more detrimental when the effective cell size of the low-power node is expanded to balance the traffic

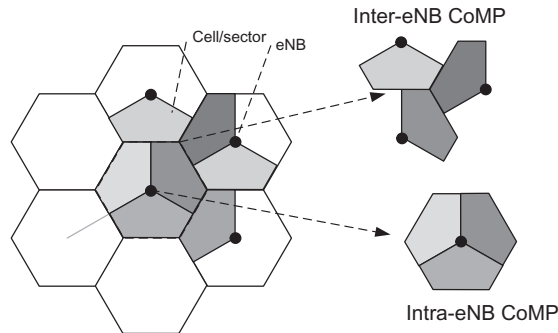
**FIGURE 12.4**

Illustration of inter-eNB and intra-eNB CoMP scenarios.

load between the macro-cell and the low-power node cell; thus, the UE may be associated with a cell that does not provide the strongest received signal power.

In general, and as shown in Figure 12.4, CoMP transmission/reception techniques can be classified into the following two major categories:

1. Inter-eNB CoMP, wherein coordination amongst eNBs is done via the X2 interface with typical feedback delay of 5–30 ms. This method requires standardization of the feedback channel with consideration for overhead and delay reduction.
2. Intra-eNB CoMP, wherein transmission points are usually connected via wide-band/low-delay optical fibers with typical feedback delay of 5 ms and with minimal impact on the X2 interface.

LTE Rel-11 has focused on the intra-eNB CoMP scenarios in order to limit the scope of specification impacts on lower protocol layers.

One recent deployment trend that is foreseen to be widely applied to LTE networks consists of splitting the base station functionalities into a baseband unit, which performs in particular the scheduling and the baseband processing functions, and a number of RRHs responsible for all RF transmission/reception aspects. The baseband processing unit is typically located at the center of the cell and is connected via optical fiber to the RRHs. In addition to suppressing the feeder loss (since the power amplifier is immediately close to the antenna), this approach allows the baseband processing unit to manage different radio sites in a central manner. Furthermore, having geographically separated RRHs controlled from the same location enables either centralized baseband processing units jointly managing the operation of several radio sites, or the exchange of very low-latency coordination messages among individual baseband processing units. The RRH deployments facilitate the tight coordination between transmission/reception points that is required for some CoMP schemes. The applicability and benefits of CoMP techniques depend to a great extent on the backhaul characteristics (latency and capacity), which determine the type of CoMP processing and the corresponding

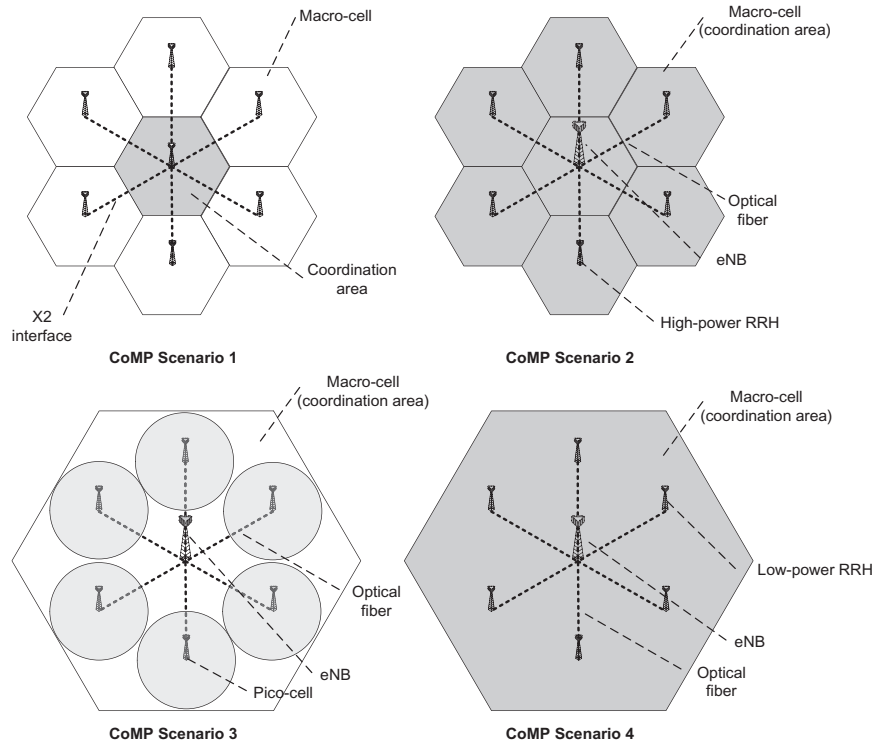
**FIGURE 12.5**

Illustration of CoMP scenarios [5].

performance. In order to account for the various possible network topologies and backhaul characteristics, the study of CoMP in 3GPP focused on the following scenarios (Figure 12.5) [5,27]:

- CoMP scenario 1 (homogeneous macro network with intra-site CoMP): Coordination among the cells (sectors) controlled by the same macro base station (where no backhaul connection is needed).
- CoMP scenario 2 (homogeneous macro network with inter-site CoMP): Coordination between cells belonging to different radio sites from a macro network.
- CoMP scenario 3 (heterogeneous network with low-power pico-cells within the macro-cell coverage area): Coordination between a macro-cell and low-power transmit/receive points within its coverage, each point controlling its own cell (with its own cell identity).
- CoMP scenario 4 (heterogeneous network with low-power RRH): Coordination between a macro-cell and low-power transmit/receive points

within its coverage, each point controlling its own cell, except that the low-power transmit/receive points constitute geographically distributed antennas of the macro-cell, and are thus all associated with the macro-cell identity.

CoMP scenario 1 is defined for homogeneous networks where the coordination area is restricted to the cells of a single site controlled by an eNB. Although the extent of coordination is limited to the cells of the same site, CoMP scenario 1 has the advantage of requiring no inter-eNB interface among different sites. Such an advantage would make CoMP scenario 1 attractive to the network operators.

CoMP scenario 2 is for homogeneous networks where the coordination area is expanded from the CoMP scenario 1 to include the cells of different sites. CoMP scenario 2 may be realized by having a single eNB control the RRHs at different sites, or by having multiple eNBs at different sites to coordinate with each other. CoMP scenario 2 is depicted in Figure 12.5 with high-power RRHs at different sites controlled by a single eNB. Depending on the number of cells involved and the latency of connections between the sites, which are both dependent on network implementation, different levels of performance gain over CoMP scenario 1 may be obtained.

CoMP scenario 3 relies on a heterogeneous network model where macro-cells with high transmission power and pico-cells with low transmission power are connected. In practice, this scenario may be realized by a single eNB controlling the high-power RRH of the macro-cell and the low-power RRHs of pico-cells within the macro-cell coverage area. Another possible network implementation is that the eNBs of the macro-cell and the pico-cells are different and coordinate with each other. Figure 12.5 illustrates CoMP scenario 3 with low-power RRHs at different sites controlled by a single eNB.

CoMP scenario 4 is defined for heterogeneous networks where low-power RRHs are distributed throughout the coverage area of a macro-cell. The difference between this scenario and the other intra-eNB scenarios is that all low-power RRHs in this case share the same physical cell identity with the macro-cell. Therefore, it can be construed that the low-power RRHs form a set of distributed antennas in the macro-cell area. Since the coordination is done among distributed antennas within the same cell, depending on the size of macro-cell, there may not be a need for conventional mobility support such as handover procedures among the RRHs. Furthermore, since each RRH is not an independent cell, a low-delay and high-capacity backhaul connection such as optical fiber can provide the radio connection between the macro-eNB and the RRHs. CoMP scenarios 3 and 4 are expected to find applications in metropolitan areas where network deployment is dense and RRHs with different transmission power levels can be deployed to improve control/data coverage and capacity [17].

A set of geographically collocated antennas that correspond to a particular sectorization scheme are traditionally configured as a cell. A UE attempts to connect to a single cell at any given time, if the measured received reference signal strength from that cell is higher relative to that from other cells. This cell then

becomes its serving cell. Given the new definition of CoMP scenarios as introduced earlier, the antennas configured as a cell may not be geographically collocated. The term transmission point can then be used to refer to a set of collocated antennas, and a cell can correspond to one or more such transmission points. Note that a single geographical site may contain multiple transmission points in the case of sectorization, with one transmission point corresponding to one sector. CoMP techniques can also be defined in a more straightforward manner as the coordination between transmission points.

A mobile station is said to be connected to a cooperating set/cluster if its serving cell belongs to the cluster. We assume no coordination between clusters, which also means that a cell belongs to one, and only one, cluster. The serving cell selection in LTE Rel-8 is based on the long-term average reference signal received power (RSRP) measurements. The cell with the strongest RSRP acts as the serving cell. The serving cell also defines the cluster to which the mobile is connected. Since each cell uniquely belongs to one cluster, the serving cluster is determined once the serving cell is selected. It is assumed that the measurement set of a UE is a subset of the cluster.

12.4.1 Air-interface and network support for CoMP schemes

In order to enable CoMP operation, the network architecture must be able to provide sufficient coordination and synchronization among different transmission points and/or cells/sites. If inter-eNB coordination is enabled, user data and/or CSI will be exchanged and shared between eNBs; thus, low-latency and high-capacity backhaul would be required to support inter-eNB CoMP deployment scenarios. The impacts on the radio interface mainly depend on type of CoMP scheme that is utilized, which may include, but is not limited to, the following [5]:

- CSI measurement and feedback mechanisms at the UE, which may include reporting dynamic channel conditions between transmission points in the CoMP measurement set and the UE. Depending on the duplex scheme, channel reciprocity may be exploited to facilitate channel estimation at the transmission points.
- Low-latency and configurable reporting mechanisms to facilitate the decision-making process concerning the set of participating transmission points.
- Static and dynamic coordination and tight synchronization are required prior to transmission of the signal over multiple transmission points.
- Reference signals with unique signatures are required to enable inter-cell/intra-cell interference and channel measurements. Depending on the CoMP scheme, the LTE Rel-10 CSI reference signal (CSI-RS) structures were found to be suitable to provide support for certain interference measurement and characterization [33].
- Improved control signaling design may be required to support signaling and feedback for certain CoMP algorithms. LTE Rel-11 provided the enhanced physical downlink control channel (ePDCCH) and other downlink control

signaling improvements, as well as transmission mode 10 to accommodate the CoMP design and operation.

Different impacts on the network architecture are foreseen depending on the CoMP scenario being deployed, including coordination among base stations, use of radio over fiber links to connect different transmission/reception points, or coordinated relaying, affecting both data-plane and control-plane protocols. The optical fiber links have a small impact on the current network architecture since the interface between base station control unit and the associated RRH can be either proprietary or based on an open standard interface such as the Common Public Radio Interface (CPRI)³ standard which defines the interface between entities known as RECs and local or RRH referred to as radio equipment (RE) [29]. It is necessary to further study the transfer of data and control information over optical fiber interfaces. Cooperation among distributed base stations has a higher impact on the network. A central control/scheduling/processing unit may be necessary depending on the required coordination scheme.

Other important aspects to be considered when deploying CoMP in a network include centralized/decentralized management of UEs connected to multiple transmit/receive points. Most proposals addressing multi-antenna schemes often assume power constraints on the sum of power transmitted by different antennas. This assumption may not hold when each antenna in a multi-antenna base station is powered by its own power amplifier and is limited by the linearity of that amplifier, or when the system uses distributed antennas belonging to the same or coordinated base stations, and each one is subject to its own power limits and emission constraints [23].

12.4.2 Downlink CoMP

A set of geographically separated points directly and/or indirectly involved in downlink data transmission to a UE over a time–frequency resource is defined as a CoMP cooperating set. Note that this set may be transparent to the UE. The transmission points in a cooperating set are either directly participating in transmission of data in the time–frequency resource, or indirectly participating in transmission,

³The CPRI is an initiative to define a publicly available specification that standardizes the protocol interface between the radio equipment control (REC) and the radio equipment (RE) in wireless base stations. This allows interoperability of equipment from different vendors and preserves the software investment made by wireless service providers. Conventional base stations are located adjacent to the antenna in a small building at the base of the antenna tower. Finding suitable sites can be a challenge because of the footprint required for the building, the need for structural reinforcement of rooftops, and the availability of both primary and backup power sources. CPRI allows the use of a distributed architecture where base stations, containing the REC, are connected to remote radio heads via low-loss fiber links that carry the CPRI data. This architecture reduces costs for service providers because only the remote radio heads containing the REs need to be situated in environmentally challenging locations. The base stations can be centrally located in less challenging locations where footprint, climate, and availability of power are more easily managed [29].

which make them candidate points for data transmission that do not transmit data but contribute in making decisions on the user scheduling/beamforming in the time–frequency resource. The CoMP transmission points (TPs) are defined as a set of points transmitting data to a UE. It is understood that CoMP TPs are a subset of the CoMP cooperating set. In general, the downlink CoMP schemes may be classified into one of the following categories (see Figure 12.6) [5]:

- Joint processing (JP) where data for a UE is available at more than one transmission point in the CoMP cooperating set for a time–frequency resource. A subcategory of JP CoMP is the joint transmission (JT) in which data is simultaneously transmitted from multiple points (part of or an entire CoMP cooperating set) to a single UE or multiple UEs in a time–frequency resource. Alternatively, the data to a UE can be simultaneously transmitted from multiple points, e.g., to (coherently or noncoherently) improve the received signal quality and/or data throughput. Another subgroup of JP CoMP is known as dynamic point selection (DPS)/muting where data is transmitted from one point (within the CoMP cooperating set) in a time–frequency resource. The transmitting/muting point may change from one subframe to another, including varying over the resource block pairs within a subframe. The data is available simultaneously at multiple points. This includes dynamic cell selection (DCS). The DPS may be combined with JT, in which case, multiple points can be selected for data transmission in the time–frequency resource.
- Coordinated scheduling/beamforming (CS/CB) in which data for a UE is only available and is transmitted from one point in the CoMP cooperating set, i.e., downlink data is transmitted from that point for a time–frequency resource but user scheduling/beamforming decisions are made with coordination among points corresponding to the CoMP cooperating set. In this case, the transmission points are selected semi-statically. Semi-static point selection (SSPS) is a method where data is transmitted to a specific UE from one point at a time. The transmitting point may only change in a semi-static manner. Muting may be applied in a dynamic and semi-static manner to the above transmission schemes (Figure 12.6).

The CS/CB scheme reduces the interference level experienced by a UE terminal by appropriately selecting the beamforming weights of interfering points to steer the interference toward the null space of the interfered UE. The JT scheme allows one or more neighboring points to transmit the desired signal rather than interfering signals from the point of view of the selected UE. The transmission point selection scheme enables the UE to be dynamically scheduled via the most appropriate transmission point by exploiting changes in the channel slow/fast fading conditions. Hybrid methods may also be implemented in a network to cope with different types of interference. A combination of JP and CS/CB schemes is possible in the downlink. Data for a UE may be available only in a subset of points in the CoMP cooperating set for a particular time–frequency resource, but user scheduling/beamforming decisions are made with coordination among points

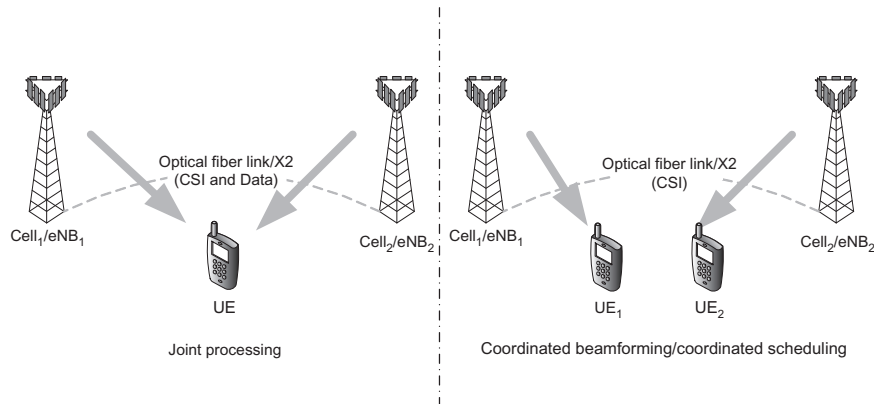
**FIGURE 12.6**

Illustration of downlink CB/CS and JT CoMP concepts.

corresponding to the CoMP cooperating set. For example, some points in the cooperating set may transmit data to the target UE according to a JP scheme, while other transmission points in the cooperating set may perform one form of CS/CB scheme. For the JT scheme, CoMP transmission points may include multiple points in the CoMP cooperating set at each subframe for a certain time–frequency resource, whereas in the case of CS/CB, DPS, SSPS, a single point in the CoMP cooperating set is the CoMP transmission point at each subframe for a certain time–frequency resource. For SSPS, this CoMP transmission point can change semi-statically within the CoMP cooperating set. Examples of static and dynamic formation of CoMP clusters (cooperating sets) are shown in [Figures 12.7 and 12.8](#).

12.4.3 Uplink CoMP

The uplink CoMP schemes may be divided into one of the following categories:

- Joint reception (JR) in which physical uplink shared channel (PUSCH) transmitted by the UE is received jointly at multiple points which are part of or the entire CoMP cooperating set at a certain time, e.g., to improve the received signal quality.
- CS/CB where user scheduling and precoding decisions are made with coordination among points within the CoMP cooperating set. The user data is only intended for one recipient point in the set.

Similar to the downlink, the uplink CoMP cooperating set is a set of geographically separated points that may be designated for data reception from a UE. The uplink CoMP reception points are a set of points for receiving data from a UE. The CoMP reception points are a subset of the CoMP cooperating set in the uplink. For the JR scheme, CoMP reception points may include multiple points in

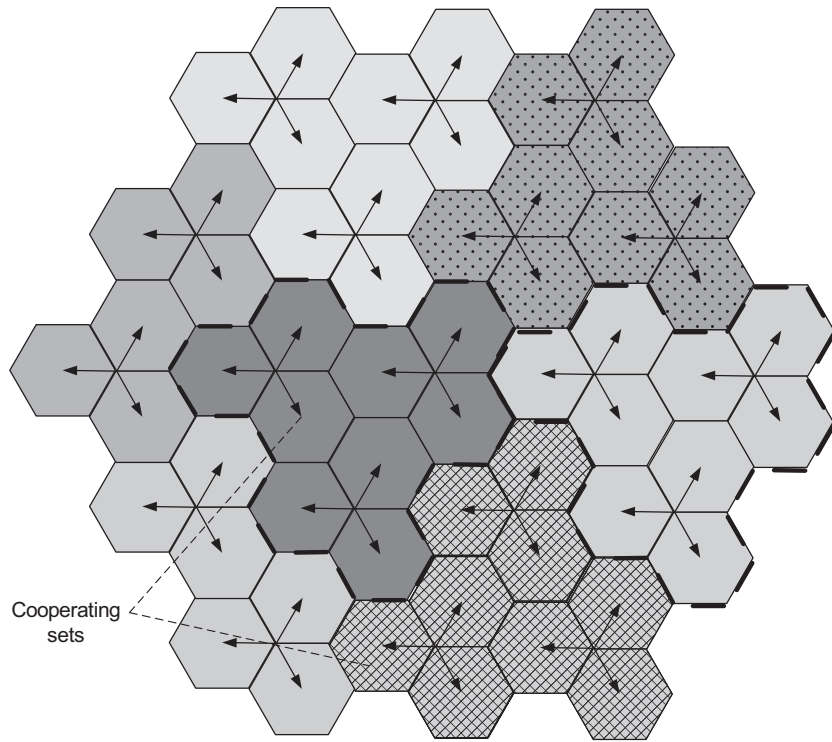


FIGURE 12.7

Illustration of static CoMP clusters (Scenario 2, 9 cells per cooperating set) [5].

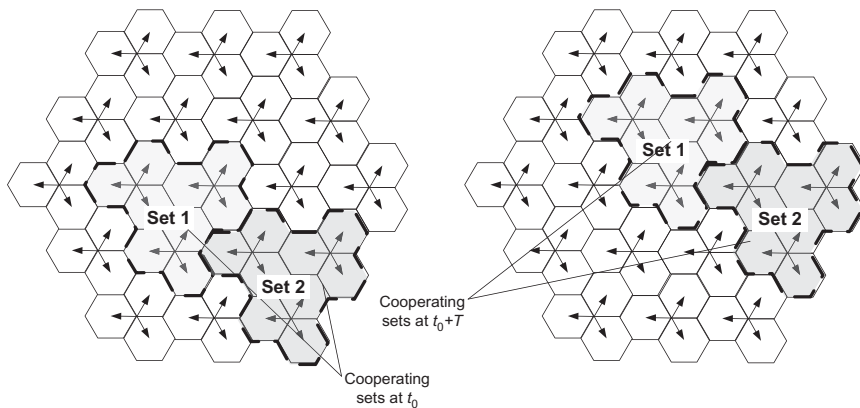


FIGURE 12.8

Dynamic clustering of CoMP (change of cooperating CoMP sets across time).

the CoMP cooperating set at each subframe for a certain time–frequency resource, whereas for uplink CS/CB, a single point in the CoMP cooperating set is the CoMP reception point at each subframe for a certain time–frequency resource [5].

In other words, uplink CoMP schemes can be divided into two major groups. The first group uses dynamic selection of the best reception point according to short-term channel quality. The second category uses joint reception, where several reception points act as a joint receiver with a larger number of antennas. Joint reception is more complex to implement, but it offers larger gains relative to DPS. One of the most important aspects of coordinated uplink reception is the decoupling of the points that transmit downlink control from those that receive uplink data. Important aspects of the implementation pertain to coordination and exchange of information among reception points in terms of selection of reception points, computation of the receive combiner, coordinated scheduling, and exchange of received signal samples (e.g., quantized received signals, locally combined signals, or log-likelihood ratios). These functions are typically centralized in the baseband processing unit connected to the coordinated eNBs via optical fiber links [17].

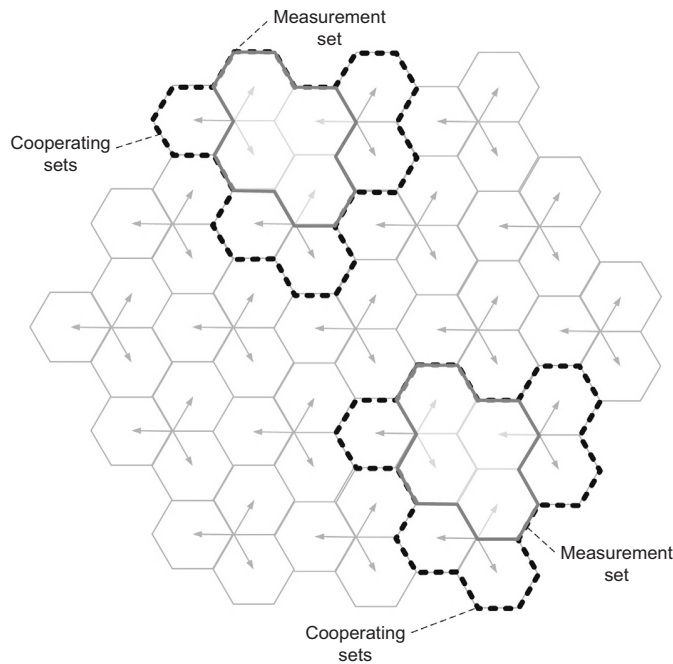
In uplink coordinated multi-point reception, the UE signals which were previously treated as interference at a reception points, other than the serving node, would become desired signals. Uplink reference signals that are used for channel estimation in the demodulation process of PUSCH are very sensitive to interference. In LTE Rel-8/9/10, the assignment of the pseudo-random base sequences for scrambling the reference signals of a UE was made by a single serving cell. It was possible to assign orthogonal sequences to the UE, whose reference signals were received by the same receiving point, via either different cyclic shifts of the same base sequence or orthogonal cover codes. At the same time, several interference randomization techniques improved the inter-cell interference generated by uncoordinated uplink scheduling assignments across multiple neighboring cells. These randomization techniques include sequence-group hopping, sequence hopping, and different cyclic shifts [1–3]. The opportunity offered by CoMP to receive the UE's signals at one cell when the UE's transmission is intended for another cell created new constraints for assigning orthogonal sequences to the users allocated in overlapping time–frequency resources [17].

LTE Rel-11 introduced new capabilities for configuring reference signal initialization parameters. In particular, the initialization of the pseudo-random sequences is no longer associated with the physical cell identity, but rather is explicitly signaled as a UE-specific virtual cell identity [1]. This enables the assignment of the same base sequence with different cyclic shifts to the UE which is connected to different cells, allowing virtual cells to be created within the coverage area of a macro-cell deployed with RRHs, as in CoMP scenario 4. Furthermore, it is possible to configure the initialization of the cyclic shift hopping in a dedicated manner for each UE, which enables grouping of UEs by orthogonal cover codes across different cells even when these UEs are assigned different base sequences [17].

12.4.4 CSI measurement and feedback in CoMP-enabled networks

A downlink CoMP measurement set is defined as a group of transmission points relative to which the UE measures and reports the CSI. The UE reports may select points for which actual feedback is transmitted. The measurement set typically encompasses cells for which the mobility-management-related measurements are conducted for the purpose of cell selection/reselection and handover. The proper operation of any CoMP scenario depends on the accuracy and timeliness of the CSI measurement and feedback in the network. Some CoMP schemes are more affected by CSI inaccuracy and feedback delays. LTE Rel-11 has specified a general control signaling framework that enables all CoMP schemes to properly operate by enhancing and extending the features that existed in the previous releases. The CoMP measurement set is alternatively defined as a set of CSI-RS resources on which the UE is required to measure and report the CSI that may include rank indicator, precoding matrix index, and channel quality indicator. There is typically a unique correspondence between a CSI-RS resource and a transmission point. As shown in Figure 12.9, the CoMP measurement set is a subset of the CoMP cluster/cooperating set ($S_{\text{measurement-set}} \subset S_{\text{cooperating-set}}$). The size of a CoMP measurement set that can be configured for a UE is limited to three CSI-RS resources in order to reduce the uplink signaling overhead. The UE at different locations may observe different sets of strong-signal transmission points; thus, the configuration of a CoMP measurement set is UE-specific. Due to UE mobility, CoMP measurement sets dynamically change and need to be reconfigured when necessary to ensure optimal CoMP performance. To assist the network in managing the CoMP measurement set of each UE, a CoMP resource management procedure based on CSI-RS measurement has been defined in LTE Rel-11. While the CoMP resource management concept can be applied to all CoMP scenarios, it is particularly useful for CoMP scenario 4 where the transmission points are not identifiable from their transmitted cell-specific reference signals, making it impossible to compare the received signal strengths based on cell-specific reference signals.

The CoMP resource management procedure requires the UE to perform CSI-RS-based received signal quality measurements on a set of CSI-RS resources that are candidates for inclusion in the CoMP measurement set. The set of CSI-RS resources explicitly configured by the network for CoMP resource management is called the CoMP resource management set. The latter set can be configured independently of the CoMP measurement set [17]. The measurement of CSI-RS received power is similar to that defined for RSRP measurement on cell-specific reference signals. Nevertheless, there are some differences between the two types of measurements. The UE is only required to conduct measurement on CSI-RS resources in the CoMP resource management set. Therefore, the UE does not autonomously detect CSI-RS resources, resulting in reduced UE operational complexity. The CoMP resource management measurement/reporting is event-driven and the triggers can be either absolute, i.e., a measurement report is triggered

**FIGURE 12.9**

Example illustration of cooperating and measurement sets.

when the received signal power goes beyond an absolute threshold, or relative, i.e., the received signal power is compared to that of another CSI-RS resource.

To ensure the CSI-RS received power measurement is immune to interference and to ensure the accuracy of the measurement, the network can mute the transmissions on the resource elements from the neighboring TPs that correspond to the CSI-RS resource elements of the transmission point being measured. When performing CSI-RS received power measurements, the UE may assume that the timing of the received CSI-RS is the same as that derived from the primary and secondary synchronization signals of the serving cell. This allows the UE to use a single timing derived from the synchronization signals of the serving cell to receive CSI-RS that might be transmitted from a different TP. While this simplifies UE implementation, the impact on the accuracy of CSI-RS received power depends on the extent of the timing error. Studies suggest that there is no significant impact on CSI-RS measurement provided that a timing error is limited to ± 3 ms [17,21,27].

Since a UE needs to measure CSI-RS to generate CSI feedback and receive UE-specific reference signals to coherently demodulate PDSCH, it is imperative that the CSI-RS and DM-RS are transmitted such that the interference among the reference signals of multiple TPs is sufficiently randomized. LTE Rel-10

addresses this requirement by defining unique initialization seeds for generating the scrambling sequences of each transmission point/cell's reference signals based on the physical cell identity. This approach may not work for CoMP scenario 4 since multiple TPs share the same cell identity. In order to provide sufficient interference randomization, LTE Rel-11 replaced the use of the physical cell identifier for initialization of the scrambling sequences with a virtual cell identifier, which is signaled to the UE using higher layer signaling, allowing flexible deployment of transmission points in CoMP scenario 4, and providing sufficient interference randomization for DM-RS and CSI-RS. In the case of CSI-RS, the interference among CSI-RSs of different TPs is further reduced by allocating different time or frequency resources for CSI-RS transmissions. The use of a virtual cell identifier provides interference randomization when the same time and frequency resources are used across different cells for CSI-RS transmissions [1].

The feedback scheme for CoMP in LTE Rel-11 is defined per CSI-RS resource, where the UE reports the CSI individually for multiple CSI-RS resources. Note that each CSI-RS resource is transmitted from one transmission point. As a result, when the UE is configured with multiple CSI-RS resources and performs per CSI-RS resource feedback, it reports individual CSIs for each of the TPs transmitting the configured CSI-RS resources. There is at least one feedback process associated with each CSI-RS resource within the CoMP measurement set. Each feedback process provides the eNB with the measured CSI (measured on a particular CSI-RS resource). The CSI feedback can be configured to be periodically reported, or scheduled for aperiodic reporting. For CS/CB, separate CSI feedback for at least two TPs can be configured where one of the processes would be used for reporting the CSI for the serving TP, and the other(s) can be used for reporting the CSI associated with the interfering TP(s). Similarly, for a dynamic point switching scheme, multiple CSI feedback processes can be configured, allowing the network to dynamically switch the transmitting TPs. The above feedback mechanism can also support other CoMP schemes including non-coherent JT, where precoding is applied individually to the transmit antennas belonging to each TP, and coherent JT in a non-standardized form by aggregating multiple TPs under a single CSI-RS resource.

The reader's attention is drawn to the fact that there are two types of feedback in general to support CoMP operation, as follows:

1. Explicit feedback which is characterized by having a channel part and a noise-and-interference part. The channel part includes reports for each point in the UE's measurement set that is reported in a given subframe that contains one or several channel properties. The channel properties include instantaneous channel matrix either in the form of full matrix or main eigen component(s) of the channel matrix; and transmit channel covariance either in the form of full covariance matrix or main eigen component(s) of the channel covariance matrix. Inter-point channel properties may also be reported including a noise-and-interference part, total interference received power, total received signal covariance matrix, and covariance matrix of the noise and interference.

2. Implicit feedback is based on certain hypotheses at the UE, and the feedback is generated depending on the operation scheme, e.g., SU-MIMO/MU-MIMO, single cell/point or coordinated transmission, and single-point CS/CB or multi-point (JP) transmission. Under this category, other forms of feedback may be considered such as precoding matrix index (PMI) with fine quantization granularity, wideband/subband PMI, and channel quality indicator (CQI). Note that CQI only accounts for interference outside the CoMP measurement set or relative received power between CoMP transmission points.

LTE Rel-11 does not specify any standardized support for coherent JT. Another important feature that has been included in LTE Rel-11 to support CoMP is the interference measurement resource (IMR), which is a set of resource elements where a UE can be configured to measure interference. Prior to LTE Rel-11, interference measurement was mainly implementation-specific and based on cell-specific reference signals. Such interference measurement schemes may not be applicable to CoMP because in CoMP scenario 4, multiple TPs may share a common cell identity. In that case, TPs within a cell are not distinguishable since they are transmitting the same cell-specific reference signals. Moreover, the interference measured using cell-specific reference signals does not allow the network to adaptively control the interference measured by the UE. As an example, if the effect of a particular TP shutdown is desired, the network can configure two separate IMRs for two feedback processes. One of the IMRs would capture the interference with the TP turned off, while the other the IMR would capture the interference with the TP turned on. The configuration of the IMR is done on a per-UE basis via higher layer signaling. Depending on the measurement reports from the UE, the network can determine which transmission points should be added to, removed from, or replaced in the CoMP measurement set in order to select the set of transmission points with the strongest signal measured at the UE [3].

12.5 Effects of X2 latency on CoMP performance

The X2 latency is defined as the accumulation of the time needed to send a message across the X2 interface, as well as the required time to process the X2 message in the eNB [20,30]. The non-zero X2-latency affects HARQ ACK/NACK round trip time and the CSI feedback delay. The HARQ ACK/NACK round trip time is defined as the time interval between the first transmission of PDSCH using a HARQ process identifier and the earliest retransmission/fresh transmission using the same HARQ process identifier. The CSI feedback delay is the time interval between the CQI measurement period at the UE and the next downlink data transmission from the eNB that is based on the knowledge of this CQI. Since both CQI as well as HARQ information need to be transmitted from the serving cells to the master cell of a cluster across the X2 interface, the X2 delay impacts

both HARQ delay as well as CQI delay. The ACK/NACK delay determines the number of HARQ processes that are needed to guarantee continuous transmission (efficient channel utilization), if the mobile station is scheduled all the time. Therefore, the impact of long HARQ ACK/NACK delays is important for low to medium cell loads. In highly loaded cells, the number of required HARQ processes decreases, since each mobile station attains less access to the channel. This impact is therefore dependent on the cell load. Due to the increased CQI delay, the CQI contains less information about the channel at the time when it is accessed. This means that it becomes more difficult to adapt the MCS and other transmission parameters to the instantaneous channel conditions.

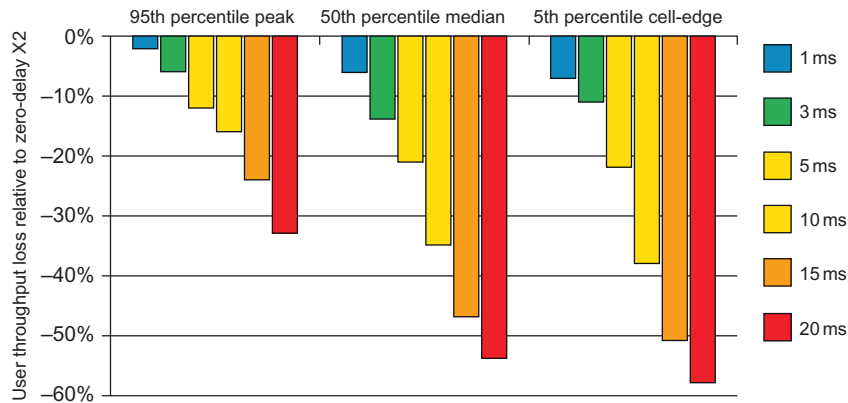
In order to investigate the effect of X2 latency on the inter-eNB JT CoMP operation, let us assume that a sufficient number of HARQ processes are available such that the impact of the X2 delay on the HARQ ACK/NACK delay can be neglected. This is ensured by setting the number of available HARQ processes to infinity. To investigate the impact of X2 latency on CQI delay, X2 delays of 0, 1, 3, 5, 10, 15, and 20 ms were simulated. Figure 12.10 shows the loss in average user throughput for various X2 delays relative to an ideal interface with zero delay. The losses are given for the 5th, 50th, and 95th percentile of the cumulative distribution function (CDF) of average user throughput without X2 delay. It can be seen that the losses become larger with increasing values of X2 delay. This indicates that inter-eNB JT CoMP is very sensitive to X2 delay.

12.6 Performance of CoMP scenarios

The performance of intra-eNB CoMP techniques has been extensively studied and evaluated in 3GPP and documented in Ref. [5] as part of the CoMP feasibility studies. The detailed simulation assumptions and simulation models used in this evaluation are described in 3GPP TR 36.814 and TR 36.819 [4,5]. The evaluations were conducted by various sources in the following deployment scenarios [31,32]:

1. Scenario 1: Homogeneous network with intra-site CoMP.
2. Scenario 2: Homogeneous network with high transmit-power RRHs.
3. Scenario 3: Heterogeneous network with low-power RRHs within the macro-cell coverage, where transmission/reception points are identified by different cell IDs.
4. Scenario 4: Heterogeneous network with low-power RRHs within the macro-cell coverage where the transmission/reception points created by the RRHs have the same cell IDs as the macro-cell.

Despite the fact that there was a detailed evaluation methodology that was used by all companies participating in the evaluations, there were discrepancies in the reported results among sources because they used different assumptions concerning (unspecified parameters) channel estimation error modeling, channel reciprocity modeling, the feedback/SRS mechanisms, scheduling algorithm, and the

**FIGURE 12.10**

Impact of X2 latency on user throughput using inter-eNB JT CoMP scheme [15,22].

receiver architecture. In the full-buffer/non-full-buffer evaluations, cell average spectral efficiency in bits/s/Hz/cell and 5% user spectral efficiency in bits/s/Hz/user were evaluated and reported. The user spectral efficiency is defined as the amount of data (file size) per time needed to download data per occupied bandwidth. The time needed to download the data starts when the packet is received in the transmit buffer, and ends when the last bit of the packet is correctly delivered to the receiver. The serving cell spectral efficiency represents the total amount of data for all users during the entire observation time per the number of cells and per occupied bandwidth.

It was observed from the evaluation results for scenarios 1 and 2 that in the downlink, CoMP schemes offer performance gains in homogeneous networks. In the uplink, considerable gain is achievable with a CoMP JR scheme in scenarios 1 and 2. The results were obtained based on ideal and realistic assumptions. It was concluded from the evaluation results in scenarios 3 and 4 that CoMP can provide performance benefits in heterogeneous networks both with full-buffer and FTP traffic models. Based on the evaluation results on the impact of backhaul constraints (capacity/latency), it was concluded that the performance of CoMP schemes relying on spatial information exchange is sensitive to the delay between two transmission points; however, the level of sensitivity depends on the CoMP scheme.

The macro-cell area average spectral efficiency in Figure 12.11 is defined as the sum of cell throughputs in the macro-cell area, which also includes pico-cells/RRHs deployed in the macro-cell area. The results of evaluations show that performance gains can be achieved using CoMP compared to the traditional single-cell schemes in both homogeneous and heterogeneous networks. CoMP performance gains are noted for UEs severely affected by interference. These UEs are typically found at the cell-edges in homogeneous networks. In general, JT CoMP

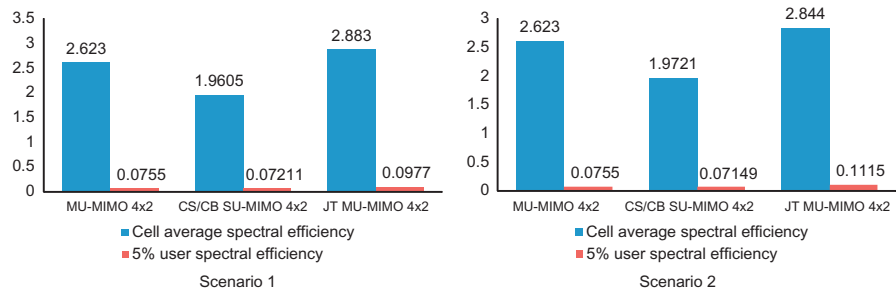


FIGURE 12.11

Comparison of the absolute performance downlink MU-MIMO, CS/CB SU-MIMO, and JT MU-MIMO (FDD, full-buffer, 3GPP spatial channel model, cross-polarized antennas) [4,5].

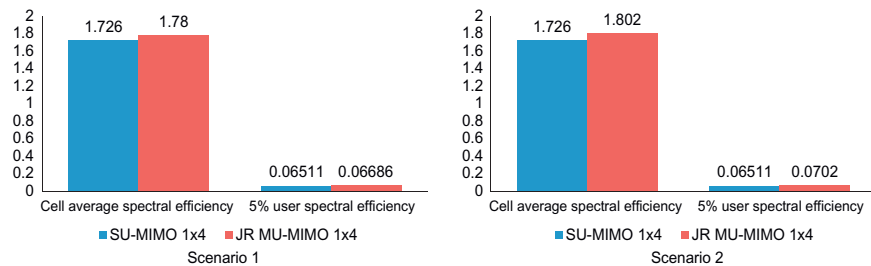


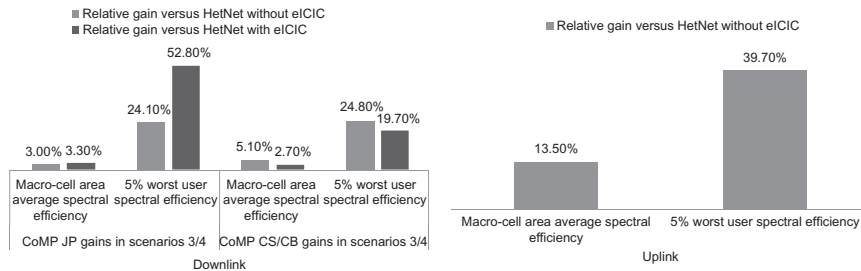
FIGURE 12.12

Comparison of the absolute performance uplink SU-MIMO and JR MU-MIMO (FDD, full-buffer, 3GPP spatial channel model, cross-polarized antennas) [4,5].

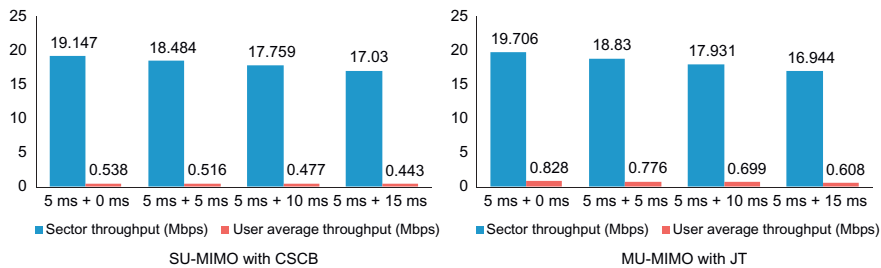
techniques provide larger performance gains relative to CS/CB CoMP schemes, but at the expense of larger backhaul overheads and more stringent requirements on backhaul capacity and latency (see Figure 12.11). These observations suggest that CoMP techniques are a promising trend for LTE-Advanced networks. CoMP will thereby contribute to providing the end users with a more consistent experience of mobile broadband across the network coverage areas (Figure 12.12).

The relative performance gains of CoMP scenarios 3 and 4 over HetNet with and without enhanced ICIC (eICIC) were evaluated and are shown in Figure 12.13.

The impact of lower capacity/higher latency links connecting the transmission points was also investigated. The evaluation results were obtained for CoMP in a homogeneous network [5]. Figure 12.14 shows the evaluation results for SU-MIMO CS/CB and MU-MIMO JT CoMP schemes with varying levels of backhaul delay. The CSI feedback delay is assumed to be 5 ms. The results suggest that the JT CoMP scheme demonstrates larger performance variation, and is more sensitive to backhaul delays compared to the CS/CB CoMP scheme.

**FIGURE 12.13**

Relative performance gain of downlink/uplink CoMP in scenarios 3/4 (FDD, full-buffer, configuration 1) [4,5].

**FIGURE 12.14**

Effect of CSI feedback delay + backhaul delay on sector and user average throughput [4,5].

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Carrier Aggregation

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LTE Rel-8/9 specified system bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz to meet different spectrum and deployment requirements. Support of wider bandwidths up to 100 MHz was one of the distinctive features of IMT-Advanced systems. The IMT-Advanced systems targeted peak data rates in excess of 1 Gbps for low mobility and 100 Mbps for high mobility scenarios [32,33]. In order to support wider transmission bandwidths, LTE Rel-10 introduced the carrier aggregation concept, where two or more component carriers with arbitrary bandwidths belonging to the same or different frequency bands could be aggregated. The support of system bandwidths up to 100 MHz would allow a substantial increase in link-level peak data rate, as well as in the system capacity and user throughput. Another advantage of carrier aggregation is to allow efficient use of fragmented spectrum in the form of a virtually wideband spectrum. The fragmented spectrum may belong to the same or different frequency bands and may be of different bandwidths. LTE Rel-11 further extended the advantages of carrier

aggregation by configuring extended carriers and carrier segments. Furthermore, carrier aggregation can be used to mitigate inter-cell interference in heterogeneous networks [30,31].

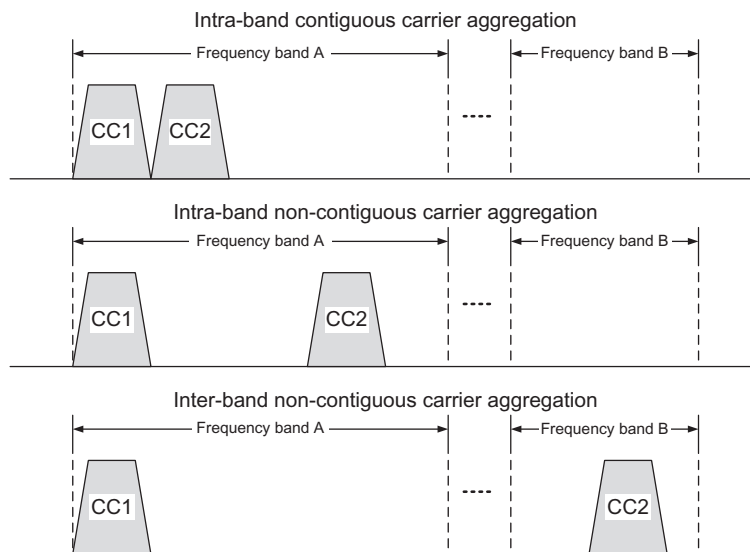
Using the carrier aggregation scheme, it would be possible to simultaneously schedule a user on multiple component carriers for downlink or uplink data transmission, resulting in some challenges in resource scheduling and load balancing across the network. In a non-contiguous inter-band carrier aggregation scenario, where the aggregated carriers belong to different frequency bands, the fading characteristics might be different between component carriers; as a result, the coverage may vary significantly from one carrier to another. At different locations in the cell, some users may only be scheduled on fewer carriers, while other users may have access to the entire carrier set, which may have a negative impact on sustained user throughput within the coverage area of an eNB.

To allow smooth network migration and upgrades to new releases, it was essential to ensure backward compatibility of LTE-Advanced with LTE Rel-8/9, as well as to support mixed operation of the legacy LTE systems and LTE Rel-10 on the same carrier in an operator's network. LTE Rel-10 carrier aggregation satisfied this requirement by configuring each component carrier in a backward compatible manner with LTE Rel-8/9, and by further supporting at least one of the bandwidths compatible with LTE Rel-8/9. The backward compatibility implies that the complete set of LTE Rel-8/9 downlink physical channels and signals are transmitted on each component carrier using LTE Rel-8/9 signaling procedures, including broadcast channel, synchronization signals, reference signals, and control channels. This would also allow reuse of the LTE Rel-8/9 RF designs and implementations at the eNB and the UE. Although we will primarily focus on carrier aggregation for FDD systems, carrier aggregation is fully supported in the TDD systems, as well.

In this chapter, we will take a pragmatic and systematic approach to describe carrier aggregation principles and its impact on different protocol layers. Various aspects of carrier aggregation including deployment scenarios, physical and MAC layer support, as well as higher-layer signaling and RF transceiver design challenges, will be discussed and examples will be provided.

13.1 Principles of carrier aggregation

In LTE-Advanced carrier aggregation terminology, a component carrier is often referred to as a serving cell, is assigned its own cell identifier, and is managed as a serving cell by the higher layers. Each individual RF carrier is known as a component carrier. A component carrier can be downlink and uplink or downlink only, but it cannot be an uplink-only RF carrier for obvious reasons. The number of downlink component carriers may be different than that of the

**FIGURE 13.1**

Carrier aggregation scenarios [16,18,20].

uplink. In general, a different number of component carriers can be aggregated for the downlink and uplink. The UE may support carrier aggregation only in the downlink or in both directions. Up to five component carriers, possibly each with different bandwidths can be aggregated, allowing transmission bandwidths of up to 100 MHz [12,14]. In FDD systems, a serving cell comprises a pair of different carrier frequencies for downlink and uplink transmissions, whereas for TDD, a serving cell is defined as a single-carrier frequency where downlink and uplink transmissions occur in different transmission time intervals. Given that component carriers do not have to be contiguous in frequency which enables utilization of fragmented spectrum, operators with a fragmented spectrum can provide high data-rate services based on the availability of a virtually wide bandwidth even though they do not own a single wideband spectrum allocation.

Each UE has a single serving cell that provides all necessary control information and functions, such as non-access stratum mobility information, security establishment, RRC connection establishment/reconfiguration, etc. This serving cell is referred to as the primary cell (PCell). Other auxiliary cells or component carriers are referred to as secondary cells (SCells).

As shown in Figure 13.1, there are three different carrier aggregation scenarios, as follows [11]:

1. Intra-band contiguous carrier aggregation: This type of carrier aggregation uses a single frequency band. It is the simplest form of carrier aggregation from an implementation point of view. In this scenario, the

carriers are contiguous and the frequency spacing between center frequencies of contiguously aggregated RF carriers is a multiple of 300 kHz in order to be compatible with the 100 kHz frequency raster of LTE Rel-8/9 and preserve orthogonality of the subcarriers with 15 kHz spacing.

2. Intra-band non-contiguous carrier aggregation: In this scenario, the aggregated carriers are not adjacent and the multi-carrier signal cannot be treated as a single signal; therefore, two transceivers may be required. This adds significant complexity particularly to the UE where form-factor, power consumption, and cost are the major concerns.
3. Inter-band non-contiguous: This type of carrier aggregation uses different frequency bands which might be appealing to network operators due to the possibility of using fragmented frequency bands. In this scenario, the UE may have to use multiple transceivers, having unavoidable impact on cost, performance, and power consumption. In addition, there are also further complexities resulting from the requirements to reduce intermodulation and cross-modulation impairments created by the transceivers. This type of carrier aggregation may improve mobility by exploiting radio propagation characteristics of different bands.

An enhanced carrier aggregation work item was approved for LTE Rel-11, where as part of that work item, new non-backward-compatible partially configured carrier types could be defined for LTE Rel-11 and beyond to address the ever-increasing demand for higher capacity and higher data rates in cellular networks [19]. The new carrier types are going to be useful in practical deployments where the size of the available frequency block does not match the provisioned bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz in LTE Rel-8/9. If the size of the frequency block is smaller than 5 MHz (corresponding to 25 resource blocks), the number of resources on the carrier segment or extension carrier may not be adequate to efficiently transmit user data and synchronization signals, broadcast and control channels. Although it is desirable to reduce the overhead of the new carrier types (i.e., extension carrier and carrier segment), in practical deployment scenarios, if the frequency gap between the reference carrier and the extension/segment carrier is excessively large, the time and frequency synchronization and slot/subframe alignment of the carriers in a carrier set may not be maintained without including synchronization signals on the extension carrier/carrier segments.

Any fully configured backward compatible carrier in a carrier set may be extended by an extension carrier or appended by segment carriers. The design of the new carrier types has been required to support the operation in the following scenarios, but not necessarily equally optimized for both cases:

- Synchronized carriers: The base carrier and the new carrier types are synchronized in time and frequency to the extent that no separate synchronization is needed in the receiver.

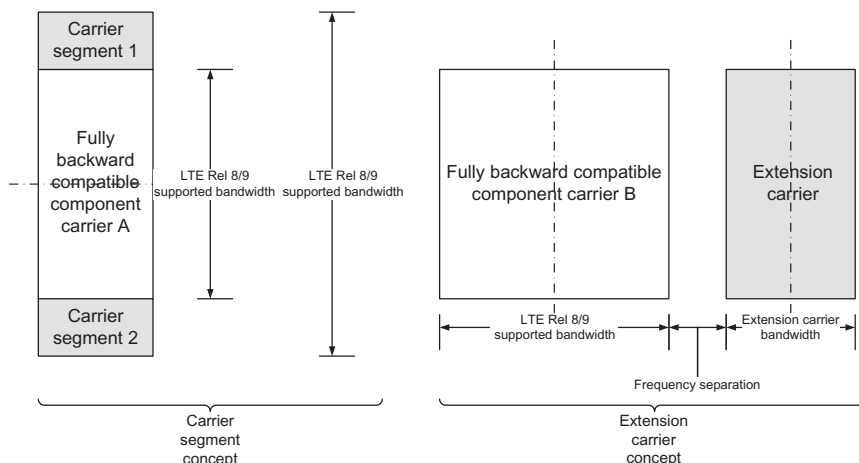
**FIGURE 13.2**

Illustration of the carrier segments and extension carriers [15].

- Unsynchronized carriers: The base carrier and the new carrier types are not synchronized with the same degree of accuracy as the synchronized carriers.

Note that synchronization is considered from the perspective of the UE receiver. Energy efficiency, flexible spectrum usage, heterogeneous network deployments, and machine type communications were identified as key objectives for the enhanced carrier aggregation project in 3GPP [19]. The considerations for the design of the additional carrier types that could assist in addressing the above goals mainly focused on operation with no cell-specific reference signals, enhanced control signaling with self-contained reference signals, and configurability of synchronization and other reference signal types when needed.

The new carrier types are defined as follows [15]:

- Carrier segment: The carrier segments are defined as the bandwidth extensions of an LTE Rel-8 compatible component carrier, provided that the total number of resource blocks is limited to 110. The combined RF carrier (i.e., LTE Rel-8 RF carrier + carrier segments as shown in Figure 13.2) utilizes the same backward compatible mechanisms of accessing the additional resources on the carrier segments as well as the base RF carrier. As an example, if two 2.5 MHz carrier segments are combined with a 5 MHz LTE Rel-8 RF carrier, the resulting 10 MHz RF carrier is going to be utilized as a 10 MHz LTE Rel-8 RF carrier. The use of carrier segments in the above manner would allow more efficient utilization of small fragments of spectrum without having to transmit additional overhead due to synchronization, broadcast, and control channels on the carrier

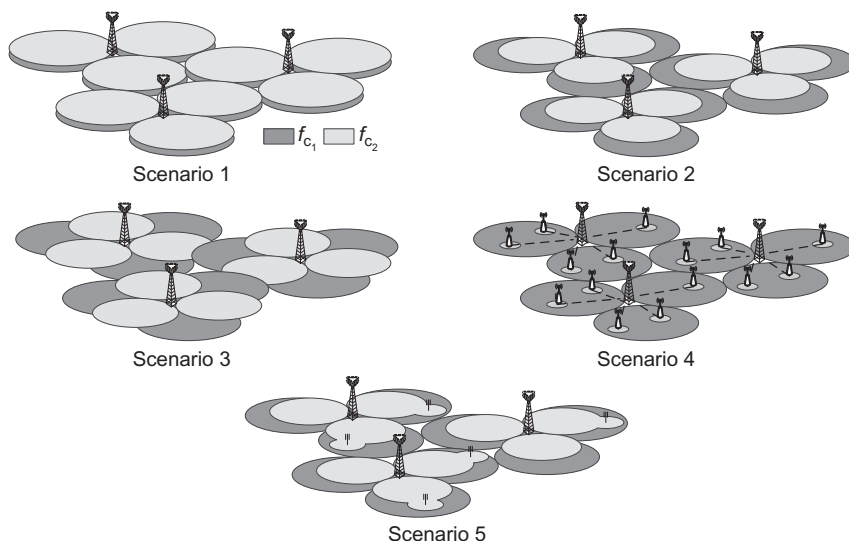
segments. The notion of carrier segment allows for aggregation of additional resource blocks to a component carrier, while still retaining the backward compatibility of the original carrier. Note that carrier segments are always adjacent and linked to one component carrier and cannot be used as stand-alone. They do not provide synchronization signals, system information, or paging, and therefore cannot be used for random access or camping. They support the same HARQ process and transmission mode as the component carrier to which they are linked.

- **Extension carrier:** The extension carrier is a carrier that cannot be operated as a single stand-alone RF carrier and must be part of a component carrier set where at least one of the carriers in the set is a stand-alone backward compatible component carrier. Depending on whether the extension carriers are adjacent or non-adjacent to a component carrier carrying synchronization signals, the extension carrier may or may not be required to carry synchronization signals. If the extension carrier does not carry the synchronization signals, then it must be located close to a component carrier with synchronization signals for reliable synchronization. No legacy control channel PDCCH, PHICH, PCFICH, and no cell-specific reference signals is another possible configuration for the extension carriers which allows reduced overhead and more efficient use of radio resources on that carrier. The extension carrier supports a separate HARQ process, PDCCH, and transmission mode, which is configured from its linked component carrier.

13.2 Deployment scenarios

Carrier aggregation enables various network deployments. In general, carrier aggregation is used to improve data rates for users within overlapped areas of the cells (cell boundaries). However, carrier aggregation can also be used to mitigate inter-cell interference in heterogeneous networks (see Chapter 14). The following network deployment scenarios were considered during the development of LTE-Advanced. Although exemplified with two component carriers at frequencies f_{c_1} and f_{c_2} as shown in Figure 13.3, the concept can be generalized to any number of component carriers [7,22,23,29]:

- **Deployment Scenario 1:** In this case, cells with carrier frequencies f_{c_1} and f_{c_2} are (geographically) collocated, and their coverage is overlaid with f_{c_1} and f_{c_2} in the same frequency band. They provide approximately the same coverage due to similar path loss characteristics within the same band. This carrier aggregation scenario achieves higher data rates throughout the cell where both layers provide sufficient coverage and mobility. An example scenario is the case where $f_{c_1} = 2000$ MHz and $f_{c_2} = 800$ MHz are of the same band where aggregation is possible between the overlaid cells.

**FIGURE 13.3**

Carrier aggregation deployment scenarios [7].

- **Deployment Scenario 2:** In this case, the cells with carrier frequencies f_{c1} and f_{c2} are collocated and overlaid with f_{c1} and f_{c2} in different frequency bands. Different coverage is provided on different carriers due to the larger path loss in the higher frequency band. Mobility is typically supported on the carrier in the lower frequency band which further provides sufficient coverage. The carrier in the higher frequency band is used to improve data rates and throughput. The cells f_{c1} and f_{c2} are collocated and overlaid, but f_{c2} has smaller coverage due to larger path loss. In other words, only f_{c1} provides sufficient coverage and f_{c2} is used to improve throughput. An example scenario would be the case where $f_{c1} = \{800 \text{ MHz}, 2000 \text{ MHz}\}$ and $f_{c2} = \{3500 \text{ MHz}\}$ where aggregation is possible between the overlaid cells.
- **Deployment Scenario 3:** In this case, the cells comprising carrier frequencies f_{c1} and f_{c2} are collocated with f_{c1} and f_{c2} in different frequency bands. The antennas for cells of f_{c2} are directed to the cell boundaries of f_{c1} to improve the cell-edge data rates and user throughput. Due to the larger path loss, coverage holes exist for cells in the higher frequency band on which mobility management is typically not performed. The carrier aggregation is supported in areas with overlapping coverage and the mobility is based on f_{c1} coverage. An example would be the case where $f_{c1} = \{800 \text{ MHz}, 2000 \text{ MHz}\}$ and $f_{c2} = \{3500 \text{ MHz}\}$ in which aggregation is possible between the overlaid cells.

- Deployment Scenario 4: In this case the cells associated with carrier frequency f_{c_1} provide macro coverage and remote radio heads (RRHs) corresponding to carrier frequency f_{c_2} are used to improve throughput at hot spots. The mobility is performed based on the cell coverage of frequency f_{c_1} . In this deployment scenario, the carrier frequencies f_{c_1} and f_{c_2} are usually of different bands. The carrier aggregation is applicable to users within the coverage of RRHs and the underlying macro-cells. An example would be the case where $f_{c_1} = \{800 \text{ MHz}, 2000 \text{ MHz}\}$ corresponds to a larger cell and $f_{c_2} = \{3500 \text{ MHz}\}$ corresponds to smaller cell, in which aggregation is possible between the overlaid cells.
- Deployment Scenario 5: This case is similar to the second scenario where frequency-selective repeaters or distributed antenna systems are additionally deployed to extend the coverage for one of the carrier frequencies. It is expected that f_{c_1} and f_{c_2} cells of the same eNB can be aggregated where coverage overlaps.

13.3 Physical and MAC layer aspects of carrier aggregation

In this section, we discuss the physical and MAC layer aspects of carrier aggregation, and we will particularly focus on the impacts of carrier aggregation on the system operation at the lower protocol layers. Note that scheduling and use of the RF carriers are related to physical and MAC layers, and to a great extent are transparent to the upper layers.

13.3.1 Physical layer aspects

The physical layer is in charge of processing and transmission of data and control signaling between the radio access network and the user device. The LTE-Advanced carrier aggregation feature enables concurrent data transmission on multiple component carriers (up to five), where the transmission schemes are largely inherited from LTE Rel-8/9 data transmission procedures per component carrier, including the multiple access scheme; modulation and coding; and multi-antenna processing. Some additional UE functionalities beyond those of LTE Rel-8/9 are supported in LTE Rel-10, including data transmissions over two clusters of contiguous bandwidth on the same carrier where the data is precoded by a single DFT unit (see Chapter 10 for a description of clustered SC-FDMA), simultaneous transmission of a control channel and a data channel in the PCell (see Chapter 10 for simultaneous PUCCH and PUSCH transmission), and data transmissions from multiple antennas with spatial multiplexing [3–6]. Nevertheless, improving the downlink and uplink control signaling to efficiently support data transmission was the main challenge in the design of LTE-Advanced carrier aggregation [29].

The PDCCH provides information on resource allocation; modulation and coding scheme HARQ; and other parameters for downlink and uplink data transmission on the physical downlink/uplink shared channel. It is possible to configure each component carrier to transmit the PDCCH for scheduling PDSCH/PUSCH on the same carrier frequency and associated linked uplink carrier, where the linkage of the downlink and uplink carriers is conveyed in SIB2 [10]. In addition, the PDCCH on a component carrier can be configured to schedule PDSCH and PUSCH transmissions on other component carriers through a cross-carrier scheduling feature. Cross-carrier scheduling was primarily developed to support heterogeneous networks comprising a combination of macro-eNBs and low-power nodes (e.g., pico-cell, femto-cell, and RRHs) where significant intercell interference may arise when those networks are deployed on the same carrier [30,31]. Since the PDCCH is transmitted across the entire bandwidth of the respective carrier, interference coordination methods based on fractional frequency reuse may not be adequate in reducing the inter-cell interference on the PDCCH. Carrier aggregation can address this issue by configuring the UE connected to different network nodes to receive the PDCCH on different carriers, thereby reducing or even eliminating inter-cell interference on the PDCCH. With cross-carrier scheduling, only one component carrier needs to be protected for the PDCCH transmission, which can be used to allocate resources on other component carriers.

Cross-carrier scheduling enables a PDCCH on a component carrier to be configured in order to schedule PDSCH and PUSCH transmissions on another component carrier using a 3-bit carrier indicator field (CIF) which is inserted at the beginning of the downlink control information (DCI) messages. The carrier aggregation can reduce or even eliminate inter-cell interference on the PDCCH using cross-carrier scheduling. Figure 13.4 shows a hypothetical heterogeneous network scenario where a component carrier at f_1 is used by the macro-cell at full power and by the pico-cells at reduced power; whereas component carrier f_2 is used by the macro-cell at reduced power and by the pico-cells at nominally low power. In this case, cross-carrier scheduling from component carrier f_2 allows inter-cell interference mitigation among the macro- and pico-cells.

Cross-carrier scheduling is also an effective mechanism to schedule data transmissions on carriers of small bandwidth from a carrier with a larger bandwidth, considering that the PDCCH reliability targets are more challenging to achieve on carriers with small bandwidth due to limited frequency diversity gain. The PDCCH search space consists of a set of PDCCH candidates over which the UE performs blind decoding operations to determine whether there is any PDCCH addressed to it in a subframe. A common PDCCH search space is monitored by all UEs only in their respective PCells for receiving system information, paging, power control, and random access-related control information. Each UE also monitors a UE-specific PDCCH search space primarily carrying scheduling grants for downlink and uplink data transmissions. The start of the UE-specific PDCCH search space is a function of the UE's radio network temporary identifier (RNTI).

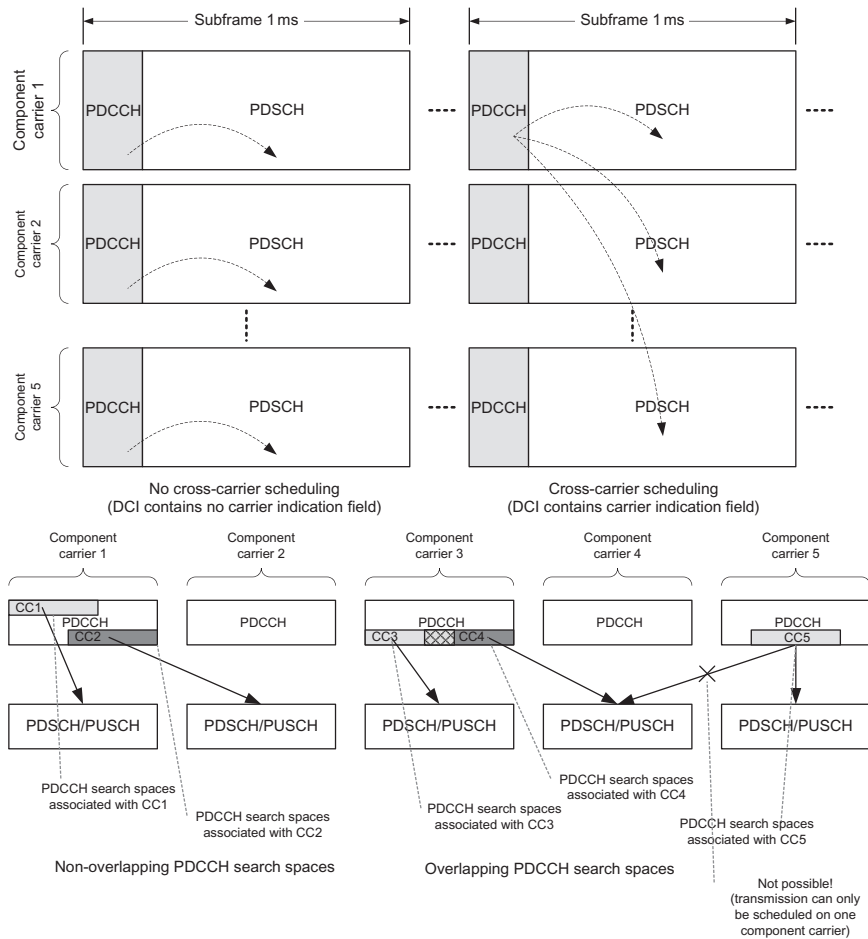
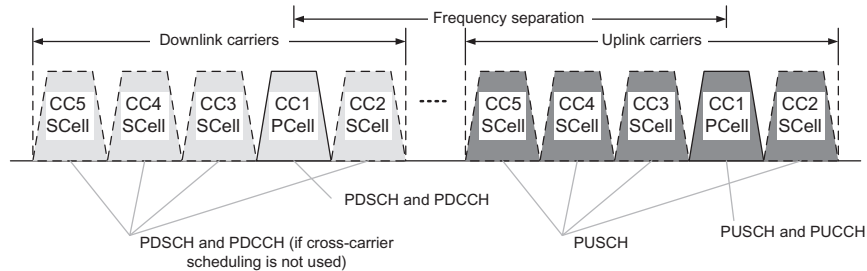
**FIGURE 13.4**

Illustration of the cross-carrier scheduling concept in carrier aggregation [13,14].

Since the same set of resources for PDCCH transmission is shared by all UEs, a PDCCH for a UE may not be transmitted due to partial overlapping with another PDCCH belonging to a different UE; this condition is referred to as PDCCH blocking. To maintain the PDCCH blocking probability at LTE Rel-8/9 level, an LTE Rel-10/11 UE monitors one UE-specific PDCCH search space for each activated component carrier. For a UE that is not configured with cross-carrier scheduling, the UE-specific PDCCH search space on each component carrier is the same as that in LTE Rel-8/9, whereas for a UE that is configured with cross-carrier scheduling, the UE-specific PDCCH search space is defined by a

**FIGURE 13.5**

Symmetric carrier aggregation in the downlink and uplink (example) [16].

combination of the UE's RNTI and the serving cell index. The number of PDCCH blind decoding operations performed by a UE scales (approximately) linearly with the number of its activated component carriers [29]. If carrier aggregation is configured, the maximum number of blind decoding operations that a UE performs is 44 for the PCell plus 32 for each active downlink SCell. An additional 16 blind decodings are needed for each uplink component carrier that is configured for uplink MIMO operation. When cross-carrier scheduling is configured, CIF is only present in the PDCCH messages in the UE-specific search space and not in the common search space [13].

The PDSCH/PUSCH on a component carrier can only be scheduled from one component carrier. Therefore, for each PDSCH/PUSCH component carrier, there is an associated component carrier, configured via UE-specific RRC signaling, where the corresponding DCI can be transmitted. Figure 13.4 illustrates an example, where PDSCH/PUSCH transmissions on component carrier 1 are scheduled using PDCCHs transmitted on component carrier 1. In this case, since cross-carrier scheduling is not used, there is no carrier indicator in the corresponding DCI formats. The PDSCH/PUSCH transmissions on component carrier 2 are cross-carrier scheduled from PDCCHs transmitted on component carrier 1. Therefore, the DCI formats in the UE-specific search space for component carrier 2 include the CIF. Note that the transmissions on a component carrier can be scheduled by the PDCCHs on one component carrier; thus, component carrier 4 cannot be scheduled by PDCCHs on component carrier 5, given that there is a semi-static association between component carriers 3 and 4 for PDCCH transmission in this example [14].

As mentioned earlier, there is one UE-specific search space per aggregation level and component carrier used for PDSCH/PUSCH. This is illustrated in Figure 13.4, where PDSCH/PUSCH transmissions on component carrier 1 are scheduled using PDCCHs transmitted on component carrier 1. There is no CIF in the UE-specific search space for component carrier 1 since cross-carrier scheduling is not used. For component carrier 2, on the other hand, a carrier indicator field exists in the UE-specific search space, given that component carrier 2 is

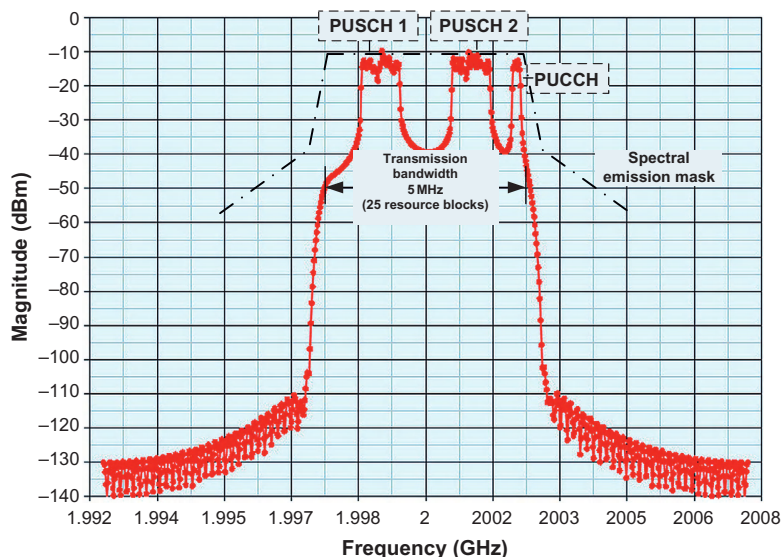
cross-carrier scheduled from the PDCCHs transmitted on component carrier 1. Search spaces for different component carriers may overlap in some subframes. In Figure 13.4, this happens for the UE-specific search spaces for component carriers 3 and 4. The terminal can identify the two search spaces independently, assuming that a CIF is used for component carrier 4, but is not used for component carrier 3. If the UE-specific and common search spaces corresponding to different component carriers happen to overlap for some aggregation levels when cross-carrier scheduling is configured, the terminal only needs to monitor the common search space. The reason for this is to avoid ambiguities arising from this condition; if the component carriers have different bandwidths, a DCI format in the common search space may have the same payload size as another DCI format in the UE-specific search space corresponding to another component carrier [14].

The PCFICH is transmitted in each subframe and conveys a control format indicator (CFI) field, which indicates the number of OFDM symbols carrying control information in each subframe (up to three OFDM symbols per subframe). The UE derives the starting OFDM symbol used for the PDSCH transmission based on the decoded CFI value. For the PDSCH scheduled by PDCCH on the same component carrier, the UE is required to decode the PCFICH in order to determine the starting OFDM symbol used for the PDSCH. When cross-carrier scheduling is utilized, the starting OFDM symbol for the PDSCH transmission is configured by the network through higher layers, and the UE is not required to decode PCFICH on that component carrier.

The physical HARQ indicator channel carries HARQ feedback (ACK/NACK) information associated with a PUSCH transmission. The PHICH structure in LTE Rel-10/11 carrier aggregation is the same as that for LTE Rel-8/9. The PHICH corresponding to a PUSCH transmission is always transmitted on the component carrier where the PDCCH schedules the PUSCH transmission.

The uplink control information (UCI) includes HARQ feedback corresponding to one or more PDSCHs, channel state information, and scheduling request. Similar to LTE Rel-8/9, the UCI can be transmitted on the PUCCH, if there is no transmission on PUSCH in a subframe, or transmitted on PUSCH, if there is a scheduled transmission on PUSCH. LTE-Advanced further supports simultaneous PUCCH and PUSCH transmissions in a subframe (see Figure 13.6). This allows the eNB to flexibly control the performance of the PUCCH and PUSCH independently and to avoid the UCI overhead on PUSCH by utilizing existing PUCCH resources. The PUCCH can only be transmitted on the PCell, since it typically has more reliable link quality and coverage relative to the SCells (see Figure 13.5). When applicable, UCI is always transmitted on a single PUSCH.

HARQ feedback indicates whether a transport block is correctly received and decoded. LTE Rel-8/9 supports transmitting a maximum of two and four ACK/NACKs in an uplink subframe for FDD and TDD, respectively. Given independent HARQ processes per component carrier, the maximum number of HARQ feedback bits in a subframe in response to PDSCH transmissions can be 10 bits

**FIGURE 13.6**

Snapshot of clustered SC-FDMA (simultaneous PUSCH and PUCCH transmission) in the uplink [17,18].

for FDD and up to 90 bits for TDD (assuming five component carriers with MIMO transmission modes per component carrier and TDD subframe configuration 5). Reliable transmission of large number of HARQ ACK/NACK bits in an uplink subframe requires a substantial amount of resources and sufficiently high signal to interference plus noise ratio. Therefore, HARQ feedback bundling/multiplexing schemes are designed for TDD systems to limit the maximum number of ACK/NACK bits in an uplink subframe to 20. Multiple HARQ feedback bits are bundled by a logical AND operation to produce one HARQ feedback bit per component carrier and per subframe for certain TDD subframe configurations. The PUCCH format 3 was introduced in LTE Rel-10 to support HARQ feedback for a UE configured with downlink carrier aggregation. The PUCCH format 3 uses a SC-FDMA waveform with five SC-FDMA symbols per slot carrying HARQ feedback information and one or two SC-FDMA symbols per slot (depending on the size of the cyclic prefix) for transmission of demodulation reference signals, to enable coherent demodulation of HARQ feedback (see Chapter 10 for more information on PUCCH format 3). An orthogonal cover code of length 5 is applied to the encoded HARQ feedback bits in the corresponding SC-FDMA symbols, allowing multiplexing of up to five UEs in one resource block. Assuming QPSK modulation, k HARQ feedback bits are encoded using the $(32, k)$ Reed–Muller code with circular rate matching into 48 encoded HARQ acknowledgment bits, which are transmitted in a subframe comprising two slots.

LTE-Advanced further supports the HARQ feedback multiplexing scheme for TDD, where two HARQ feedback bits are generated per component carrier, representing the number of consecutively correctly received PDSCHs on the component carrier. PUCCH format 1b can be used to carry four acknowledgments when channel selection is used, i.e., the PUCCH payload carries two acknowledgments and the selection of PUCCH resources carries the other two acknowledgments. The use of bundled acknowledgments in a single uplink subframe is not limited to the TDD duplex mode. The carrier aggregation in FDD with a different number of uplink and downlink component carriers encounters the same problem. In LTE Rel-10, there is only one PUCCH that is always transmitted on the primary component carrier. Hence, even in asymmetric carrier aggregation scenarios, the possibility to transmit more than two HARQ acknowledgment bits in the uplink must be supported. This is performed via resource selection or by using PUCCH format 3. The acknowledgments in response to PUSCH transmissions are transmitted using multiple PHICHs, where the PHICH is transmitted on the same downlink component carrier as the uplink scheduling grant which initiated the uplink transmission.

The channel-state information feedback enables the eNB to perform PDSCH scheduling including resource allocation, MCS selection, transmission rank adaptation, and the choice of precoding matrix. To accommodate different channel conditions and interference levels among different component carriers, CSI is fed back for each component carrier. Both periodic and aperiodic CSI feedbacks are supported in LTE Rel-10/11, where periodic CSI is transmitted on a set of semi-statically configured subframes, and aperiodic CSI is dynamically scheduled by the eNB via the PDCCH. Periodic CSI feedback is independently configured for each component carrier and transmitted on the PUCCH using PUCCH format 2. Since the payload size of PUCCH format 2 is limited, the periodic CSI for only one component carrier can be unconditionally transmitted in a subframe. A priority based on the periodic CSI reporting type determines the component carrier for which periodic CSI is reported in the event that periodic CSI feedback of multiple carriers collide in a subframe. If the collisions involve the same periodic CSI reporting type, the priority is according to ascending cell index. Aperiodic CSI feedback is transmitted on PUSCH and typically carries more CSI bits than periodic CSI feedback. LTE Rel-10/11 supports aperiodic CSI feedback for a single or multiple component carriers in a subframe so that the eNB can balance the CSI accuracy and feedback overhead [29].

Uplink power control is a mechanism to instruct the UEs to determine the PUSCH/PUCCH transmission power with the objective of ensuring that the target reception reliability of that channel is met. The uplink power control supported in LTE Rel-8/9/10 consists of an open-loop component adjusting for the path loss between the UE and its serving eNB, and of a closed-loop component based on transmission power control commands in the PDCCH. The uplink power control processes are independent among the respective activated cells and each process is the same as LTE Rel-8/9. The resulting transmission power for PUSCH or

PUCCH is referred to as nominal transmission power. The key differentiation with respect to the LTE Rel-8/9 uplink power control operation occurs when the sum of the nominal transmission powers from the UE exceeds the total maximum output power for which the UE is configured in a specific subframe. Depending on whether the UE is configured for simultaneous PUCCH and PUSCH transmissions, on the UCI types for transmission, and on the existence of any PUSCH transmission, the UE may transmit in a subframe one PUCCH, one PUSCH with UCI, one or more PUSCH transmissions without UCI, or any other combination. As control information is more important than data information and does not benefit from the use of HARQ, the UE transmission power is distributed by descending priority to the PUCCH, PUSCH with UCI, and PUSCH without UCI, where the nominal transmission power for a channel with higher priority is first guaranteed until the UE total maximum output power is reached. For one or more PUSCH transmissions without UCI, the UE scales each respective nominal PUSCH transmission power by the same factor, considering that the same quality of service for data transmission is required on all component carriers [29].

The eNB may not know the exact UE transmission power due to the possibility of missing power control commands, UE-specific implementation of maximum power reduction (MPR),¹ and additional maximum power reduction (A-MPR)² in order to meet regulatory requirements. To provide the eNB with more accurate information on the UEs transmission power, power headroom reporting was supported in LTE Rel-8/9. The UE may report type 1 and/or type 2 power headroom for an activated cell. The type 1 and type 2 power headroom reports indicate the amount of remaining the UEs transmission power beyond those already used for PUSCH, or PUSCH and PUCCH transmission in a subframe, respectively [29].

13.3.2 MAC layer aspects

From the MAC perspective, the carrier aggregation simply provides additional conduits, thus the MAC sublayer plays the role of a multiplexing entity for the aggregated component carriers. Figure 13.7 shows an overview of the downlink

¹The purpose of MPR is to allow the UE, in some configurations, to lower its maximum output power in order to meet the general requirements on signal quality and out-of-band (OOB) emissions. Note that MPR is an allowance and the UE is not required to use it [13].

²The eNB may inform the UE of the possibility of further lowering its maximum power by signaling an additional MPR (A-MPR). The need for an A-MPR occurs with certain combinations of E-UTRA bands, channel bandwidths, and transmission bandwidths for which the UE must meet additional (more stringent) requirements for spectrum emission mask and spurious emissions. As with MPR, the A-MPR is an allowance, not a requirement, and it applies in addition to MPR. Regardless of whether the UE makes use of the allowed MPR and A-MPR, the additional requirements for spectrum emission mask and spurious emissions that are signaled by the network always apply. The reason for the complex set of conditions for the relaxation is the expected intermodulation products which may fall into adjacent bands which have different levels of sensitivity (e.g., public safety bands) [13].

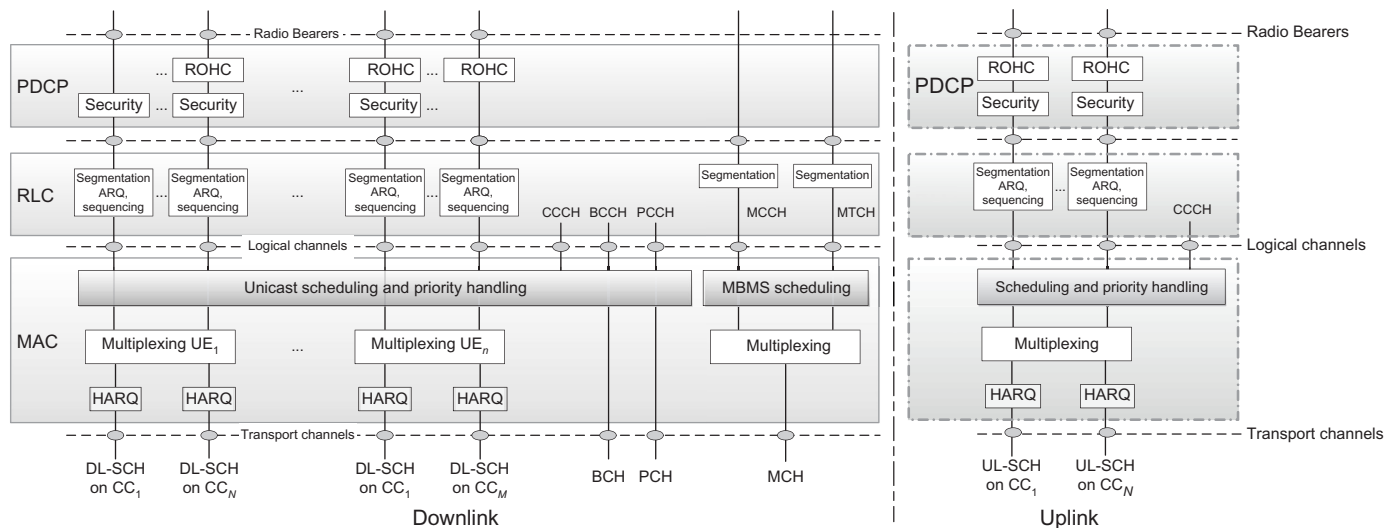


FIGURE 13.7

LTE-Advanced downlink/uplink layer 2 structure when carrier aggregation is configured [7].

user-plane protocol stack at the base station, as well as the corresponding mapping of the most essential radio resource management functionalities for carrier aggregation. Each user has at least one radio bearer which is referred to as the default radio bearer. The exact mapping of data to the default bearer is up to the operator policy and is configured via the traffic flow template. In addition to the default radio bearer, users may have additional bearers configured. There is one PDCP and RLC entity per radio bearer, including functionalities such as robust header compression, security, segmentation, and ARQ. As mentioned in the previous chapters, the interface between the RLC sublayer and MAC sublayer is referred to as the logical channel.

There is one MAC entity per user, which controls the multiplexing of data from all logical channels to the user, and further controls how this data is transmitted on the available component carriers. As illustrated in Figure 13.7, there is a separate HARQ entity per component carrier, which essentially means that if data transmission is on the i th component carrier, the HARQ retransmissions in case of erroneous reception must be performed on the i th component carrier. The interface between the MAC sublayer and the physical layer, which are referred to as transport channels, is also separate for each component carrier. The transport blocks sent on different component carriers can be transmitted with independent MCSs as well as different MIMO schemes. The latter allows data on one component carrier to be transmitted with open-loop transmit diversity (transmission mode 2), whereas data on another component carrier sent with dual-layer beamforming (transmission mode 8). There is independent link adaptation per component carrier in order to take advantage of more accurate link adaptation on different component carriers according to their respective propagation and radio channel conditions. Semi-persistent scheduling can only be configured for the PCell, and PDCCH allocations for the PCell can override the corresponding semi-persistent scheduling resource allocation.

The LTE Rel-8/9 control-plane protocol stack also applies to LTE-Advanced with multiple component carriers, meaning that there is one RRC per user, independent of the number of component carriers. Similarly, idle mode mobility procedures of LTE Rel-8/9 also apply in a network supporting carrier aggregation. It is also possible for a network to configure only a subset of component carriers for idle mode camping [26].

E-UTRA in general supports a synchronized uplink by means of an uplink timing advance (TA) adjustment procedure. The carrier aggregation in LTE Rel-10 only supports a single timing advance value which is applied to all component carriers. This means that the base station transceivers for different carriers should be at the same location to avoid different propagation delays. The use of RRHs, distributed antennas, and repeaters was limited. The signal should be received within the cyclic prefix length for a correct reception by a regular UE. The timing advance group (TAG) was introduced in LTE Rel-11 for supporting multiple timing advances typically encountered in inter-band carrier aggregation scenarios. A TAG includes one or more serving cells with the same uplink timing advance and

the same downlink timing reference cell. If a TAG contains the PCell, it is referred to as the primary timing advance group (pTAG). If a TAG contains only SCell(s), it is denoted as the secondary timing advance group (sTAG). There is one timing reference cell and one time alignment timer (TAT) per TAG, and each TAT may be configured with a different value. For pTAG, the PCell is used as the timing reference cell, whereas for sTAG, the UE may use any activated SCell from the same sTAG as the timing reference cell. From an RF requirement point of view, the number of component carriers is limited to two for LTE Rel-11; thus, if the sTAG is configured, there is only one SCell in the sTAG [7].

The initial uplink timing alignment of the sTAG is obtained by an eNB initiated random access procedure similar to the pTAG. The SCell in a sTAG can be configured with random access channel resources, and the eNB may instruct the UE to perform random access on the SCell. The Msg2 (or random access response) in response to the SCell preamble is transmitted on the PCell using an RA-RNTI that conforms to the LTE Rel-8 RACH procedure. The grant in Msg2 is valid for the SCell in which the preamble was transmitted. The UE stops transmission of the random access preamble on the SCell when reaching the maximum number of transmissions. However, the UE will not indicate a random access problem to upper layers, if the maximum number of preamble transmissions is reached for the random access procedure on the SCell. The UE tracks the downlink frame timing change of the SCell and adjusts the uplink transmission timing following the timing advance commands from the eNB [7].

13.4 Protocol and signaling aspects of carrier aggregation

In order to enable mobility when supporting carrier aggregation, a UE handles a component carrier in the same way as it would deal with another carrier frequency in LTE Rel-8/9. The UE performs various measurements as instructed by the eNB including intra- and inter-frequency measurements which are used for selecting LTE carriers, as well as inter-RAT measurements which are meant for non-LTE RAT selection. As of LTE Rel-10/11, the following event-triggered reporting criteria are defined [10]:

- Event A1: Serving cell becomes better than absolute threshold.
- Event A2: Serving cell becomes worse than absolute threshold.
- Event A3: Neighbor cell becomes better than an offset relative to the serving cell.
- Event A4: Neighbor cell becomes better than absolute threshold.
- Event A5: Serving cell becomes worse than one absolute threshold and neighbor cell becomes better than another absolute threshold.
- Event A6: Intra-frequency neighbor becomes better than an offset relative to an SCell (LTE Rel-10/11 only).

For inter-RAT mobility, the following criteria for measurement reporting are defined [10]:

- Event B1. Neighbor cell becomes better than absolute threshold.
- Event B2. Serving cell becomes worse than one absolute threshold and neighbor cell becomes better than another absolute threshold.

The new measurement event A6 was introduced for LTE-Advanced carrier aggregation to compare the neighbor cells' component carriers to the current SCell, thus allowing reconfiguration of SCells.

The discontinuous reception (DRX) mode was defined in LTE Rel-8/9. If one or more SCells are configured for a UE in addition to the PCell, the same DRX mode is applied to all serving cells. According to network configuration and ongoing HARQ processes, the UE determines the DRX activity cycle which is common to all serving cells. This means that the active times for PDCCH monitoring are identical across all downlink component carriers (see Figure 13.8).

The SCell activation/deactivation is an efficient mechanism to reduce the UE power consumption in LTE Rel-10/11 carrier aggregation in addition to DRX. On a deactivated SCell, the UE neither receives downlink signals nor transmits any uplink signal. The UE is also not required to perform measurements on a deactivated SCell. Deactivated SCells can be used as a path loss reference for measurements in uplink power control. It is assumed that these measurements would be less frequent while the SCell is deactivated in order to conserve the UE power. On the other hand, for an activated SCell, the UE performs normal activities for downlink reception and uplink transmission. Activation and deactivation of SCells is controlled by the eNB. As shown in Figure 13.8, the SCell activation/deactivation is performed when the eNB sends an activation/deactivation command in the form of a MAC control element. A timer may also be used for automatic deactivation, if no data or PDCCH messages are received on an SCell for a certain period of time. This is the only case in which deactivation can be executed autonomously by the UE. Serving cell activation/deactivation is performed independently for each SCell, allowing the UE to be activated only on a particular set of SCells. Activation/deactivation is not applicable to the PCell because it is required to always remain activated when the UE has an RRC connection to the network [29].

As already mentioned, if the UE is configured with one or more SCells, the network may activate and deactivate the configured SCells. The PCell is always activated. The network activates and deactivates the SCell(s) by sending an activation/deactivation MAC control element as described in Chapter 8. Furthermore, the UE maintains an *sCellDeactivationTimer* per configured SCell and deactivates the associated SCell upon its expiration. The same initial timer value is applied to each instance of the *sCellDeactivationTimer* and it is configured by RRC signaling. The configured SCells are initially deactivated upon addition and after a handover [9].

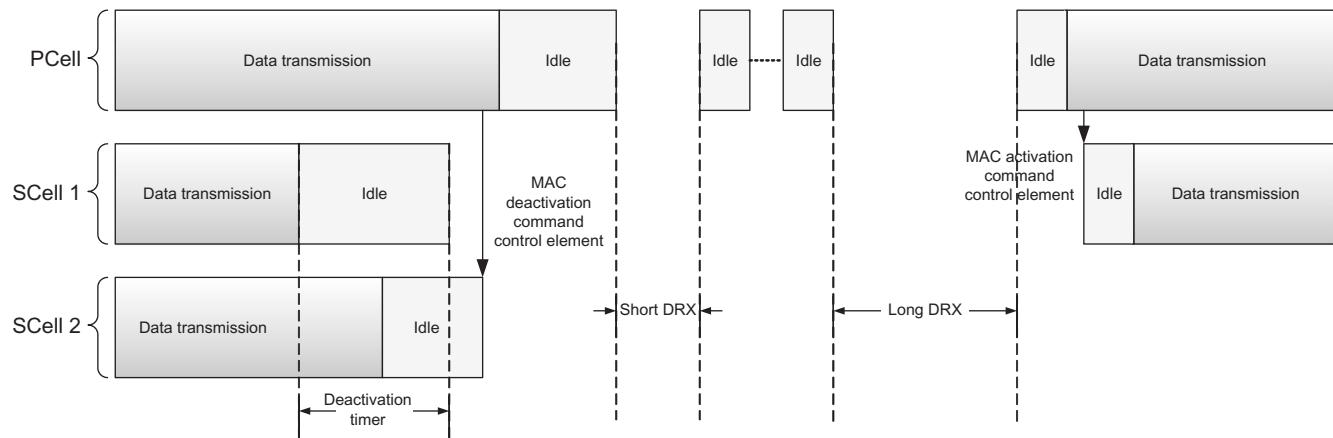


FIGURE 13.8

Illustration of SCell activation/deactivation procedure [20].

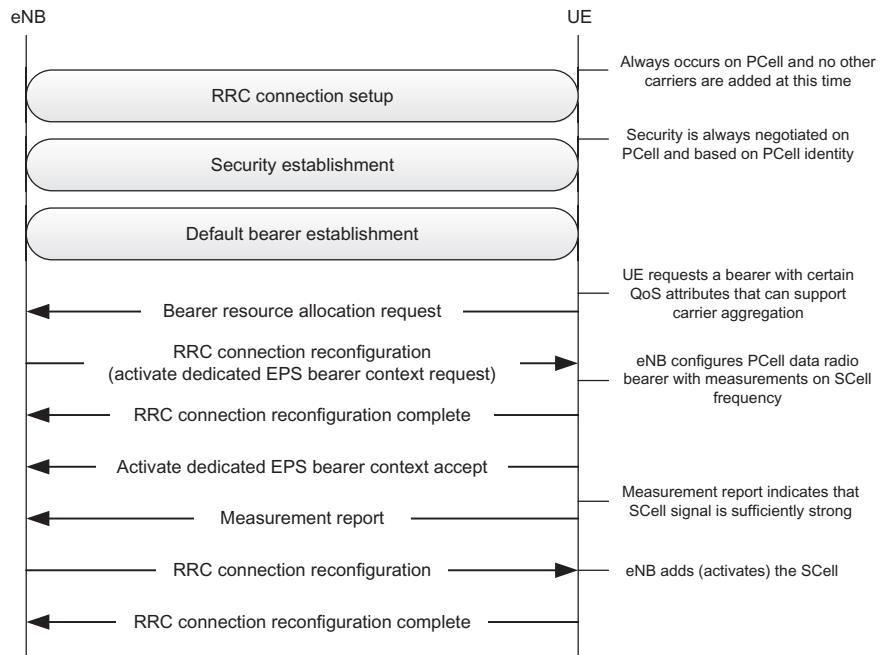
As mentioned earlier, the activation or deactivation of downlink component carriers are performed through a MAC control element. A command to activate a component carrier takes effect eight subframes after the receipt of the activation/deactivation command, i.e., if the MAC control element is received in subframe n , then the SCells are activated/deactivated starting from subframe $n + 8$. There is also a timer-based mechanism for deactivation such that a terminal may deactivate SCells after a configurable time with no activity. Note that the primary component carrier is always active. In the uplink, there is no explicit means of activation for uplink component carriers. However, whenever a downlink component carrier is activated or deactivated, the corresponding uplink component carrier is also activated or deactivated [14].

13.5 Radio resource management aspects of carrier aggregation

Cell management is the control procedure enabling the network to add, remove, or change SCells, or to switch the PCell of a UE. A UE in the RRC_IDLE state establishes RRC connection on a serving cell, which automatically becomes its PCell. Depending on the carrier where initial access is performed, different UEs in a network with carrier aggregation capability may have different PCells. With the RRC connection established on the PCell, the network can further configure one or more SCells for a carrier-aggregation-capable UE, considering the UEs capability [8] to meet the UE's data service requirements. The necessary information, including system information of an SCell is conveyed to the UE via dedicated RRC signaling. Addition, removal, or reconfiguration of SCells for a UE is performed via dedicated RRC signaling (see Figure 13.9). The network can further change the PCell of a UE to improve the link quality of the PCell on which critical control information is sent, or to provide load balancing among different SCells. The change of PCell in LTE Rel-10 carrier aggregation can only be performed via a handover procedure, and it does not necessarily require the UE to switch to single-carrier operation. Intra-LTE handover in LTE-Advanced allows the target PCell to configure one or more SCells for the UE to use immediately after handover [29].

The carrier aggregation additional SCells cannot be activated immediately at the time of RRC connection establishment, since there is no provision in the RRC connection setup procedure for SCells. SCells are added or removed from the set of serving cells through the RRC connection reconfiguration procedure. Note that, since intra-LTE handover is treated as an RRC connection reconfiguration, SCell handover is supported. The carrier aggregation-related information sent by the eNB pursuant to the RRC connection reconfiguration procedure can be summarized as follows [20]:

- Cross-carrier scheduling configuration: This indicates if scheduling for the referenced SCell is managed by that SCell or by another cell.

**FIGURE 13.9**

Summary of message exchange for addition of SCells [20].

- SCell PUSCH configuration: This indicates whether resource block group hopping is utilized on the SCell.
- SCell uplink power control configuration: This carries a number of primitives related to the SCell uplink transmit power command, including the path loss reference-linking parameter.
- SCell CQI reporting configuration: This carries a number of primitives related to CQI measurement reporting for SCells.

13.6 RF and implementation aspects of carrier aggregation

Although not considered a problem for the base station, carrier aggregation will undoubtedly pose major difficulties for the UE, which must handle multiple (simultaneously operating) transceivers. The addition of simultaneous non-contiguous transmitters creates a highly challenging radio environment in terms of spurious signal emissions and self-blocking. Carrier aggregation brings new technical challenges, especially for the LTE Rel-10/11 UE implementation. The complexity of the UE's RF front-end module can vary greatly, depending on which type(s) of carrier aggregation are supported, with contiguous carrier aggregation being the least

complex scenario. In LTE Rel-10 devices, contiguous carrier aggregation will not exceed two component carriers or 40 MHz maximum bandwidth. It may be possible to support this configuration with a single wideband transceiver in the UE. For non-contiguous component carrier allocations, the UE will have to use multiple transceivers or a single, extremely wide wideband transceiver. Using multiple transceivers may be more realistic in the sense that such configuration requires only the addition of parallel paths to process each frequency band, as in existing multiband devices. However, using multiple transceivers also increases the size, cost, and power consumption of the mobile device [12–14].

In a wideband transceiver, a single transceiver must process the multi-band non-contiguous carrier aggregation using wideband RF components. There are two main issues with this approach. First, as the bandwidth increases, the effective noise bandwidth increases, thus resulting in increased noise power. Second, with a wider bandwidth, more unwanted signals are likely to be received from other sources. Therefore, for non-contiguous carrier aggregation, most proposals today are leaning toward the use of multiple transceivers instead of a single wideband approach. In addition to increasing the RF front-end complexity, using simultaneous non-contiguous transmitters creates a highly challenging radio environment in terms of spurious signal management and self-blocking. Because these challenges particularly impact UE design, more work needs to be done before interband carrier aggregation can be successfully introduced in the uplink [14].

Simultaneous transmit or receive with mandatory MIMO support would aggravate the challenge of antenna design. The frequency bands designated for the deployment of LTE are mostly the existing IMT-2000 bands, or the bands where the legacy systems, including UMTS and GSM, were deployed. The frequency bands in some regions are defined in a technology-neutral manner, which means that coexistence among different technologies is a necessity. In general, the requirements for LTE operation in different frequency bands do not impose any specific requirements on the radio-interface design. However, there are implications for the RF requirements and the way they are defined in order to support coexistence between operators in the same geographical area, collocation of base station equipment of different operators, and coexistence with services in adjacent frequency bands and across country borders [14].

Operators may deploy LTE or other IMT-2000 technologies such as HSPA or EDGE in their respective bands. Such coexistence requirements to a large extent are developed within 3GPP, but there may also be regional requirements defined by regulatory bodies in some frequency bands. There are in many cases limitations to where base station equipment can be deployed. The base station sites are often shared between operators, or an operator will deploy multiple technologies in one site. This imposes additional requirements on base station transceivers. The use of the RF spectrum is regulated through international agreements governed by ITU-R. As a result, there are requirements for coordination among operators in different countries, and for coexistence with services in adjacent frequency bands. Coexistence between operators of TDD systems in the same band

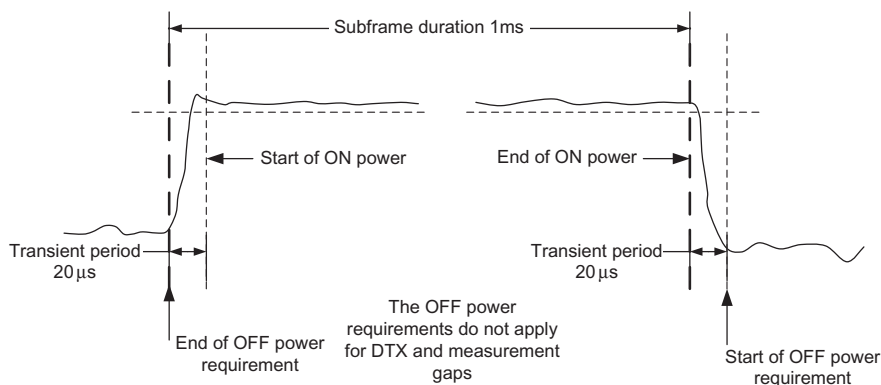
is provided by inter-operator synchronization in order to avoid interference between downlink and uplink transmissions of different operators. Through the release-independent principle, it is possible to design terminals based on an early release of 3GPP specifications that support a frequency band added in a later release [14].

The requirements for carrier aggregation are defined for carrier aggregation configurations with associated bandwidth combination sets. For inter-band carrier aggregation, a *carrier aggregation configuration* is a combination of operating bands, each supporting a carrier aggregation bandwidth class. For intra-band contiguous carrier aggregation, a carrier aggregation configuration is a single operating band supporting a carrier aggregation bandwidth class. For each carrier aggregation configuration, requirements are specified for all bandwidth combinations contained in a *bandwidth combination set*, which is indicated per supported band combination in the UE radio access capability [8]. A UE can indicate support of several bandwidth combination sets per band combination [1].

13.6.1 Temporal/spectral masks and unwanted emissions

E-UTRA needs to ensure user orthogonality in the time-domain similar to UMTS systems. In UMTS, the requirements for user orthogonality were based on ON/OFF masks, which defined the allowable transmit power during the OFF and ON periods of transmission. In E-UTRA, similar requirements exist for the eNB for FDD and TDD operation modes. However, for the LTE UE, the requirements are considerably more complex than those for UMTS, due to the characteristics of the SC-FDMA scheme used for the uplink transmissions. Figure 13.10 shows the general ON/OFF mask in time which applies whenever the UE is required to switch on or off. Note that although the requirement is given in terms of a mask, it actually applies to the average power during the ON and OFF periods. In UMTS the transient period 20 μ s is centered on the slot boundary, whereas in LTE, the transient period is in general shifted into the next subframe. Therefore, the first few SC-FDMA samples are more susceptible to corruption by insufficient transmit power or inter-UE interference, whereas the samples at the end of the subframe are protected. For PRACH, the transient periods are located outside the preamble in order to protect the entire random access preamble. The same principle applies to sounding reference signals to allow reliable uplink channel sounding without impairments arising from transient periods. This is also applicable to discontinuous transmission measurement gaps [1,13].

For TDD, where two sounding reference signals can be transmitted on adjacent symbols in the UpPTS field, the transient periods are located between the two sounding reference signals. The general temporal masks apply in the case of transitions into and out of the OFF power state. A general output power dynamic requirement also exists for continuous transmission at slot boundaries where frequency hopping occurs, and at subframe boundaries for either frequency hopping or power changes. In all these cases, the transient periods are symmetric around

**FIGURE 13.10**

General ON/OFF temporal mask [1].

the slot or subframe boundaries. The transient power masks are applied in transition from the PUCCH/PUSCH to sounding reference signal with DTX after sounding reference signal, from the PUCCH/PUSCH to sounding reference signal to PUCCH/PUSCH, from DTX to sounding reference signal to PUSCH/PUCCH, or from PUCCH/PUSCH to DTX in a sounding reference signal symbol to PUCCH/PUSCH [1,13].

A radio transmitter is required not to transmit any signal outside its designated transmission band. However, in practice, all radio transmitters do transmit unwanted signals outside their designated transmission bands. The LTE specifications define two separate types of unwanted emissions: OOB emissions and spurious emissions. OOB emissions are unwanted emissions immediately outside the channel bandwidth resulting from the modulation process and non-linearity in the transmitter, but excluding spurious emissions. Spurious emissions are emissions which are caused by unwanted transmitter effects such as harmonics emission, parasitic emission, intermodulation products,³ and frequency conversion products, but exclude OOB emissions. The OOB emissions requirement for the eNB transmitter is specified both in terms of adjacent channel leakage power ratio (ACLR) and operating band unwanted emissions. The operating band unwanted emissions define all unwanted emissions in the downlink operating band plus the frequency ranges 10 MHz above and 10 MHz below the band. Unwanted emissions outside of this frequency range are limited by a spurious emissions requirement. For an eNB supporting multi-carrier or intra-band contiguous carrier

³Intermodulation or intermodulation distortion (IMD) is the amplitude modulation of signals containing two or more different frequencies in a system with non-linearities. The intermodulation between each frequency component will form additional signals at frequencies that are not just at harmonic frequencies (integer multiples) of either, but also at the sum and difference frequencies of the original frequencies, and at multiples of those sum and difference frequencies.

aggregation, the unwanted emission requirements apply to channel bandwidths of the outermost carrier larger than or equal to 5 MHz. The occupied bandwidth is the width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage $\beta/2$ of the total mean transmitted power. The value of $\beta/2$ is set to 0.5%. This requirement also applies during the transmitter ON period [1].

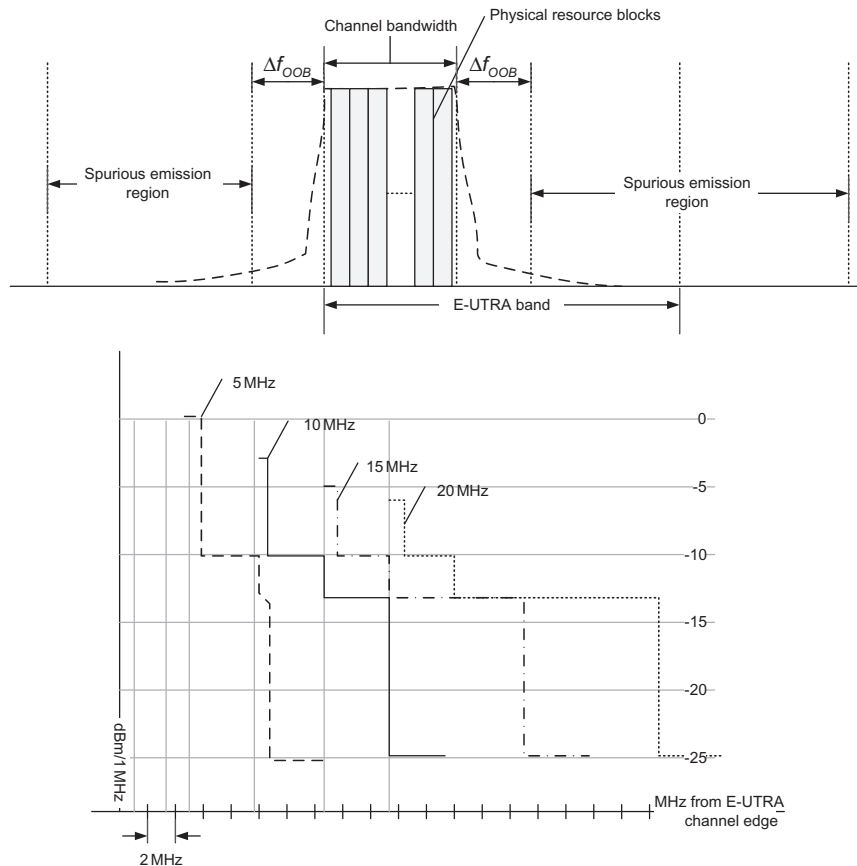
ACLR is the ratio of the filtered mean power centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency. The requirements apply outside of the edges of the RF bandwidth regardless of the type of transmitter considered, i.e., single carrier or multi-carrier. It applies to all transmission modes provisioned by the manufacturer's specification. In addition, for an eNB operating in non-contiguous spectrum, the ACLR applies to the first adjacent channel inside any sub-block gap with a sub-block gap size $W_{\text{gap}} \geq 15$ MHz. The ACLR requirement for the second adjacent channel applies inside any sub-block gap with a sub-block gap size $W_{\text{gap}} \geq 20$ MHz. This requirement is also applied during the transmitter ON period [1].

Since OOB emissions occur close to the desired signal transmission, increasing the power level of the desired signal will usually increase the level of the unwanted emissions. On the other hand, reducing the transmit power is usually an effective method for reducing the OOB emissions, thus providing one possible solution to network-signaled power-reduction requirements. The OOB emissions are an inevitable by-product of the modulation process, and are often caused by non-linearities in power amplifiers. In fixed-bandwidth radio systems, the OOB emission requirements were defined with respect to the center frequency of the transmission. Since E-UTRA supports variable bandwidth, it is more convenient to define OOB requirements with respect to the edge of the channel bandwidth rather than the center of the channel, as shown in Figure 13.11. In LTE, the OOB emissions are defined by means of spectrum emission masks and ACLR requirements.

The spectrum emission mask is a power attenuation function defined for out-of-channel emissions relative to the in-channel power spectrum. The spectrum emission mask of the UE applies to frequencies within Δf_{OOB} of the edge of the assigned LTE channel bandwidth, as shown in Figure 13.11. For intra-band contiguous carrier aggregation the spectrum emission mask of the UE applies to frequencies Δf_{OOB} starting from the $\pm$ edge of the aggregated channel bandwidth (see Figure 13.11). For intra-band contiguous carrier aggregation and bandwidth class C, the power of any UE emissions are required not to exceed the levels specified in Table 13.1 within the specified channel bandwidth [1].

13.6.2 Operating bands for carrier aggregation

E-UTRA was designed to operate in the frequency bands defined in [1,2]. The requirements were defined for 1.4, 3, 5, 10, 15, and 20 MHz bandwidths with a specific configuration in terms of number of physical resource blocks. Using carrier

**FIGURE 13.11**

Transmitter RF spectrum and UE spectrum emission mask [1,13].

aggregation, a number of contiguous and/or non-contiguous frequency bands can be aggregated to create a virtually larger bandwidth. The channel raster is 100 kHz, which means the center frequency must be a multiple of 100 kHz [1]. To support transmission in paired and unpaired spectrums, two duplexing schemes are supported, i.e., FDD, allowing both full and half-duplex terminal operation, as well as TDD.

Figure 13.12 illustrates the relation between the channel bandwidth (BW_{Channel}) and the transmission bandwidth, i.e., the number of permissible physical resource blocks (N_{RB}). The channel edges are defined as the lowest and highest frequencies of the carrier separated by the channel bandwidth, i.e., $f_C \pm \frac{1}{2}BW_{\text{Channel}}$. In the case of carrier aggregation, the aggregated channel

Table 13.1 General E-UTRA Carrier Aggregation Spectrum Emission Mask for Bandwidth Class C [1]					
Spectrum Emission Limit (dBm/$BW_{\text{channel-CA}}$)					
Δf_{OoB} (MHz)	50 RB + 100 RB (29.9 MHz)	75 RB + 75 RB (30 MHz)	75 RB + 100 RB (34.85 MHz)	100 RB + 100 RB (39.8 MHz)	Measurement Bandwidth (MHz)
$\pm 0-1$	-22.5	-22.5	-23.5	-24	0.030
$\pm 1-5$	-10	-10	-10	-10	1
$\pm 5-29.9$	-13	-13	-13	-13	1
$\pm 29.9-30$	-25	-13	-13	-13	1
$\pm 30-34.85$	-25	-25	-13	-13	1
$\pm 34.85-34.9$	-25	-25	-25	-13	1
$\pm 34.9-35$		-25	-25	-13	1
$\pm 35-39.8$			-25	-13	1
$\pm 39.8-39.85$			-25	-25	1
$\pm 39.85-44.8$				-25	1

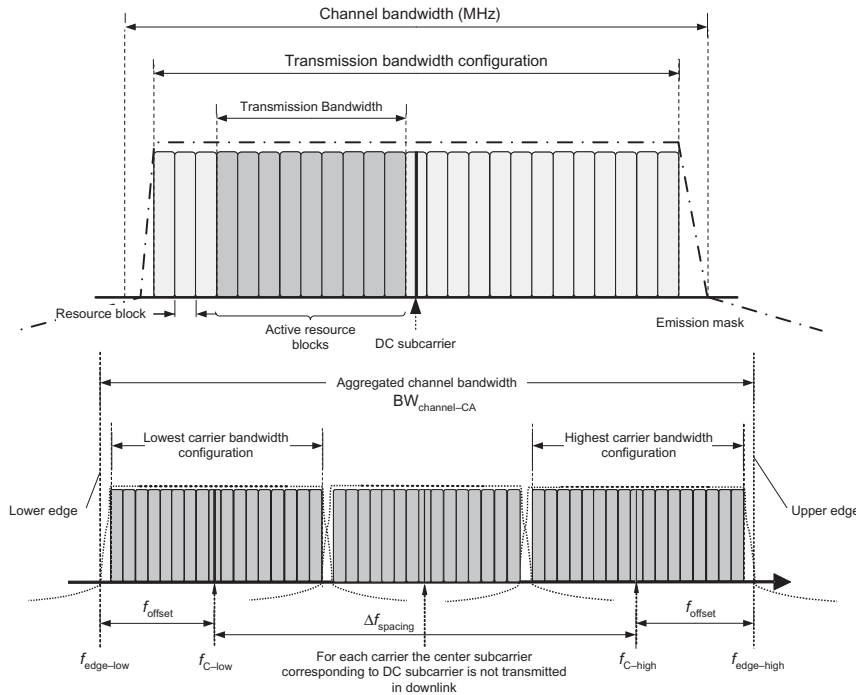


FIGURE 13.12

Relationship between channel bandwidth and transmission bandwidth in E-UTRA [2].

bandwidth $BW_{\text{Channel-CA}}$ is defined as $BW_{\text{Channel-CA}} = f_{\text{edge-high}} - f_{\text{edge-low}}$ (see Figure 13.12). The lower band edge $f_{\text{edge-low}}$ and the upper band edge $f_{\text{edge-high}}$ of the aggregated channel bandwidth are used as the reference points in frequency for transmitter and receiver requirements, and are subsequently defined as follows: $f_{\text{edge-low}} = f_{C\text{-low}} - f_{\text{offset-low}}$ and $f_{\text{edge-high}} = f_{C\text{-high}} + f_{\text{offset-high}}$. The lower and upper frequency offsets depend on the transmission bandwidth configurations of the lowest and highest assigned edge component carriers, and are defined as $f_{\text{offset-low}} = 0.18N_{\text{RB-low}}/2 + BW_{\text{Guard-band}}$ and $f_{\text{offset-high}} = 0.18N_{\text{RB-high}}/2 - BW_{\text{Guard-band}}$ where $N_{\text{RB-low}}$ and $N_{\text{RB-high}}$ denote the transmission bandwidth configurations for the lowest and highest assigned component carrier, respectively, and $BW_{\text{Guard-band}}$ denotes the nominal guard band size. Note that the 0.18 multiplier in the equations is the bandwidth of a physical resource block in MHz. The aggregated transmission bandwidth is defined as the number of the aggregated resource blocks within the entire assigned aggregated channel bandwidth, and is defined per carrier aggregation band class.

As shown in Figure 13.12, the spacing between carriers depends on the deployment scenario and the size of the frequency block available to the network operator, as well as the channel bandwidth. The nominal channel spacing between

two adjacent E-UTRA carriers is defined as $\Delta f_{\text{spacing}} = (BW_{\text{Channel}(1)} + BW_{\text{Channel}(2)})/2$ where $BW_{\text{Channel}(1)}$ and $BW_{\text{Channel}(2)}$ parameters are the channel bandwidths of the two respective E-UTRA carriers. The channel spacing can be adjusted to optimize performance in a particular deployment scenario. For intra-band contiguous carrier aggregation bandwidth, the nominal channel spacing between two adjacent E-UTRA component carriers is specified as follows [1,2]:

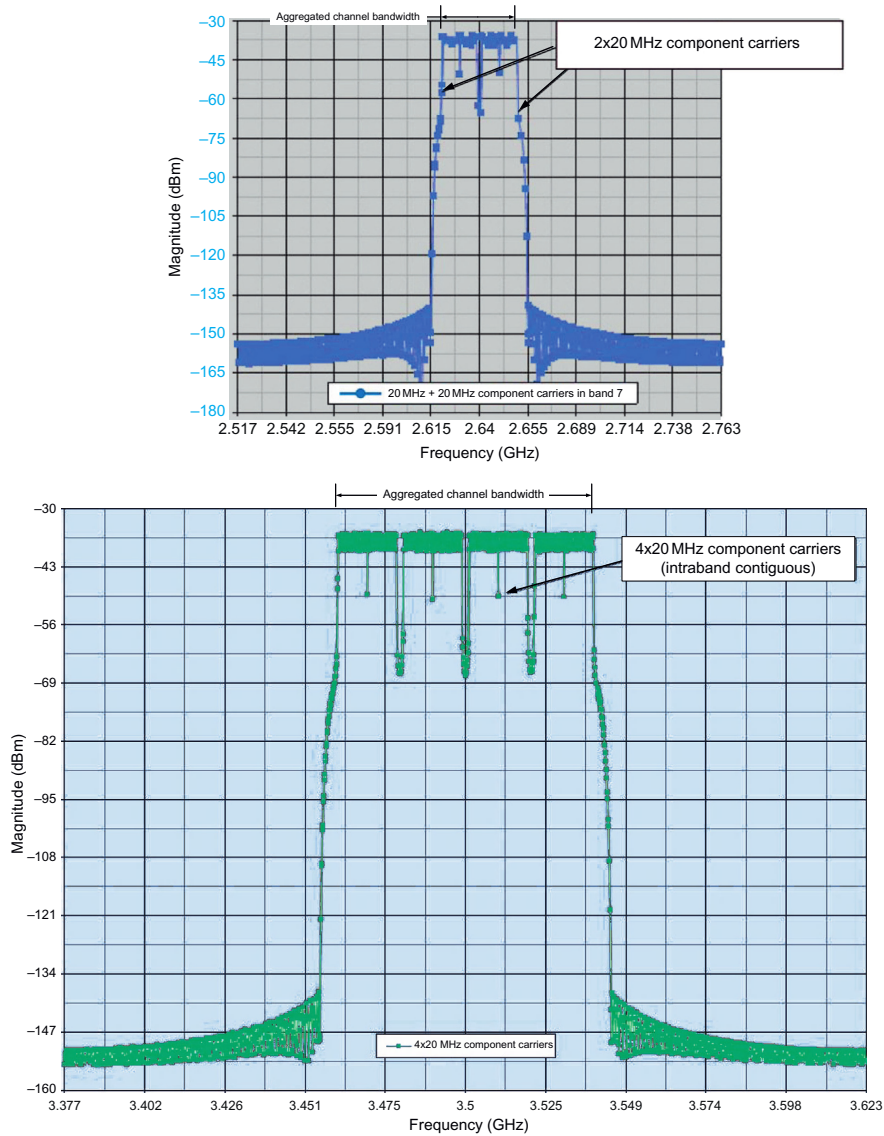
$$\Delta f_{\text{spacing-CA}} \text{ (MHz)} = 0.3 \left\lfloor \frac{BW_{\text{Channel}(1)} + BW_{\text{Channel}(2)} - 0.1 |BW_{\text{Channel}(1)} - BW_{\text{Channel}(2)}|}{0.6} \right\rfloor$$

The channel spacing for intra-band contiguous carrier aggregation can be adjusted to any integer multiple of 300 kHz (less than the nominal channel spacing) to optimize performance in a particular deployment scenario. The E-UTRA channel raster (including the carrier aggregation scenarios) is 100 kHz for all bands, which means that the carrier center frequency must be an integer multiple of 100 kHz.

The carrier frequency in the downlink/uplink directions is designated by the E-UTRA absolute radio frequency channel number (EARFCN) in the range of 0–65,535. The relation between EARFCN and the downlink carrier frequency (in MHz) is given by $f_{\text{DL}} = f_{\text{DL-low}} + 0.1(N_{\text{DL}} - N_{\text{Offset-DL}})$, where $f_{\text{DL-low}}$, N_{DL} , and $N_{\text{Offset-DL}}$ parameters are given in [1,2]. Similarly, the relationship between EARFCN and the uplink carrier frequency (in MHz) for the uplink is defined as $f_{\text{UL}} = f_{\text{UL-low}} + 0.1(N_{\text{UL}} - N_{\text{Offset-UL}})$, where $f_{\text{UL-low}}$, N_{UL} , and $N_{\text{Offset-UL}}$ parameters are provided in [1,2]. Note that N_{DL} and N_{UL} in the latter equations are the downlink and uplink EARFCN, respectively. Figure 13.13 shows a snapshot of four adjacent 20 MHz component carriers chosen from the 3.5 GHz band that are aggregated with the adjacent center frequency spacing set to 20.1 MHz (a multiple of 300 kHz). This figure also shows the spectrum of two 20 MHz component carriers chosen from Band 7 in 2600 MHz that are aggregated with the center frequency spacing set to 20.1 MHz [18].

The channel numbers that designate carrier frequencies which are extremely close to the operating band edges are not used. This implies that the first 7, 15, 25, 50, 75, and 100 channel numbers at the lower operating band edge, and the last 6, 14, 24, 49, 74, and 99 channel numbers at the upper operating band edge are not utilized for channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz, respectively.

A sub-block is defined as one contiguous allocated block of spectrum for transmission and reception by the same eNB. There may be multiple instances of sub-blocks within an RF bandwidth. Sub-block bandwidth is defined as the bandwidth of one sub-block. The frequency gap between two consecutive sub-blocks within an RF bandwidth is referred to as sub-block gap, where the RF requirements in the gap are based on coexistence for uncoordinated operation. The lower sub-block edge of the sub-block bandwidth $BW_{\text{Channel-block}}$ is defined as $f_{\text{edge_block_low}} = f_{C_block_low} - f_{\text{offset}}$. The upper sub-block edge of the sub-block

**FIGURE 13.13**

Snapshot of spectrum of two and four aggregated adjacent component carriers [17,18].

bandwidth is defined as $f_{\text{edge_block_high}} = f_{c_\text{block_high}} + f_{\text{offset}}$. The sub-block bandwidth $BW_{\text{Channel-block}}$ is alternatively defined as $BW_{\text{Channel-block}} = f_{\text{edge_block_high}} - f_{\text{edge_block_low}}$ in MHz [2].

LTE Rel-10 specified the radio frequency aspects of inter-band carrier aggregation only for FDD, assuming aggregation of bands 1 and 5. However, network operators are interested in various band combinations, as shown in Table 13.2, depending on their available spectrum resources. Radio frequency properties of each band combination must be specified to comply with the regulations. In addition, inter-band carrier aggregation for TDD needs to be supported in future releases with the possibility of having different TDD uplink–downlink subframe configurations on different bands to coexist with the already deployed TDD systems in that band.

A carrier aggregation bandwidth class is defined by the aggregated transmission bandwidth configuration and the maximum number of component carriers supported by a UE. Table 13.3 shows supported bandwidth classes for LTE Rel-11 UE as defined in [1]. Figure 13.14 illustrates the standard notation used by the UE to indicate its support of carrier aggregation for a particular frequency band or band combination to the network. The example shows that in order to indicate support for intra-band, non-contiguous carrier aggregation in band 5 based on bandwidth class A, the notation would be CA_5A_5A. It informs the network that this device is able to receive (or transmit) two separate carriers in frequency band 5, each with a maximum bandwidth of 100 resource blocks, i.e., 20 MHz. Another example is CA_1C which indicates that the UE can operate with two contiguous component carriers with a maximum of 200 resource blocks which can be in the form of 15 + 15 or 20 + 20 MHz. Note that there might be different bandwidth combinations for each E-UTRA carrier aggregation configuration [1]. Table 13.4 summarizes some important parameters associated with UE categories as of LTE Rel-11.

13.6.3 Transmitter characteristics for carrier aggregation

The transmitter characteristics not only define RF requirements for the desired signal transmitted from the UE and the eNB, but also for the unavoidable unwanted emissions outside the transmission bandwidth. These requirements are fundamentally categorized as follows: (1) output power-level requirements set the limits for the maximum permissible transmitted power corresponding to dynamic variation of the power level during transmission; (2) transmitted signal quality requirements define the cleanliness of the transmitted signal and also the relationship between multiple transmitter branches; and (3) unwanted emissions requirements set the limits for all emissions outside of the transmitted carrier(s) operating band which are tightly coupled to regulatory requirements and coexistence with other systems. The following is a list of major UE and eNB transmitter attributes [14]:

- eNB: Output power level (maximum output power, output power dynamics, and on/off power for TDD), transmitted signal quality (frequency error, error vector magnitude (EVM), and time alignment between transmitter branches),

Table 13.2 Carrier Aggregation Bands and Band Aggregation as of LTE Rel-11 [1]

Band Combination	Carrier Aggregation Scenario	Uplink Frequency Range (MHz)	Downlink Frequency Range (MHz)	Duplex Mode
		$f_{UL-low} - f_{UL-high}$	$f_{DL-low} - f_{DL-high}$	
1	Intra-band contiguous	1920–1980	2110–2170	FDD
7		2500–2570	2620–2690	FDD
40		2300–2400	2300–2400	TDD
41		2496–2690	2496–2690	TDD
1 and 5	Inter-band	1920–1980	2110–2170	FDD
		824–849	869–894	
1 and 18		1920–1980	2110–2170	FDD
		815–830	860–875	
1 and 19		1920–1980	2110–2170	FDD
		830–845	875–890	
1 and 21		1920–1980	2110–2170	FDD
		1447.9–1462.9	1495.9–1510.9	
2 and 17		1850–1910	1930–1990	FDD
		704–716	734–746	
2 and 29		1850–1910	1930–1990	FDD
		N/A (downlink only SCell)	717–728	
3 and 5		1710–1785	1805–1880	FDD
		824–849	869–894	
3 and 7		1710–1785	1805–1880	FDD
		2500–2570	2620–2690	
3 and 8		1710–1785	1805–1880	FDD
		880–915	925–960	
3 and 20		1710–1785	1805–1880	FDD
		832–862	791–821	
4 and 5		1710–1755	2110–2155	FDD
		824–849	869–894	
4 and 7		1710–1755	2110–2155	FDD
		2500–2570	2620–2690	
4 and 12		1710–1755	2110–2155	FDD
		699–716	729–746	
4 and 13		1710–1755	2110–2155	FDD
		777–787	746–756	
4 and 17		1710–1755	2110–2155	FDD
		704–716	734–746	
4 and 29		1710–1755	2110–2155	FDD
			717–728	

(Continued)

Table 13.2 (Continued)

Band Combination	Carrier Aggregation Scenario	Uplink Frequency Range (MHz) $f_{UL-low} - f_{UL-high}$	Downlink Frequency Range (MHz) $f_{DL-low} - f_{DL-high}$	Duplex Mode
5 and 12		N/A (downlink only SCell)		FDD
		824–849	869–894	
		699–716	729–746	
5 and 17		824–849	869–894	FDD
		704–716	734–746	
7 and 20		2500–2570	2620–2690	FDD
		832–862	791–821	
8 and 20		880–915	925–960	FDD
		832–862	791–821	
11 and 18		1427.9–1447.9	1475.9–1495.9	FDD
		815–830	860–875	

unwanted emissions (operating band unwanted emissions, ACLR, spurious emissions, occupied bandwidth, and transmitter intermodulation).

- UE: Output power level (transmit power, output power dynamics, and power control), transmitted signal quality (frequency error and transmit modulation quality), unwanted emissions (spectrum emission mask, ACLR, spurious emissions, occupied bandwidth, and transmit intermodulation).

The ACLR is directly related to the operating point of the power amplifier. In general, leakage into adjacent channels increases abruptly as the power amplifier is driven into its non-linear operating region at the highest output power levels due to the intermodulation products. As a result, it is important that the peak output power of the UE does not drive the power amplifier too far into its non-linear region. On the other hand, most power amplifiers are designed to operate efficiently only in a small region at the top of the linear operating region. This corresponds to the rated output power of the power amplifier below which the efficiency drops abruptly. Since high efficiency is crucial to ensuring a long battery life for the UE, it is also desirable to maintain the power amplifier operating as close as possible to the top of the linear operating region. If the ACLR and spectrum mask requirements cannot be met, typically the UE output power must be reduced to bring the leakage to acceptable levels. This can be achieved without excessive loss of efficiency by reducing the peak output power of the power amplifier, a process known as derating. The amount of derating required is highly dependent on the peak to average power ratio (PAPR) and bandwidth of the transmitted signal. In general, for any given channel bandwidth and power amplifier, transmissions with a larger occupied bandwidth create more OOB emissions,

Table 13.3 Carrier Aggregation Bandwidth Classes and Corresponding Nominal Guard Bands [1]

Carrier Aggregation Bandwidth Class	Aggregated Transmission Bandwidth Configuration	Maximum Number of Component Carriers	Nominal Guard Band $BW_{\text{Guard Band}}$
A	$N_{\text{RB-Aggregated}} \leq 100$	1	$0.05BW_{\text{Channel-1}}$
B	$N_{\text{RB-Aggregated}} \leq 100$	2	—
C	$100 < N_{\text{RB-Aggregated}} \leq 200$	2	$0.05\max(BW_{\text{Channel-1}}, BW_{\text{Channel-2}})$
D	$200 < N_{\text{RB-Aggregated}} \leq 300$	—	—
E	$300 < N_{\text{RB-Aggregated}} \leq 400$	—	—
F	$400 < N_{\text{RB-Aggregated}} \leq 500$	—	—

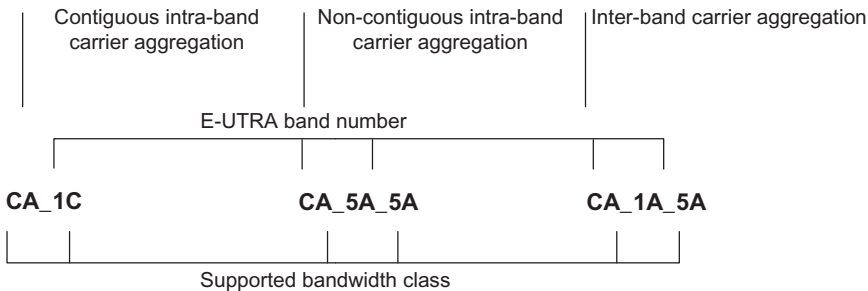


FIGURE 13.14

Standard notation for carrier aggregation support (type, frequency band, and bandwidth) [1,16].

resulting in larger adjacent channel leakage than transmissions with lower occupied bandwidth. The increase in OOB emissions from the larger occupied bandwidth of the LTE signal is mainly due to increased adjacent channel occupancy by third and fifth order intermodulation products (see Figure 13.15). For an LTE uplink transmitted signal, certain combinations of resource block allocations and modulation schemes create more OOB emissions than others [13].

For low-bandwidth applications such as VoIP, which typically use QPSK modulation, no power derating is required from the normal-rated maximum UE output power, ensuring broad coverage for such applications, since full output power of the power amplifier can be used to counter the path loss effect at the cell-edge. Moreover, the structure of the LTE uplink signal, with control information being usually positioned at the channel edge and high-bandwidth data transmissions toward the middle of the band, helps to improve OOB emissions and reduce ACLR. Taking the above considerations into account, the total power

Table 13.4 UE Categories as of LTE Rel-11 [8]

UE Category	Peak Data Rate Downlink/Uplink (Mbps)	Maximum Number of DL-SCH Transport Block Bits Received within a TTI	Maximum Number of Bits of a DL-SCH Transport Block Received within a TTI	Total Number of Soft Channel Bits in the Downlink	Maximum Number of Supported Layers for Spatial Multiplexing in the Downlink	Maximum Number of UL-SCH Transport Block Bits Transmitted within a TTI	Maximum Number of Bits of a UL-SCH Transport Block Transmitted within a TTI	Support for 64QAM in Uplink	Total Layer 2 Buffer Size (Bytes)	Maximum Number of Bits of an MCH Transport Block Received within a TTI
Category 1	10/5	10,296	10,296	250,368	1	5160	5160	No	150,000	10,296
Category 2	50/25	51,024	51,024	1,237,248	2	25,456	25,456	No	700,000	51,024
Category 3	100/50	102,048	75,376	1,237,248	2	51,024	51,024	No	1,400,000	75,376
Category 4	150/50	150,752	75,376	1,827,072	2	51,024	51,024	No	1,900,000	75,376
Category 5	300/75	299,552	149,776	3,667,200	4	75,376	75,376	Yes	3,500,000	75,376
Category 6	300/50	301,504	149,776 (4 layers)	3,654,144	2 or 4	51,024	51,024	No	3,300,000	(75,376)
Category 7	300/150	301,504	75,376 (2 layers)	3,654,144	2 or 4	102,048	51,024	No	3,800,000	(75,376)
Category 8	1200/600	2,998,560	149,776 (4 layers)	35,982,720	8	1,497,760	149,776	Yes	4,220,0000	(75,376)
			75,376 (2 layers)							

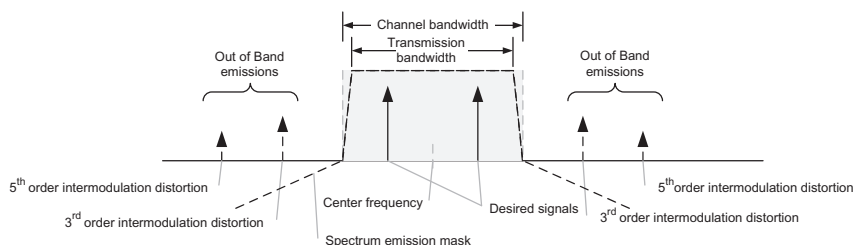
**FIGURE 13.15**

Illustration of the IMD components [20].

derating required to meet a target ACLR value can be decomposed into a term corresponding to the occupied bandwidth as a proportion of the channel bandwidth, and a term corresponding to the waveform of the transmitted signal. Small resource assignments at the edges of the band behave as tones and hence may produce highly concentrated IMD products [14]. Therefore, for simultaneous PUSCH and PUCCH transmission, the spectral emission mask is expected to be the limiting requirement, as it is for LTE Rel-8 with full resource allocation (see Figure 13.6).

As mentioned earlier, the ACLR metric defines the ratio of the power transmitted in the assigned channel bandwidth to the power of the unwanted emissions transmitted in an adjacent channel. There is a corresponding receiver requirement known as adjacent channel selectivity (ACS), which defines a receiver's ability to suppress a signal in an adjacent channel. Therefore, from the receiver's point of view, the unwanted emissions as a result of transmissions in the adjacent bands in the desired signal's receiver bandwidth are represented by ACLR, and the ability of the receiver to suppress the interfering signal in the adjacent channel is defined by ACS. The two parameters when combined define the total leakage between two transmissions on adjacent channels. That ratio is called the adjacent channel interference ratio (ACIR), and is defined as the ratio of the power transmitted on one channel to the total interference received by a receiver on the adjacent channel due to both transmitter RF filter imperfection (ACLR) and receiver RF filter imperfection (ACS) [14].

In LTE, the EVM is required to be less than 17.5% for QPSK, 12.5% for 16QAM and 8% for 64QAM (applicable to the downlink only). The EVM values are designed to correspond to no more than 5% loss in average and cell-edge throughputs in typical deployment scenarios. At the link level, EVM is equivalent to signal to noise ratio loss [13]. The occupied bandwidth is defined as the bandwidth containing 99% of the total integrated mean power of the transmitted spectrum on the assigned channel. The occupied bandwidth for all transmission bandwidth configurations (resource blocks) must be less than the channel bandwidth. For intra-band contiguous carrier aggregation the occupied bandwidth is a measure of the bandwidth containing 99% of the total integrated power of the

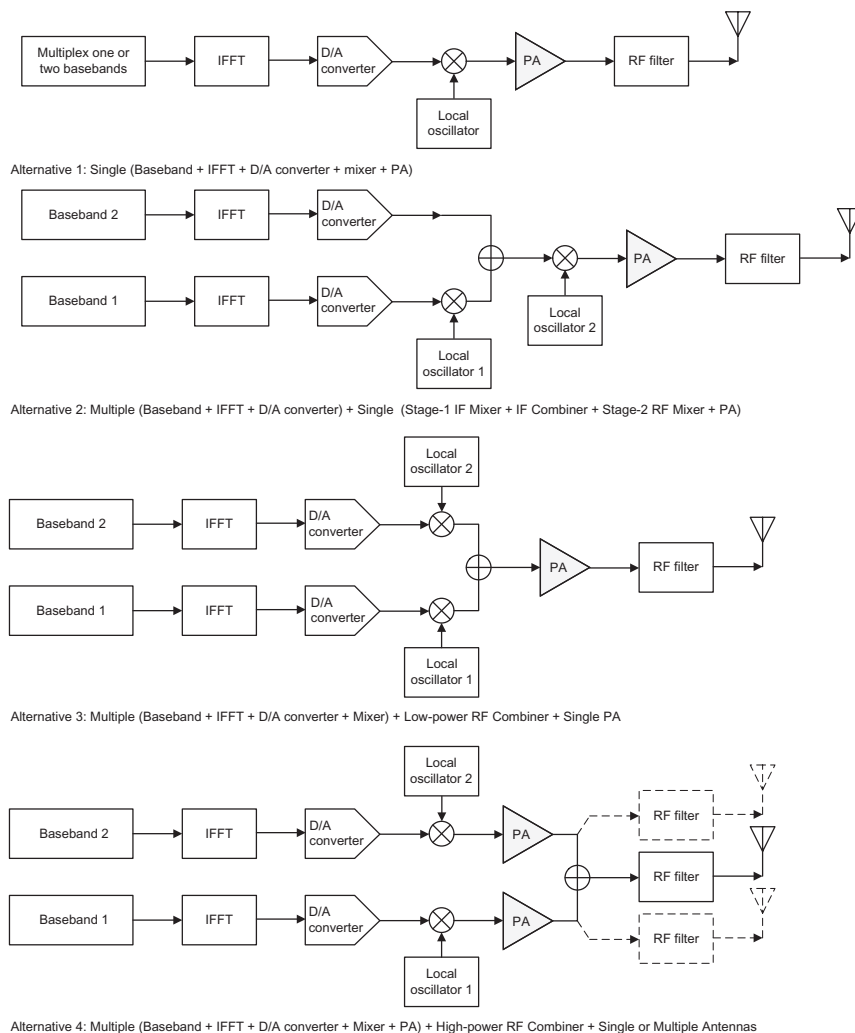
transmitted spectrum. The occupied bandwidth must be less than the aggregated channel bandwidth [1].

The output power dynamics are impacted by the UE transmitter architecture, which may be based on single or multiple power amplifiers. Figure 13.16 illustrates various options for UE transmitter architecture which can be used to support different carrier aggregation scenarios. As shown in Figure 13.16 for alternative 1, if two component carriers are contiguous, then a single IFFT module can be used to generate both OFDM signals. A single RF mixer can be used to convert the baseband signal frequency to RF frequency followed by a single power amplifier to amplify the power of the transmitted signal. If two component carriers are non-contiguous but within the same frequency band, then alternatives 2 or 3 shown in Figure 13.16 may be used as a general transmitter architecture. However, for non-contiguous component carriers in different frequency bands, separate IFFT modules, mixers, and power amplifiers would be required to process the OFDM signals, unless a multi-band power amplifier is utilized.

13.6.4 Receiver characteristics for carrier aggregation

Although the requirements for LTE receivers are similar to those defined for UMTS, they are defined differently due to the flexible bandwidth properties of LTE. The receiver RF requirements are primarily divided into three categories: (1) sensitivity and dynamic range requirements for receiving the desired signal; (2) receiver susceptibility to interfering signals defining receiver's vulnerability to different types of interfering signals at different frequency offsets; and (3) unwanted emission limits. The following is a list of attributes for the UE and eNB receivers [14]:

- eNB: Sensitivity and dynamic range (reference sensitivity, dynamic range, and in-channel selectivity), receiver susceptibility to interfering signals (OOB blocking, in-band blocking, narrowband blocking, ACS, and receiver intermodulation), and unwanted emissions from the receiver (receiver spurious emissions). The spurious emissions power is the power of emissions generated or amplified in a receiver that appear at the eNB receiver antenna connector. The requirements apply to all eNBs with separate receive and transmit antenna ports. The test for the FDD eNB must be performed when transmitter and receiver are on, with the transmit port properly terminated. For the TDD eNB with a common receive and transmit antenna port, the requirement applies during the transmitter OFF period. The blocking characteristic is a measure of the receiver's ability to receive a desired signal at its assigned channel in the presence of an unwanted interferer. Narrowband blocking is similar to ACS, but with interfering signals consisting of only one resource block.
- UE: Sensitivity and dynamic range (reference sensitivity power level and maximum input level), receiver susceptibility to interfering signals (OOB blocking,

**FIGURE 13.16**

Example transmitter implementation for intra-band/inter-band carrier aggregation [11].

spurious response, in-band blocking, narrowband blocking, ACS, and intermodulation characteristics), and unwanted emissions from the receiver (receiver spurious emissions). Third and higher order mixing of the two interfering RF signals can produce an interfering signal in the band of the desired channel. Intermodulation response rejection is a measure of the capability of the receiver to receive a wanted signal on its assigned channel frequency in

the presence of two interfering signals (a continuous wave and E-UTRA signals).

The LTE RF receiver requirements were partly derived from UMTS. This was meant to ensure that the implementation of an LTE RF receiver is not going to be more complex than that of UMTS in order to reduce redesigning efforts. The main differences between the LTE and UMTS RF receiver requirements arise from the variable channel bandwidth and the different multiple access schemes. The receiver RF requirements are based on a number of specific assumptions for testing purposes including integrated antennas with 0 dBi gain; two antenna ports; test signals of equal power level applied to each antenna port; and use of a maximal ratio combining to combine the signals. It is assumed that the signals are received from independent AWGN channels, thus signal addition would provide 3 dB diversity gain.

LTE supports different MCSs; however, the RF receiver specifications are defined for only two MCSs, referred to as reference channels, which are at the extremes of the available range, in order to reduce the number of conformance tests which have to be performed. The low-SNR reference channel uses QPSK with a code rate of 1/3, while the high SNR reference channel uses 64QAM with a code rate of 3/4. For each of the reference channels, the SINR requirements, at which 95% throughput is achieved, are specified.

When the LTE receiver is tested in full-duplex FDD mode, the transmitter must also be operating so that signal leakage from the transmitter to the receiver due to insufficient isolation of the duplexer is taken into consideration. This condition does not apply to half-duplex FDD or TDD operation. In practice, the transmitted signal leakage interferes with the receiver not only because of the power of the fundamental components, but also because of the OOB phase noise of the transmitted signal when it falls into the receiver band. In LTE, the spurious emissions from the UE transmitter in its own receive band are required to be -47 dBm or less, measured in a 1 MHz bandwidth. This corresponds to -107 dBm/Hz. The maximum transmit power for an LTE mobile device is $+23$ dBm for power class 3, thus the spurious emissions requirement is -130 dBc/Hz. The LTE receiver sensitivity is measured with the transmitter operating at the full power for its class. In order to allow the transmitter to degrade the receiver sensitivity by no more than 0.5 dB, the transmitter noise needs to be 9 dB below the noise floor at the antenna connector. If we assume that the spurious emissions of the transmitter in the corresponding receiver band are just at the limit of the specifications, it can be shown that the duplexer isolation needs to be at least 78 dB for the LTE FDD mode. However, making duplexers smaller and cheaper is often achieved at the expense of compromised isolation, and typical duplexers might provide just 45–55 dB isolation [14]. Therefore, the transmit signal could substantially desensitize the receiver. This is not acceptable, thus the LTE transmitter has to achieve spurious emissions about 20 dB lower than the transmitter requirements within the receiver band. The

transmit power at the input to the low-noise amplifier is equal to the transmit power at the antenna plus the duplexer attenuation from transmit port to antenna (about 2 dB) minus the duplexer transmit-to-receiver isolation (~ 50 dB). Therefore, at the maximum LTE UE output power of +23 dBm, the mean transmitter power leakage to the low-noise amplifier is -25 dBm [13].

This value is calculated based on the average transmit power, but the transmitted signal contains amplitude modulation, and therefore the peak signal will be higher. The transmitter leakage problem presents a particularly challenging requirement, if applied to RF bands with a small frequency separation. In FDD systems, when performing a selectivity or blocking test with a single interfering signal in one of the adjacent channels, the receiver is also exposed to its own transmitted signal as a second interferer, which, in the worst case scenario, can cause intermodulation, in which the interferers are mixed together to generate in-band IMD products.

The maximum input level is the maximum mean received signal strength, measured at each antenna port, at which there is sufficient SINR for a specified modulation scheme to meet a minimum throughput requirement. In LTE, the maximum input level is only specified for the high SINR reference channel, assuming that the high SINR reference channel is about 4 dB higher due to the PAPR of the signal. The downlink requirement is for a maximum average input level of -25 dBm at any channel bandwidth with full resource block allocation. In FDD systems, the requirement must be met when the transmitter is set at 4 dB below the maximum output power. If PAPR is measured on a bitwise basis and plotted as a complementary cumulative probability distribution, then for the LTE downlink it reaches a value of around 11 dB for QPSK and 11.5 dB for 64QAM, over a window of 106 bits. In OFDM, the PAPR is dominated by the multi-carrier nature of the signal, and therefore does not vary much with modulation [13].

The primary purpose of the reference sensitivity requirement is to verify the receiver noise figure, which is a measure of how much the receiver's RF signal chain degrades the SNR of the received signal. For this reason, a low-SNR transmission scheme using QPSK is chosen as a reference channel for the reference sensitivity test. The reference sensitivity is defined at a receiver input level where the throughput is 95% of the maximum throughput for the reference channel. For the base station, reference sensitivity could potentially be defined for a single resource block up to a group covering all resource blocks. Considering the complexity, a maximum granularity of 25 resource blocks has been chosen, which means that for channel bandwidths larger than 5 MHz, sensitivity is verified over multiple adjacent 5 MHz blocks, while it is only defined over the full channel for smaller channel bandwidths. For the UE, reference sensitivity is defined for the full channel bandwidth signals and with all resource blocks allocated to the desired signal. For channel bandwidths greater than 5 MHz in some operating bands, the nominal reference sensitivity needs to be met with a minimum number of allocated resource blocks [14]. In other words, the reference sensitivity level is the minimum mean received signal strength applied to both antenna ports (assuming two receive antennas) at which there is sufficient SINR for the specified modulation scheme to meet a

minimum throughput requirement of 95% of the maximum possible value. It is measured with the transmitter at full power. The reference sensitivity is a range of values that can be calculated as $P_{\text{Reference_Sensitivity}} = 10\log(kT_0B) + NF + \text{SINR} + L_{\text{Implementation_Margin}} - 3$ (dBm), where kT_0B is the thermal noise power in dBm, B is the noise equivalent bandwidth ($\sim$ system bandwidth), NF is the maximum receiver noise figure, SINR is the minimum SINR for the chosen MCS, $L_{\text{Implementation_Margin}}$ is the implementation margin, and -3 represents the receive diversity gain [13]. Note that the noise floor for any receiver is defined as $\text{Noise_Floor} = 10\log(kT_0B) + NF = -174 + NF + 10\log B$ (dBm), where $NF = \text{SNR}_{\text{in}} - \text{SNR}_{\text{out}}$ (in dB) is a measure of SINR degradation by the components in the RF signal path, including the RF filters and low-noise amplifier. The thermal noise power density $kT_0 = -174$ dBm/Hz is measured at typical room temperature of 290°K . The LTE specifications require $NF \leq 9$ dB for the UE and $NF \leq 5$ dB for the eNB, nevertheless, commercial RF components and UE receivers can achieve lower than these limits [13].

The UE receiver dynamic range requirement is meant to ensure that the receiver can operate at received signal levels considerably higher than the reference sensitivity. The base station dynamic range testing assumes the presence of increased interference and corresponding higher signal levels, thereby testing the effects of different receiver impairments. In order to drive the receiver to the worst condition, a higher SNR transmission scheme using 16QAM is applied for the test. In order to further drive the receiver to processing higher signal levels, an interfering AWGN signal at 20 dB above the assumed noise floor is added to the received signal. The dynamic range requirement for the UE is specified as a maximum signal level at which the throughput requirement is met.

Blocking corresponds to the scenario when strong interfering signals received outside the operating band (OOB blocking) or inside the operating band (in-band blocking), but not adjacent to the desired signal. In-band blocking includes interferers in the first 20 MHz outside the band for the base station and the first 15 MHz for the UE. The scenarios are modeled with a continuous wave signal for the OOB case and an E-UTRA signal for the in-band case. There are additional base station's blocking requirements for the scenario when the base station is collocated with another base station in a different operating band. For the UE, a fixed number of exceptions are allowed from the OOB blocking requirement, for each assigned frequency channel and at the respective spurious response frequencies. At those frequencies, the UE must comply with the more relaxed spurious response requirement. Note that these effects and satisfaction of the requirements become more challenging when carrier aggregation is supported.

ACS is the case when there is a strong signal in the channel adjacent to the desired signal, and is closely related to the corresponding ACLR requirement. For the UE, the ACS is specified for two cases with a lower and a higher signal level. In-channel selectivity is the case when there are multiple received signals of different received power levels inside the channel bandwidth, where the performance of the weaker desired signal is verified in the presence of the stronger interfering

signal. In-channel selectivity is only specified for the base station. Narrowband blocking is an adjacent strong narrowband interferer, which in the requirement is modeled as a single resource block LTE signal for the base station and a continuous wave signal for the UE. Receiver intermodulation occurs when there are two interfering signals in the spectral proximity of the desired signal, where the interferers are one continuous wave and one LTE signal. The interferers are placed in frequency in such a way that the main intermodulation product falls within the desired signal's channel bandwidth. There is also a narrowband intermodulation requirement for the base station where the continuous wave signal is very close to the wanted signal, and the LTE interferer is a single resource block signal. For all requirements except in-channel selectivity, the wanted signal uses the same reference channel as in the corresponding reference sensitivity requirement. When the interference is added, the same 95% relative throughput is met as for the reference channel, but at a desensitized higher desired signal level [14].

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Enhanced Inter-cell Interference Coordination and Multi-radio Coexistence

14

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In this chapter, we discuss two important features that were included in the recent releases of LTE to address inter-cell interference problems in LTE systems and in-device inter-radio interference issues, where both problems adversely affect the system capacity, user throughput, and normal operation of the LTE system.

The proliferation of Internet-connected mobile devices will continue to drive growth in data traffic in an exponential order, forcing network operators to dramatically increase the capacity of their networks. The ever-increasing demand for mobile communication services has made it difficult for the conventional homogeneous networks to provide the required capacity and user throughput as they have approached their theoretical limits. One of the most promising and cost-effective solutions to improve the system capacity is to increase the node density, i.e., to deploy low-power nodes such as relay, pico-cell, femto-cell, and remote radio heads in homogeneous networks. The new network architecture is known as heterogeneous networks (HetNets). The deployment of low-power nodes can

provide a more flexible and more effective way to eliminate the coverage holes in macro-cells and improve the system capacity. Therefore, it is considered as a promising approach in the next generation wireless communication systems such as systems beyond IMT-Advanced [16,17]. One of the key issues in the new network architecture is the handover performance deterioration. In co-channel HetNets, the cell-edge UEs can experience more serious interference. The basic principle of inter-cell interference coordination (ICIC) is to avoid high-power transmission on time–frequency resources on which cell-edge users are scheduled in neighboring cells, users that would otherwise experience high interference and correspondingly low data rates. In the next sections, we study the causes and remedies of inter-cell interference in the HetNets [2].

We will then discuss signaling and procedures for in-device coexistence (IDC) and for interference avoidance. An increasing number of UEs are equipped with multiple radio transceivers for LTE, Wi-Fi, Bluetooth (BT), Global Navigation Satellite System (GNSS), and so on. The studies conducted for LTE Rel-11 IDC work item have shown that existing radio resource management mechanisms in some cases are not adequate to overcome the coexistence issues, and some enhanced signaling and other procedures are necessary to avoid or mitigate the collocated multi-radio interference in the identified usage scenarios. Therefore, a new IDC indication message has been defined in LTE Rel-11. This message enables the UE to alert the network to an interference issue, and provide information regarding the direction and nature of the interference, which may be identified in either the time- or frequency-domain. Upon receipt of the IDC message, the network will take appropriate steps to alleviate the problem by reallocating radio resources or configuring discontinuous reception mode parameters [1].

14.1 Intra-cell/inter-cell interference mitigation methods

The classic design principle of cellular communications systems is to divide a geographical area into non-overlapping cells, each served by a single base station. The intercell interference is a serious problem of such systems, in particular when frequency reuse one is utilized. One way to reduce the inter-cell interference within the system is to employ efficient interference averaging mechanisms that organize transmission such that the interference is evenly distributed among all users.

There are three major frequency reuse schemes in cellular systems for mitigating inter-cell interference: hard frequency reuse; fractional frequency reuse (FFR); and soft frequency reuse. A hard frequency reuse scheme splits the system bandwidth into a number of non-overlapping sub-bands according to a predetermined reuse factor, and lets neighboring cells transmit on different sub-bands (scenario A in Figure 14.1). As shown in Figure 14.2, an FFR scheme partitions the given bandwidth into an inner and an outer partition. It then allocates the inner part to the users closer to the base station with reduced power and applies a

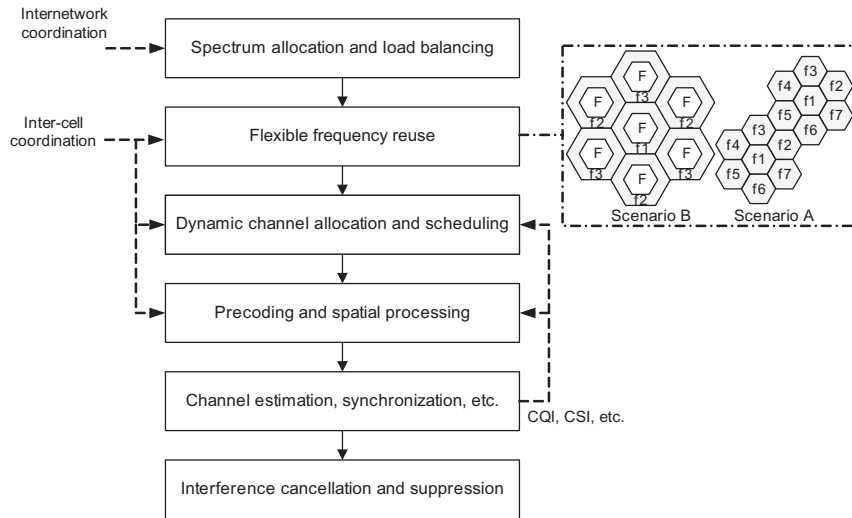


FIGURE 14.1

Co-channel interference mitigation schemes [12].

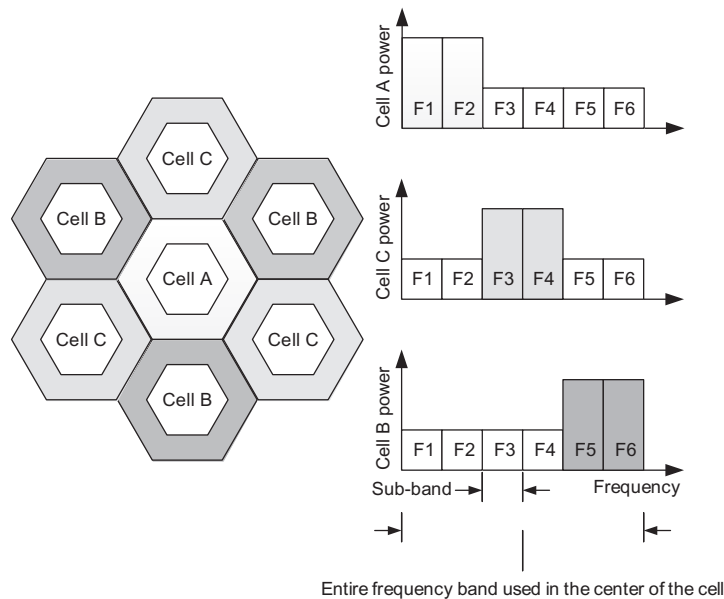


FIGURE 14.2

Illustration of fractional frequency reuse concept [17].

frequency reuse factor of 1, i.e., the inner part is completely reused by all base stations. For users closer to the cell-edge, a fraction of the outer part of the bandwidth is dedicated with a frequency reuse factor greater than 1 (see scenario B in Figure 14.1). With soft frequency reuse, the overall bandwidth is shared by all base stations, i.e., a reuse factor of 1 is applied, but for the transmission on each sub-band, the base stations are restricted to a certain power limit.

Depending on whether noise or inter-cell interference is the dominant effect, the cellular system is referred to as *noise-limited* or *interference-limited*. In an interference-limited system, the carrier to interference plus noise ratio (CINR) can approximately be replaced by the carrier to interference ratio (CIR), and the inter-cell interference plays an important role in terms of achievable system capacity and coverage. In a network deployment with a smaller frequency reuse factor, severe inter-cell interference may occur in the system. In fact, the closer the user is to the cell-edge, the more severe the inter-cell interference can be. Due to a large distance between the transmitter and the receiver, the desired signal power P_{C_j} is then relatively weak compared to the inter-cell interference signal strength. By increasing the frequency reuse factor, the inter-cell interference can be effectively limited, however, at the expense of sacrificing the available bandwidth for each cell and more complex network planning. In addition, in order to increase the data rate and spectral efficiency without requiring more spectrum resources in cellular networks, two traditional spatial reuse mechanisms, cell splitting and sectorization are often utilized. Several advanced antenna techniques such as MIMO and adaptive beamforming can also be used to enhance cellular system performance.

When properly selected transmission format and link adaptation are employed, the capacity of cellular systems depends essentially on the average quality of the received radio signals, which can be characterized by a CINR metric, defined as follows:

$$\text{CINR} = \frac{P_{C_j}}{P_N + \sum_{k \neq j} P_{I_k}}$$

where P_{C_j} is the received carrier signal power from the j th (serving) cell, P_{I_k} denotes the received co-channel interference signal from the k th cell (other than the serving cell), and P_N is the noise power. The received signal power P_{C_j} is determined by the distance between the transmitter and the receiver, the transmission power, and the associated path loss caused by the environment. The most dominant noise type is thermal noise originated from hardware components in the system. The background radiation originating from cosmic or terrestrial sources picked up by the receive antennas also adds to the overall noise in the receiver. As for the perceived interference, actually, the interference P_{I_k} includes not only co-channel interference, which is also known as inter-cell interference, but also intra-cell interference. Since inter-cell interference is the dominant component in an OFDMA system (due to orthogonality of the users in time and frequency) compared to the intra-cell interference, our focus in this section will therefore be only on the

inter-cell interference. The inter-cell interference depends on the number of co-channel cells, the distance between these cells, the transmission power, and the terrain characteristics, in which the first two factors depend on the choice of the frequency reuse factor.

The minimization of the inter-cell interference is desirable to fulfill the following objectives: (i) maximization of the overall network capacity; (ii) maximization of the cell-edge throughput; and (iii) enhancements in terms of both the overall network capacity and the cell-edge performance. Interference mitigation techniques can be generally classified into three major categories: interference cancellation, interference randomization, and interference coordination techniques.

Inter-cell interference cancellation techniques have been investigated and deployed with varying degrees of success in terrestrial mobile networks for more than 20 years. The basic principle of inter-cell interference cancellation techniques is to regenerate the interfering signals and subsequently subtract them from the desired signal. Various inter-cell interference cancellation techniques have been proposed in the literature, and they are mainly characterized as filter-based and multi-user detection (MUD) schemes [8–10]. Filter-based approaches try to mitigate intercell interference by means of linear filters and interference models. In contrast, MUD directly includes the interfering signals in the decoding process. This is done by jointly decoding the desired signal and the interfering signals, or by decoding and subtracting the interfering signals from the signal of interest. Inter-cell interference cancellation techniques can also be jointly used with multi-user MIMO techniques, if the UEs are equipped with multiple-receive antennas. From an implementation viewpoint, interference cancellation does not require any modification of the standards, making it an attractive technique. Although inter-cell interference cancellation promises significant gains and its algorithms are mature, it is considered mostly as a technique for the uplink due to processing complexity which scales exponentially with the number of active users. Furthermore, it requires exchange of information in real-time between the base stations about every few milliseconds to maximize the system gain. Moreover, inter-cell interference cancellation can potentially improve channel performance to that of AWGN if accurate channel estimation is available [8–10].

In contrast to inter-cell interference cancellation, which tries to eliminate the effect of interfering sources in the received signal, inter-cell interference randomization, which is also known as interference whitening or interference averaging, attempts to make the inter-cell interference appear as background noise, i.e., it averages the interference across the data symbols of a data block or the entire frequency band. The approaches include frequency hopping and interleave division multiple access. However, these methods randomize the interference into white Gaussian noise, which cannot reduce interference in nature. Therefore, these approaches can hardly achieve a substantial performance improvement [8–10].

ICIC techniques, also known as inter-cell interference avoidance, in OFDMA radio access systems have recently gained much attention from both the academia

and the standardization communities. In order to reduce inter-cell interference in cellular networks, the ICIC methods apply restrictions to resource management in a coordinated manner among neighboring cells. Resources for coordination can be space (with beamforming antennas), time, frequency, code resources, or transmit power. The restrictions can be in the form of time/frequency resource availability to the resource manager, and/or restrictions on the transmit power that can be applied to certain time–frequency resources. The impact on the system architecture as a result of support of ICIC schemes can be mainly divided into four major categories depending on the degree of distribution: global; distributed; decentralized; and local ICIC schemes.

Global ICIC schemes require an omniscient central entity with full system knowledge, which is capable of acquiring the global system state in zero time, and can distribute scheduling and other decisions instantly to all network nodes. Distributed ICIC schemes rely on one or more central components, which exchange information potentially with all nodes in the network. The central components thereby collect state information and distribute information relevant for coordination to the network nodes, e.g., coordinated multi-point transmission/reception. Decentralized ICIC schemes are distinguished from distributed schemes by having no central entity involved in the coordination process. The coordination is performed exclusively by communication and information exchange among the network nodes. Local ICIC schemes are based mainly on information that is available locally in each eNB. There is no coordination-related communication and information exchange among neighboring eNBs. The local information includes feedback received from the UEs about the strongest interferers. Information exchange among eNBs or with a central coordinator could result in higher performance gains at the expense of increased system complexity [8–10].

A global ICIC scheme is practically unfeasible, although it may potentially attain the highest performance improvements among all ICIC schemes. Local ICIC schemes require no separate network equipment and provide the most flexibility with respect to the network design, although using local ICIC schemes may not achieve the highest performance gain.

An interference mitigation scheme based on beamforming transmits a narrow beam toward the desired user instead of transmitting in the conventional omnidirectional or sectorized manner [12]. This scheme is capable of reducing the interference imposed on users of the system, particularly benefiting the cell-edge users. Therefore, the classic beamforming technique is sometimes also referred to as interference alignment. Beamforming techniques may be further classified into two types, namely, non-adaptive and adaptive beamforming, where both types require partial or full channel state information feedback. Adaptive beamforming techniques adapt the antenna complex-valued weights according to diverse optimization criteria by exploiting the channel knowledge. A particularly beneficial adaptive beamforming technique is the well-known eigen beamforming, where the antenna weights are chosen to be the eigenvector of the largest eigenvalue of the spatial MIMO channel covariance matrix. On the other hand, a beam-switching

technique uses the best-oriented beam among a number of preselected beams, where each array-weight vector is a function of the beam direction, as well as of the antenna element's position. In a typical 120° antenna pattern sector generated by a uniformly spaced linear array having four antenna elements, a total of eight beams may be created, where the adjacent beams are evenly spaced by an angle of 13° [12]. The index of the best beam vector resulting from the maximum mean channel gain measured at the receiver is signaled back to the transmitter, where the channel gain is averaged over a certain time period, a set of subcarriers, and over the spatial domain constituted by the receive antennas, depending on the accuracy of the CSI feedback as well as depending on the affordable feedback bit rate.

The combination of more advanced opportunistic transmission and beamforming techniques may attain further performance improvement in multi-user environments. The concept of beam hopping may be further utilized to intelligently avoid directional interference. Regardless of the use of the adaptive or non-adaptive variant, when transmitting directionally by exploiting the maximum equivalent channel gain, the received signal power and the SINR are enhanced, or alternatively, the transmitted power may be reduced despite maintaining a certain received SINR. As a result, the interference imposed on the adjacent cells is reduced, and the overall interference level in the entire system is reduced. In contrast to the directivity exploited by the above-mentioned beamforming techniques, the benefits of transmit diversity may be limited by transmitting the same signal from different antennas, provided that they experience independent fading. Since the transmit power required for maintaining a certain error probability may be reduced as a benefit of transmit diversity, the interference imposed becomes lower [10].

The concept of distributed antennas has been exploited to ensure that the antenna elements are sufficiently geographically dispersed and far apart to guarantee that the signals generated by each antenna are uncorrelated. The advantage of employing distributed antennas is the increased macro-diversity effect, which is particularly beneficial for the cell-edge users, which would otherwise suffer from severe co-channel interference. In contrast to the conventional single-cell transmission, where each user is served by its local base station only and suffers from co-channel interference caused by the adjacent cells, in the distributed antenna multi-cell transmission, each user is served by several coordinated base stations and each base station jointly processes multiple users' information, which is shared via the backhaul using a high-capacity low-latency optical fiber link. This leads to an equivalent distributed MU-MIMO system [10].

14.2 Heterogeneous networks

One of the most promising and cost-effective solutions to improve the system capacity is to deploy low-power nodes such as relays, pico-cells, femto-cells, and

remote radio heads overlaid by macro-cell networks. The new network architecture is known as heterogeneous networks (as shown in Figure 14.3) can provide a flexible and effective way to eliminate the coverage holes in macro-cells and improve the system capacity. One of the key issues in the new network architecture is the handover performance deterioration in co-channel HetNets, where the cell-edge UEs can experience more serious interference [2,13–15].

The output power of the low-power nodes varies depending on the type of deployment and usage scenario. If the low-power nodes are intended for outdoor deployments, their transmit power ranges from 250 mW to approximately 2 W. They do not require an air-conditioning unit for the power amplifier, and are much lower in cost than traditional macro base stations, where their transmit power typically varies between 5 and 40 W. Femto base stations are meant for indoor use, and their transmit power is typically 100 mW or less. Unlike pico base stations, femto base stations may be configured with a restricted association, allowing access only to its closed subscriber group (CSG) members, or alternatively they can be configured as an open subscriber group (OSG), allowing full or partial access to the public. A network that consists of a mix of macro-cells and low-power nodes, where some may be configured with restricted access and some may lack wired backhaul, is referred to as a HetNet [11,16].

Cellular systems have been traditionally deployed as homogeneous networks using a macro-node-centric planning process. A homogeneous cellular system is a network of base stations in a planned layout and a collection of user terminals, in which all the base stations have similar transmit power levels, antenna patterns, receiver noise floors, and similar backhaul connectivity to the packet data network. Furthermore, all base stations offer unrestricted access to user terminals in

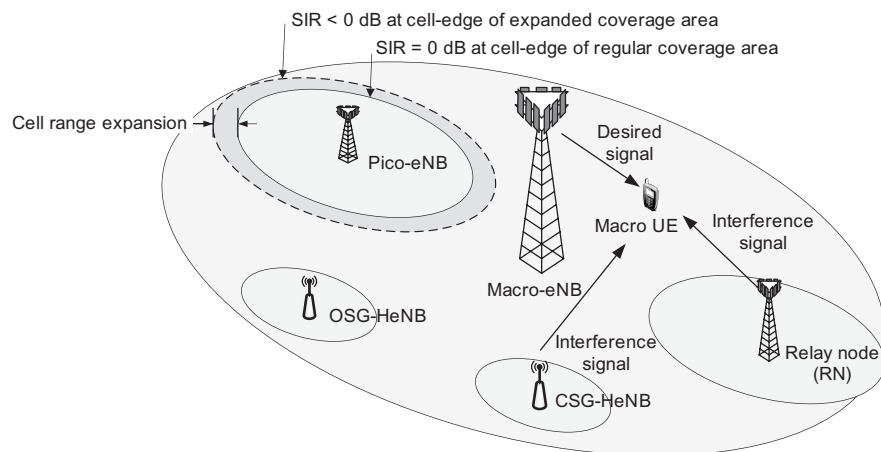


FIGURE 14.3

An example HetNet topology [22].

the network, and can serve approximately the same number of user terminals, all of which carry similar data flows with similar QoS requirements.

The locations of the macro base stations are carefully chosen through network planning, and the base station settings are properly configured to maximize the coverage and to control the interference between base stations. As the data traffic grows and the RF environment changes, the network relies on cell splitting or additional carriers to overcome capacity and link budget limitations in order to maintain uniform user experience. However, this deployment process is complex and iterative. Moreover, site acquisition for macro base stations with towers is becoming more difficult in a dense urban environment, thus a more flexible deployment model is needed for operators to improve broadband user experience in a ubiquitous and cost-effective way.

In a homogeneous network comprising macro-cells, each mobile terminal is served by the base stations with the strongest signal strength, while the unwanted signals received from other base stations are usually treated as interference. In a HetNet, such principles can lead to significantly suboptimal performance. In such systems, smarter resource coordination among base stations, better server selection strategies, and more advanced techniques for efficient interference management can provide substantial gains in throughput and user experience as compared to a conventional approach of deploying macro-cellular network infrastructure.

A pico base station is characterized by a substantially lower transmit power relative to a macro base station. The potentially large disparity between the transmit power levels of macro and pico base stations implies that in a mixed macro/pico deployment, the downlink coverage of a pico base station is much smaller than that of a macro base station. This is not the case for the uplink, where the strength of the signal received from a user terminal depends on the terminal transmit power, which is the same for uplink paths from the terminal to different base stations. Therefore, the uplink coverage of all the base stations is similar and the uplink handover boundaries are determined based on channel gains. This can potentially create a mismatch between downlink and uplink handover boundaries, and make the base station to device association or cell selection more difficult in HetNets, compared to homogenous networks, where downlink and uplink handover boundaries are closely matched (Figure 14.4).

If the cell selection is predominantly based on downlink signal strength, as in LTE Rel-8, the usefulness of pico base stations will be greatly diminished. In this scenario, the larger coverage of high-power base stations limits the benefits of cell splitting by attracting a large fraction of user terminals toward macro base stations based on signal strength without having enough macro base station resources to efficiently serve these user terminals, while lower power base stations may not be serving any user terminals. Therefore, from the point of view of network capacity, it is desirable to balance the load between macro and pico base stations by expanding the coverage of pico base stations and subsequently increasing cell splitting gains [11,16].

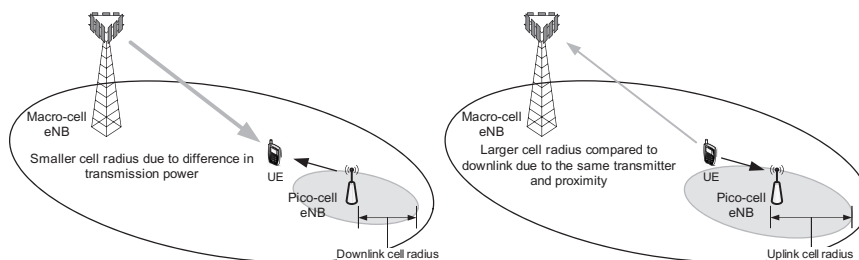
**FIGURE 14.4**

Illustration of uplink/downlink imbalance in HetNets [11].

Balanced load distribution between macro and pico base stations can be achieved if base station to device association is based on path loss (associating the base station with the minimum path loss rather than the base station with the maximum downlink signal strength), and a fixed partitioning of resources between the macro and pico base stations. As a result, more users are associated with the pico base stations, and the network is able to provide more equitable distribution of radio resources to each user. The effect is even more pronounced in hotspot layouts where users are clustered around pico base stations. Capacity gains can be achieved through sharing of the resources allocated for low-power base stations, while sufficient coverage is provided by high-power base stations on the resources that are allocated to them.

In a HetNet, in order for a user terminal to obtain service from a low-power base station in the presence of macro base stations with stronger downlink signal strength, the pico base station needs to perform interference coordination, for control and traffic channels, with the dominant macro interferers, and the user terminals need to support advanced receivers for interference cancellation. In the case of femto base stations, only the owner or subscribers of the femto base station may be allowed to access the femto base stations. For user terminals that are close to these femto base stations, but barred from accessing them, the interference caused by the femto base stations to the user terminals can be particularly severe, making it difficult to establish a reliable downlink communication to these user terminals. Therefore, as opposed to homogeneous networks, where resource sharing is a good transmission strategy, femto networks necessitate more coordination via resource partitioning across base stations to manage inter-cell interference.

The introduction of low-power nodes in a macro network creates imbalance between uplink and downlink coverage (see Figure 14.4). Due to the larger transmit power of the macro base station, the handover boundary is shifted closer to the low-power node, which can lead to severe uplink interference problems as the UEs served by macro base stations create strong interference to the low-power nodes. Given the relatively small footprint of low-power nodes, even in the case of the most optimized placement, low-power nodes may become underutilized due to geographic changes in data traffic. The performance of a mixed deployment of

macro-, pico-, and open femto-cells was evaluated in the literature [1,11,17,22], which showed that the limited coverage of low-power nodes is the main reason for limited performance gain in HetNets. Furthermore, some of the deployed femto-cells may have enforced restricted association, which effectively creates a coverage hole and aggravates the interference problem. In order to cope with the interference, it is necessary to introduce techniques that can adequately address these issues. Due to restricted association, a CSG femto-cell creates a downlink coverage hole at the vicinity of the femto-cell for non-member UEs. In order to reduce the effect of the coverage hole, a femto-cell could adapt the transmitted power intelligently such that interference is contained within the intended coverage area such as a residential site. Since the femto-cell coverage and femtocell interference to the macro-UE are directly proportional to the femto-to-macro signal strength ratio, a femto-cell could set the proper transmit power by estimating the additional interference that could be tolerated by a non-member UE near the femto-cell. As a result, the femto-cell maintains a similar coverage area regardless of its location within the overlaid macro-cell.

Pico-cells are eNBs with lower transmit power than traditional macro-cells. They are typically equipped with omnidirectional antennas and are deployed indoors or outdoors, often in a planned manner. Their transmit power ranges from 250 mW to approximately 2 W for outdoor deployments, while it is typically 100 mW or less for indoor deployments. Since pico-cells are regular eNBs from an architecture perspective, they can benefit from X2-based ICIC.

In light of the above challenges in the operation of HetNets, an ICIC scheme is critical to HetNet deployment. A basic ICIC technique involves resource coordination among interfering base stations, where an interfering base station avoids use of some resources in order to enable control and data transmissions to the victim user terminal. More generally, interfering base stations can coordinate their transmission power and/or spatial beams with each other in order to enable control and data transmissions to their corresponding user terminals.

The resource partitioning can be performed in time-domain, frequency-domain, or spatial-domain. Time-domain partitioning can better adapt to user distribution and network load variations, and is the most attractive method for spectrum-constrained environments. For example, a macro base station can choose to reserve some of the subframes in each radio frame for use by pico base stations, based on the number of user terminals served by pico and macro base stations, and/or based on the data rate requirements of the user terminals. Frequency-domain partitioning offers less granular resource allocation and flexibility, but is a viable method especially in an asynchronous network. Spatial-domain partitioning can be supported by a CoMP transmission/reception scheme, which was discussed in Chapter 12. For time-domain resource partitioning, a macro base station can use almost blank subframes (ABS) to reserve some subframes for pico nodes. The macro base station continues transmission of legacy common control channels during almost blank subframes to maintain backward compatibility with legacy user terminals. The user terminals can cancel interference on common

control channels within almost blank subframes caused either by higher power macro base stations or by nearby femto stations that they are prohibited to access. An interference cancellation receiver can handle colliding and non-colliding reference signal scenarios, and can eliminate the need for cell planning for heterogeneous deployment [22].

The studies in 3GPP concerning HetNet mobility improvement have continued in LTE Rel-11 [2]. The comprehensive simulations conducted in these studies concluded that handover performance of HetNets was not as good as homogeneous macro-cell deployments. Furthermore, it was shown that the UE speed has significant impact on the handover performance, and that careful DRX configurations are required to avoid negative impact on handover performance. The objective in LTE Rel-12 is thus to enhance handover performance in HetNet scenarios (e.g., minimization of handover failure rate, minimization of ping-pong effects, recovery from radio link failure), as well as supporting UE mobility and longer DRX cycles. The enhancement of mobility in small-cell scenarios with focus on inter-frequency schemes will also be part of the LTE Rel-12 development.

14.3 Enhanced inter-cell interference coordination (eICIC)

The basic principle of ICIC is to avoid high-power transmission on time–frequency resources on which cell-edge users are scheduled in neighboring cells, users that would otherwise experience high interference and correspondingly low data rates. In LTE Rel-8, ICIC is performed over the frequency-domain by transmission of messages across a standardized backhaul inter-eNB interface such as X2. Because the latency over X2 is typically in the order of a few milliseconds, it is expected that any updates or reconfiguration to the ICIC messages are relatively infrequent (in the order of seconds). The LTE Rel-8 frequency-domain ICIC in the downlink is based on event-triggered message exchange between eNBs approximately every 200 ms to allow adaptive FFR. Uplink ICIC is based on event-triggered *overload indicator* and *high interference indicator* messages exchanged between the eNBs approximately every 20 ms. In the context of ICIC, the following metrics are defined [11,7]:

- *High interference indicator (HII)*: The HII provides information about a set of resource blocks on which an eNB is going to schedule transmissions for cell-edge terminals, i.e., resource blocks on which a neighboring cell can expect higher inter-cell interference. Although it is not explicitly specified how an eNB should respond to an HII message (or any other ICIC-related X2 signaling) received from a neighboring eNB, a reasonable action for the receiving eNB would be to avoid scheduling its own cell-edge terminals on the same resource blocks, reducing the uplink interference to cell-edge transmissions in its own cell, as well as in the cell from which HII message was received. The HII is an indicator which is sent as a bitmap with one bit per resource

block/sub-band that the serving cell intends to use for scheduling cell-edge UEs, potentially causing high inter-cell interference to the neighboring cell. An eNB can send HII with different, neighbor-cell-specific contents to different neighbor cells.

- *Relative narrowband transmit power (RNTP)*: For the downlink, the relative narrowband transmit power is defined to support ICIC operation. The RNTP is similar to the HII in the sense that it provides information for each resource block whether the relative transmit power of that resource block exceeds a threshold level. Similar to the HII, a neighboring cell can use the information provided by the received RNTP when scheduling its own terminals, especially terminals in the cell-edge that are more likely to be interfered by the neighboring cell. The RNTP message is signaled using a bitmap wherein each RNTP bit value indicates whether the corresponding resource block pair is limited by a transmit power threshold. Upon receipt of the RNTP message, the recipient eNBs can take into account this information while making their scheduling decisions for subsequent subframes. One such example may be that the recipient eNB avoids scheduling UEs in resource blocks where the source eNB (e.g., macro-cell eNB) is transmitting above a certain power limit.
- *Overload indicator (OI)*: The overload indicator is an indicator exchanged over the X2 interface, reflecting the uplink interference plus noise level (low, medium, or high) of a resource block measured by an eNB. Although the reaction of the recipient eNB upon receipt of the OI is not standardized, a possible reaction to the OI by the recipient eNB would be to limit the maximum transmit power of a UE scheduled on resource blocks indicated by the OI to have high interference.

During LTE Rel-10 standardization, 3GPP developed two approaches to coordinate inter-layer interference, primarily targeting the aforementioned deployment scenarios. Both approaches rely on a semi-static resource partitioning across layers, but take two different approaches to ICIC of control and data channels. In one approach, interference avoidance is addressed by means of ICIC in the frequency-domain, relying on carrier aggregation (CA) as introduced in LTE Rel-10. In the other approach, interference avoidance is addressed by means of ICIC in the time-domain, relying on ABS. Both approaches target scenarios with low-power nodes, assuming time-synchronization with the macro-eNB.

14.3.1 CA-based eICIC schemes

In CA, a terminal may simultaneously receive/transmit data and control on multiple components carriers (CCs), where a component carrier is fully backward compatible with LTE Rel-8. A terminal supporting carrier aggregation can be configured by higher layer signaling to enable cross-carrier scheduling on certain component carriers. This implies that a terminal receiving a downlink assignment on one component carrier may receive associated data on another component carrier. One of

the main motivations for introducing cross-carrier scheduling was to enhance operations in HetNets in a multi-carrier deployment. The basic idea in CA-based ICIC is to create a protected component carrier for reliable reception of downlink physical signals, system information, and control channels at victim layers, but data can be received on any configured downlink component carrier via cross-carrier scheduling. This, in conjunction with RNTP at aggressor layers, forms the basis of CA-based eICIC. As shown in Figure 14.5, assume a macro–pico deployment scenario with two downlink component carriers, CC1 and CC2. In this particular scenario, a macro-cell creates a protected component carrier by reducing its transmit power on CC1 in order to enable larger picocell coverage on CC1. On CC2, the macro-cell transmits with its nominal output power, implying that the size of the pico-cell associated with CC2 will be reduced in comparison with the pico-cell coverage on CC1. The dashed areas in the figure represent cell range expansion zones, i.e., areas with reduced reception reliability of the downlink control channels, PDCCH, PHICH, and PCFICH [11,22].

As shown in Figure 14.5, it is obvious that without use of eICIC, a terminal configured with CC1 and CC2 can simultaneously receive from both carriers only in the following scenarios: (i) it operates within the coverage of the pico-cell associated with CC2 when connected to the pico-cell; (ii) it operates within the coverage of the macro-cell on CC1 when connected to the macro-cell. However, with cross-carrier scheduling a pico-cell-edge user can receive PDCCH on the protected CC1, whereas the associated PDSCH is received on CC2, on which the macro-cell will have reduced its transmit power on PDSCH in resource blocks known by the pico-cell via X2 signaling of RNTP. It is also shown that the operation of the CA-based eICIC, in which the macro-cell avoids transmissions or reduces its transmission power of PDSCH in resource blocks in the upper band of CC2, the users operating in the cell range expansion zones receive data via cross-carrier scheduling, whereas users closer to the eNB sites do not need to rely on data reception via cross-carrier scheduling. A UE typically associates with a base station that exhibits strong downlink SINR. If the macro-cell transmission interferes with that of a low-power node, the UE may not be able to select the low-power node. With cell range expansion, a UE can associate with a low-power node despite the fact that the downlink SINR may be much lower than 0 dB. Time-domain resource partitioning enables load balancing between high- and low-power nodes. Note that resource partitioning is dynamically adapted to network load. Capacity gains in HetNets are achieved by off-loading traffic from macro-cells to pico-cells, and the amount of off-loading is increased by cell range expansion. Cell range expansion virtually increases the footprint of the low-power node. The operating signal-to-interference ratio (SIR) in the expanded cell range may be less than 0 dB. The ABS facilitate serving UEs in the expanded cell range by the victim nodes. However, interference from cell-specific reference signals and other control signals within ABS limits the cell range expansion. LTE Rel-10 supports cell range expansion with $SIR = -6$ dB, which was further decreased to -9 dB in LTE Rel-11 [11,22].

In CA-based eICIC, the primary cell associates with a protected component carrier. Pico-cell users would then have CC1 as their primary cell, whereas macro-cell users would have CC2 as their primary cell. The CRS transmission from an aggressor cell (necessary for backward compatibility with legacy LTE systems) will potentially create inter-cell interference toward victim users. Therefore, LTE Rel-10 introduced transmission mode 9 for which demodulation of PDSCH relies entirely on the UE-specific reference signals for data demodulation, and CSI reference signals for CSI measurement. Through RNTP signaling, DM-RS collisions across different cells can be avoided since DM-RS are only transmitted in resource blocks carrying PDSCH. Such UE-specific configuration is useful in HetNet scenarios where the CRS reception might be deteriorated. Furthermore, a terminal can be configured to conduct measurements corresponding to mobility and radio link monitoring on its primary cell only, i.e., the cell with the best CRS quality [5–7].

14.3.2 Non-CA-based eICIC

The underlying concept of time-domain eICIC is that an aggressor layer creates protected subframes for a victim layer by reducing its transmission activity in certain subframes. To do so, the aggressor eNB reduces its transmission power of some downlink signals, or alternatively mutes their transmission during a set of low-interference subframes designated as ABS whose occurrences are known in advance at the coordinated eNBs. The ABS patterns can be constructed by configuring MBSFN subframes and/or by not scheduling unicast traffic, or alternatively by reducing transmit power in certain subframes. During ABS, the aggressor eNB does not transmit PDSCH but may transmit CRS, critical control channels, and broadcast and paging information. If the victim cell schedules its UEs in subframes that overlap with aggressor cell ABS, the victim cell protects its UEs from strong inter-cell interference, thereby increasing the likelihood of successful PDCCH/PDSCH reception (Figure 14.6).

Backward compatibility is ensured by transmitting essential physical signals, system information, and paging in the same way as in LTE Rel-8. This implies that CRS transmission at the aggressor layers will create interference on either PDSCH signal or CRS signals at victim layers even during ABS, although the CRS interference on PDSCH can be reduced by configuring MBSFN subframes, since the CRS is not transmitted in the MBSFN region of MBSFN subframes. Furthermore, the primary and secondary synchronization signals, as well as system information, are transmitted in the zero and fifth subframes of a radio frame, and will thus be inter-layer interference sources that cannot be avoided by introducing ABS. In the case of a macro–femto deployment, CSG femto-cells represent the aggressor layer, whereas in the case of a macro–pico deployment, macro-cells represent the aggressor layer. With the time-domain ICIC, a macro-cell eNB may schedule users during protected subframes when they are in the proximity of CSG femto-cells, whereas a pico-cell eNB may schedule their cell-edge users only during protected subframes (Figure 14.7). The information

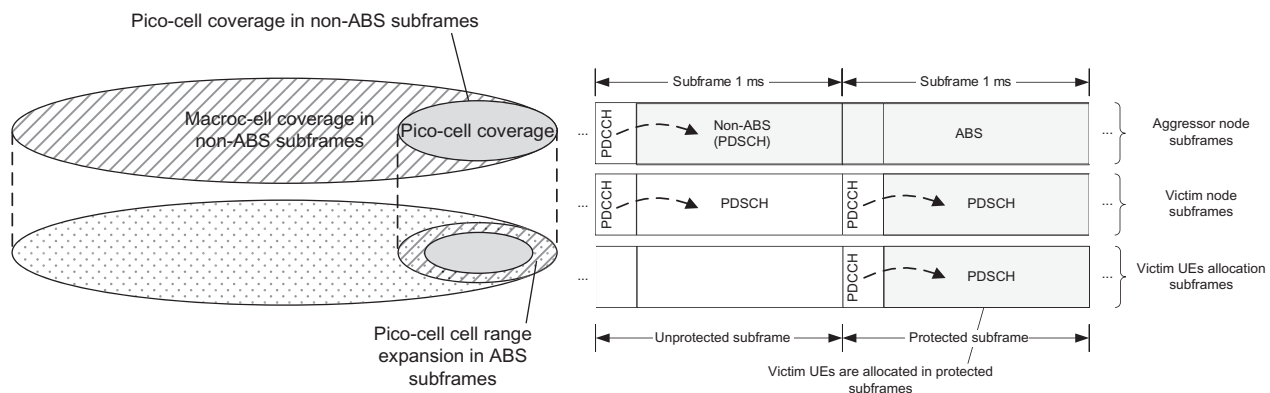


FIGURE 14.6

Illustration of the non-CA-based eICIC concept [11].

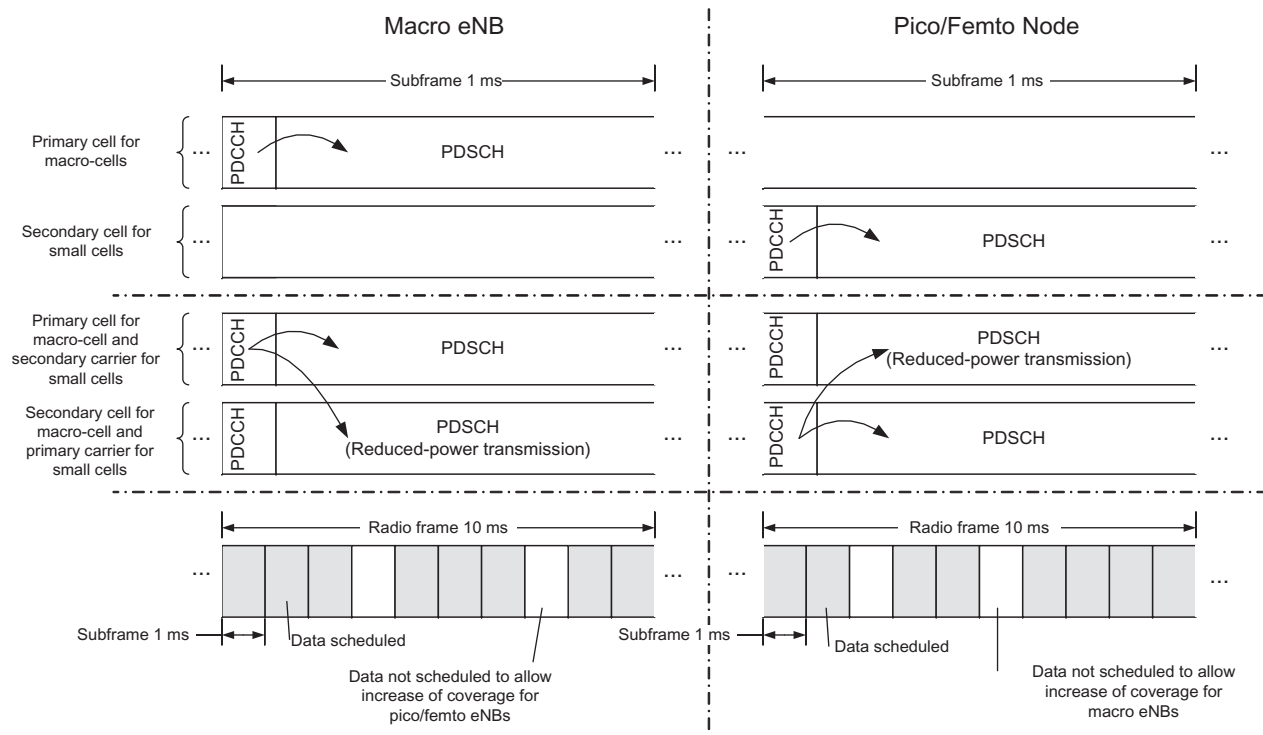


FIGURE 14.7

Illustration of CA-based and non-CA-based eICIC methods [16].

regarding the subframes on which coordinated low-interference transmission occurs is exchanged between coordinating eNBs via bitmap patterns. Upon receiving the bitmap pattern either via customized network operation administration and maintenance, or via the X2 interface, the recipient eNB can schedule data for its victim UEs on subframes that overlap with the aggressor ABS transmissions, as shown in Figure 14.7. In order to enable this, the time-domain eICIC requires time-synchronized eNB transmissions at least at the subframe boundaries. In an FDD system, for optimal operation with a synchronous uplink HARQ in a HetNet, a bitmap of length 40 bits (which is equivalent to a 40-ms periodicity) is used. Additional interference mitigation through subframe shifting is required to avoid cross-layer interference from broadcast channel and synchronization signals. It is also desirable to configure paging occasions, and scheduled system information, in non-ABS at the aggressor layer and in protected subframes at the victim layer [11].

In LTE Rel-8, a UE may average channel and interference estimates over multiple subframes to derive a CSI feedback. When time-domain eICIC is used, the interference level of these two types of subframes, i.e., protected and unprotected subframes, can be significantly different. In order to ensure that the UE does not average interference across the two different types of subframes, the eNB can configure two subframe subsets such that the UE only averages the channel and interference estimates over subframes within the subset, but not across the two subsets. The UE then reports the CSI measurements separately for the two subsets either periodically (with the respective configured reporting periods for each subset) or aperiodically (i.e., one of the CSI measurements from two subframe subsets is reported via PUSCH, when triggered by PDCCH) [11].

In the connected mode, where a UE's mobility is controlled by the network, the network may perform an inter-frequency or inter-RAT handover to a different carrier frequency when the network determines that a non-CSG UE (range-extended pico-cell UE) is in the proximity of a CSG femto-cell based on the UE's measurement reports. In the idle mode, where the mobility is controlled by the UE within the network, the UE autonomously performs an inter-frequency or inter-RAT cell reselection to a base station on a different carrier when the UE moves close to a dominant interferer. Thus, in both cases, an inter-frequency/inter-RAT handover can potentially create LTE coverage loss, possibly leading to LTE service discontinuity on a collocated carrier. To avoid occurrence of LTE coverage holes, LTE Rel-10 eICIC developed mobility support and radio link monitoring (RLM) [11].

In LTE, the UE performs RRM measurements to manage its network connection and to facilitate handover. In the connected mode, the UE reports RSRP and/or RSRQ of the serving and the neighboring cells to the serving eNB (see Chapter 9 for a description of RSRP and RSRQ). The network then performs a handover, transferring the UE to a neighbor cell when the serving cell's RSRP falls below the neighbor cell's RSRP plus an offset to ensure UE service continuity during mobility. In LTE Rel-10, a victim UE can be configured to perform

resource-specific RRM measurements only on protected subframes. The resource-specific RRM measurements can improve accuracy of RSRP/RSRQ reporting by eliminating persistent interference on the CRS. Note that the collision of CRSs transmitted from different cells can be avoided by properly assigning the physical cell identities.

Radio link monitoring is a measurement function for ensuring that UEs maintain time synchronization and can reliably receive their control information. In LTE, the UE continuously evaluates the quality of the serving eNB in the downlink, and ensures that it is time synchronized to the serving eNB. If downlink synchronization is lost, the UE must suspend its uplink transmissions and should try to recover its existing link or to find a new serving cell with which a reliable downlink channel can be established. The RLM functionality comprises out-of-sync and in-sync evaluation procedures where the UE monitors CRS quality of the serving cell in the presence of co-channel interference. If the UE's serving cell is not the strongest measured cell due to severe interference, the UE can potentially declare a radio link failure. In order to ensure predictable UE behavior, LTE Rel-10 provides a mechanism so that the serving eNB can configure resource-specific RLM measurements at the UE for recording its radio link quality as experienced by the UE in protected subframes. This ensures that the link quality is tied to that of the protected subframes, and the UEs can continue to maintain their connection in HetNet scenarios [11].

In summary, time-domain eICIC may be utilized for pico-cell users which are served in the edge of the serving pico-cell, e.g., for traffic off-loading from a macro-cell to a pico-cell, allowing such UEs to receive service from the pico-cell on the same frequency layer. The inter-cell interference in this case may be mitigated by the macro-cell(s) utilizing ABS to protect the corresponding pico-cell's subframes from interference. A UE served by a pico-cell uses the protected resources for cell measurements (RRM), RLM, and CSI measurements. For a UE served by a pico-cell, the RRM/RLM/CSI measurement resource restriction may allow more accurate measurement of the pico-cell under severe interference from the macro-cell(s). The pico-cell may selectively configure the RRM/RLM/CSI measurement resource restriction only for those UEs subject to strong inter-cell interference. Furthermore, for a UE served by a macro-cell, the network may configure a RRM measurement resource restriction for neighbor cells in order to facilitate mobility from the macro-cell to a pico-cell [3].

14.3.3 Further enhanced ICIC

Due to time limitations, some enhanced ICIC techniques were deprioritized in LTE Rel-10. Particularly, the impact of legacy transmissions on control and data channel demodulation when using ABS was left for consideration in LTE Rel-11, leading to a further enhanced ICIC (FeICIC) scheme development. The work on the FeICIC scheme attempted to identify the UE performance requirements, possible air-interface changes, and eNB signaling improvements. In order to significantly

improve detection of physical cell identity and system information in the presence of dominant interferers, the study focused on UE receiver implementation, UE performance requirements, and eNB signaling required for UE measurement/reporting, as well as network assisting information for CRS interference cancellation and usage of reduced-power ABS. In LTE Rel-11, the enhanced downlink physical control channel has been developed to allow improved control channel inter-cell interference mitigation.

Co-channel deployments are of interest due to cost-effectiveness and high spectral efficiency. The resource partitioning can effectively mitigate interference from the traffic channels. However, inter-cell interference originated from the synchronization and control channels as well as CRSs will persist, since transmission of these signals is necessary for legacy support. Subframe time shifting can be utilized in FDD systems to avoid collision of the control/synchronization channels between eNBs of different power classes that require partitioning, but it cannot be applied to TDD systems. There is no network solution for CRS interference mitigation for either FDD or TDD systems. Without additional interference mitigation of the aforementioned channels and CRS, only limited SIR bias values (approximately 6–10 dB) can be supported, which limits the potential for cell range expansion. It must be ensured that UEs are able to detect and acquire a weak cell and measure and report the measurements to the network, which is a prerequisite for handover and cell range expansion. The CRS interference mitigation has an important role in system performance. Strong CRS interference, even though present only in a relatively small fraction of resource elements, can significantly degrade turbo code performance and the overall SINR; therefore, the potential gains of cell range expansion can be severely reduced. Given that the aforementioned interference sources are all broadcast at full power targeting UEs at the cell-edge, it must be ensured that a robust UE-based interference cancellation solution is feasible, which decodes the strongest signal, performs channel gain estimation toward the interfering cell, cancels the interfering signal, and continues the procedure until the desired signals of the serving cell are acquired.

As mentioned earlier, adaptive inter-cell interference management in LTE Rel-10 is enabled by coordination of resources used for scheduling data traffic through the X2 interface. The granularity of the negotiated resource is a single subframe (Figure 14.8). The resource partitioning enables cell range expansion through use of a bias for cell range determination. In a typical case, cell range expansion is enabled to improve system capacity, and a cell bias is applied to low-power nodes. The bias value refers to a threshold that triggers handover between two cells [16]. A positive bias means that the UE will be handed over to a pico-cell as soon as the difference in the signal strength from the macro-cell and pico-cell falls below a threshold. The macro base station informs the pico base station which resources will be utilized for scheduling a macro-UE, and which subframes are assigned as ABS. Therefore, the low-power nodes are informed of the interference pattern from the high-power base station, and can

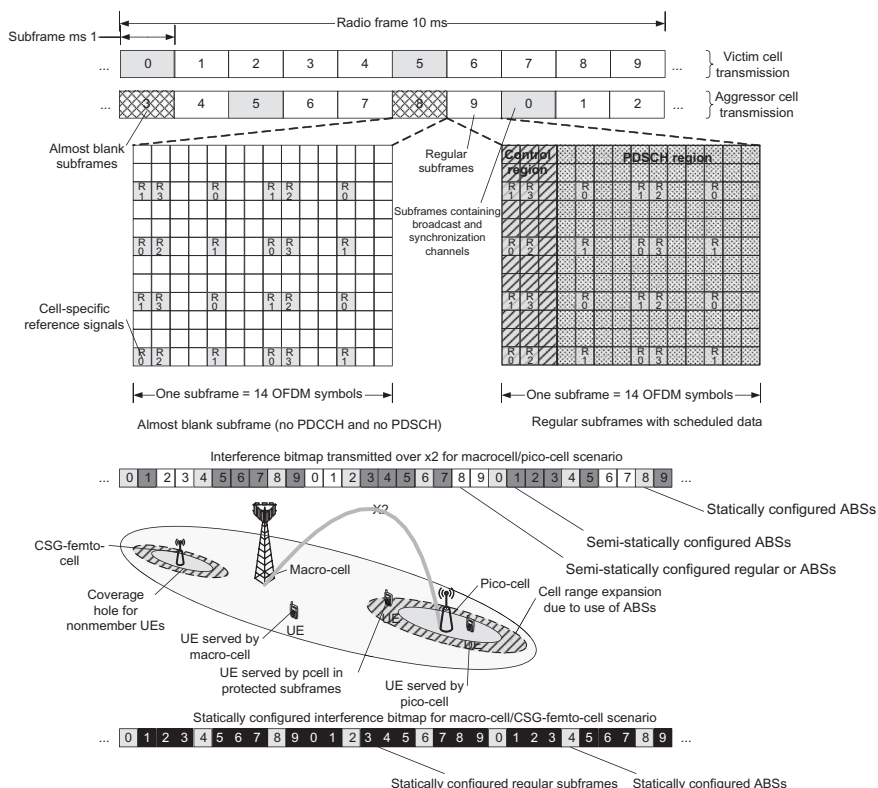
**FIGURE 14.8**

Illustration of the static/semi-static interference management eICIC schemes for FDD systems in macro-cell/pico-cell and macro-cell/CSG-femto-cell scenarios [16].

schedule the UE in the extended cell areas on subframes protected from high-power interference. Interference coordination is performed by means of a bitmap, where each bit in the bitmap is mapped to a single subframe (see Figure 14.8). The size of the bitmap is 40 bits, suggesting that the interference pattern repeats every 40 ms. Depending on the traffic volume, the pattern can change every 40 ms. The aggressor node effectively controls which resources can be used to serve the UE in the cell range expansion zones. An example of coordination between a macro-cell and pico-cell is shown in Figure 14.8. Note that the cell range expansion may be desirable for a macro base station as well. A typical use case for cell range expansion in the macro base station is to reduce the number of handovers. In a scenario with a large number of high-mobility users, the number of handovers in the network can become problematic, particularly in the deployment of pico base stations, the cells become small. The same resource partitioning

schemes can then be utilized to allow high-mobility macro-UEs to remain attached to a macro-cell while inside the coverage area of a pico-cell [16]. In this case, the pico base station needs to restrict scheduling data traffic on some resources. In a macro–femto scenario (see Figure 14.8), due to the lack of an X2 interface between the eNB and the HeNB, only a static network-configured solution is feasible when CSG-femto nodes are deployed on the same frequency as the macro-cell. Due to the static nature of the solution, the resource partitioning pattern cannot be adapted to the instantaneous characteristics of actual data traffic [16].

14.4 Multi-radio coexistence and interference avoidance

There has been a significant increase in the use of wireless devices equipped with a number of different radio technologies collocated on a single hardware platform in recent years, where each radio technology (depending on availability and coverage) can facilitate certain user applications/network services. A typical configuration of multi-radio mobile terminals consists of one or more wide-area RATs such as HSPA +, LTE, mobile WiMAX, cdma2000, and a number of short-range wireless technologies such as Bluetooth and Wi-Fi operating in the industrial, scientific, and medical (ISM) bands, as well as a GNSS or global positioning system (GPS) receiver for positioning. When these radios operate simultaneously in adjacent or overlapping RF spectrums, it results in interference from transmission of one radio to the reception of the other radios. This condition is referred to as in-device coexistence interference. IDC interference occurs when the frequency separation of less than 50 MHz is allotted between UMTS/LTE and the ISM-band radios (Table 14.1). With a frequency separation of less than 20 MHz, typically 50 dB of isolation is required to avoid IDC effects. The small form factor of mobile terminals usually provides only 10–30 dB isolation. As a result, an effective solution is required to mitigate the IDC interference without degrading the performance of the wireless access systems collocated on the user terminal [1,18].

Table 14.1 Experimental Results Concerning Minimum Frequency Gap Requirements [1]

Aggressor	Victim	Minimum Frequency Gap Requirement (MHz)		
		Antenna Isolation		
		10 dB	15 dB	20 dB
LTE Band 40	Wi-Fi	58	52	50
Wi-Fi	LTE Band 40	56	50	46
LTE Band 7	Wi-Fi	60	52	50

The commercial applications of GNSS receivers typically use the L1 band (1575.42 MHz) for location-based services. The uplink direction of LTE Band 13 (777–787 MHz) and Band 14 (788–798 MHz) can disrupt the operation of a GNSS receiver using the L1 band. This is because the second harmonic of Band 13 (i.e., 1554–1574 MHz) and the second harmonic of Band 14 (i.e., 1576–1596 MHz) are extremely close to the L1 band [1].

14.4.1 Collocated multi-radio coexistence issues

As shown in Figure 14.9, the lower portion of the ISM band is very close to LTE Band 40 (TDD). In the case of LTE-BT simultaneous operation, the LTE transmitter causes interference to the BT receiver, and the BT transmitter causes interference to the LTE receiver by desensitizing the receiver. Similar interference issues exist for LTE-Wi-Fi concurrent operation. It is also shown in Figure 14.9 that there is less than 20 MHz frequency separation between BT and LTE Band 7 (FDD uplink). Thus, the LTE transmitter causes interference to the BT receiver. There is no impact on the LTE receiver from the BT transmitter, because the

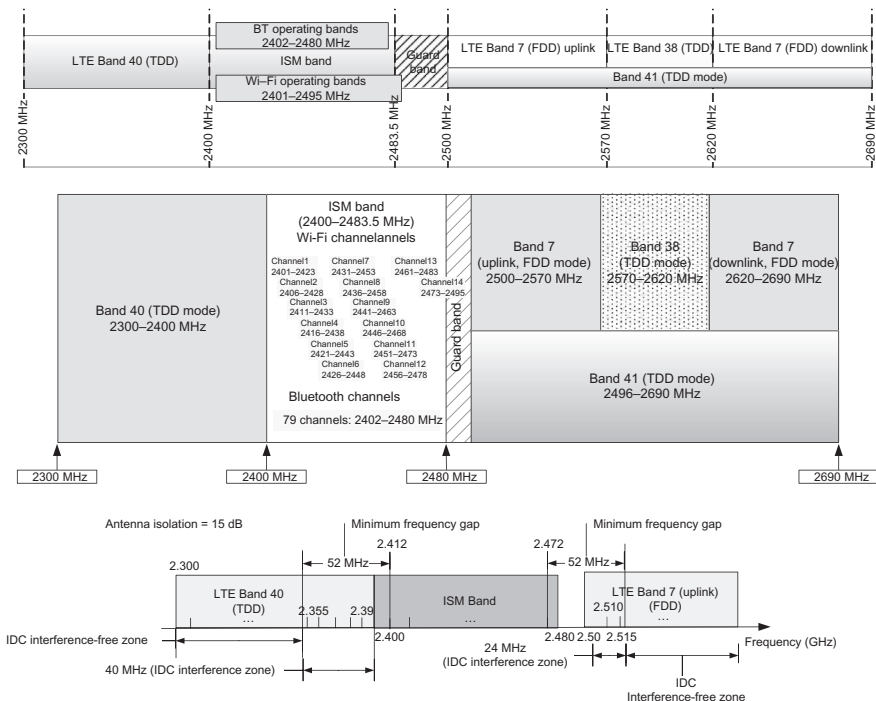


FIGURE 14.9

E-UTRA frequency bands around 2.4 GHz ISM band [1].

corresponding LTE Band 7 (FDD downlink) is far away from the ISM band. There is only 5 MHz separation between Wi-Fi and the LTE Band 7 uplink; however, since Wi-Fi operation is limited to channel 13 in most countries except Japan, there is often a frequency separation of 17 MHz. In the case of LTE-Wi-Fi coexistence, only the Wi-Fi receiver will be affected by the LTE uplink transmitter [1].

Interference between LTE Bands 7 and 40/41 with the 2.4 GHz ISM band is significant when operating in adjacent bands, where current RF filtering schemes are not adequate to mitigate the problem in a number of practical scenarios according to 3GPP RAN Working Group 4 studies [1]. The IDC interference level and its impact on the receiver performance depends on transmit power and receiver blocking characteristic of each radio, and physical characteristics of transceivers (e.g., filter frequency responses, antenna isolation). LTE Rel-8/9/10 already defined some mechanisms such as DRX mode and measurement gaps which would allow mitigation of some coexistence scenarios; however, these schemes are solely controlled by the eNB. The network-controlled UE assisted (i.e., providing triggers) and UE-based autonomous solutions were considered as part of the LTE Rel-11 IDC work item. The interference between LTE and the 2.4-GHz ISM band is significant when operating in adjacent bands, as shown in Figure 14.9. Those problems can be summarized as follows [1]:

- LTE Band 40 to ISM interference: LTE deployed in the upper 30 MHz of Band 40 can desensitize¹ the entire ISM band. LTE in any channel in Band 40 can desensitize the lower 20 MHz of the ISM band.
- ISM to LTE Band 40 interference: ISM in the lower 20 MHz can desensitize all channels in LTE Band 40. ISM in any part of its band can desensitize the upper 20 MHz of LTE Band 40.
- LTE Band 7 to ISM interference: LTE Band 7, in the uplink direction, deployed in 2510 MHz channel can desensitize the entire ISM band.
- With LTE deployed in Band 40, in some scenarios, and BT as a master can cause about 44% downlink error rates, and BT as a slave can cause about 55% downlink error rate.
- With LTE deployed in Band 7, the BT receiver error rate is 100% with high data rate applications on LTE.
- LTE Band 7/13/14 transmitter induces interference to GNSS receiver.

As shown in Figure 14.9, there are 14 channels in the ISM band designated for Wi-Fi operation. Each channel has 5 MHz separation from other channels,

¹Desensitization is a common performance degradation indicator, where the desensitization is relative to an assumed reference sensitivity value. The desensitization is approximated as $10\log_{10}x$, where x is the ratio between the coexistence interference and the noise floor at the receiver sensitivity level. Using desensitization as the performance measure provides an indication of the degradation that can be expected when the victim system is in its most vulnerable state at the edge of its coverage, and thus may be descriptive of a worst case scenario. The error vector magnitude (EVM) measure can also indicate potential degradation in receiver performance because a signal with large EVM would likely be incorrectly decoded at the receiver.

with the exception of channel 14 where separation is 12 MHz. Channel 1 starts with 2401 MHz and channel 14 ends at 2495 MHz. Different countries have different policies for the number of allowed channels of Wi-Fi operation [21]. Since E-UTRA Band 7 is an FDD band, there is no impact on the LTE receiver from the Wi-Fi transmitter; however, the Wi-Fi receiver is interfered by the LTE uplink transmitter in this frequency band. Bluetooth operates in 79 channels, each having 1 MHz bandwidth in the ISM band. The first channel starts at 2402 MHz, and the last channel ends at 2480 MHz [20]. The LTE Band 40 and BT will adversely affect each other, and the transmission of LTE Band 7 in the uplink direction will affect BT reception, as well.

14.4.2 In-device coexistence scenarios

In order to find an efficient and effective solution for the IDC issues that were mentioned above, it is important to identify the use cases that are commonly encountered. This is due to the fact that different usage models result in different assumptions about the behavior of the LTE transceiver and other collocated radio technologies, which eventually impact solutions. The IDC scenarios of interest in this study are as follows [1]:

1. *LTE + BT earphone (VoIP service)*: In this scenario, LTE is used for VoIP, and the BT earphone is used to send or receive voice packets. The activities of LTE and BT transceivers are going to be very similar in this case because of the end-to-end latency requirement.
2. *LTE + BT earphone (multimedia service)*: In this scenario, multimedia content is downloaded via the LTE link, and audio is routed to a BT headset, where the activities of LTE and BT are correlated. The requirements for scheduling/unscheduled periods for a typical streaming application can be set based on the LTE and BT characteristics. Activity time for BT can vary dynamically with a streaming application. The BT audio stream typically uses the advanced audio data profile (A2DP) [20], in which transmission delays greater than 60 ms can cause audible playback artifacts; consequently, the scheduling period of LTE should not exceed this limit. The latency requirement is less stringent on the LTE side in this case, and depends on the QoS class of the content. The maximum unscheduled period for LTE can be as long as 150 ms. However, in order not to degrade the LTE performance, it is desirable to minimize the LTE unscheduled period, and the smallest unscheduled period is determined by the on-time needed by the BT transceiver to sustain the data rate, depending on the link condition. This number typically ranges from 15 to 60 ms. As a result, the LTE scheduling period should be less than 60 ms, and the unscheduled period should be between 15 and 60 ms [1].
3. *LTE + Wi-Fi portable router*: In this scenario, LTE is considered a backhaul link providing access to the Internet, and the connectivity is shared by other

local users using Wi-Fi. The Wi-Fi transceiver is operated as an access point and has full control over frequency channel and transmitting power. Given the ability of the Wi-Fi transceiver to select the frequency channel, it may be possible to avoid interference to/from Wi-Fi by moving the Wi-Fi signal away from the LTE band, as shown in Figure 14.10. In the downlink, the worst case latency will be for a packet arriving at the eNB at the beginning of the LTE unscheduled period; thus, the latency is the sum of the LTE unscheduled period (waiting time for LTE scheduling) and the LTE scheduling period (waiting time for Wi-Fi scheduling). In the uplink, the scheduling/unscheduled periods can be made as small as 1 ms to minimize latency, but this is not desirable due to the impact on retransmissions and other sensitive timings in LTE and Wi-Fi operation. In order to fulfill the latency requirements of

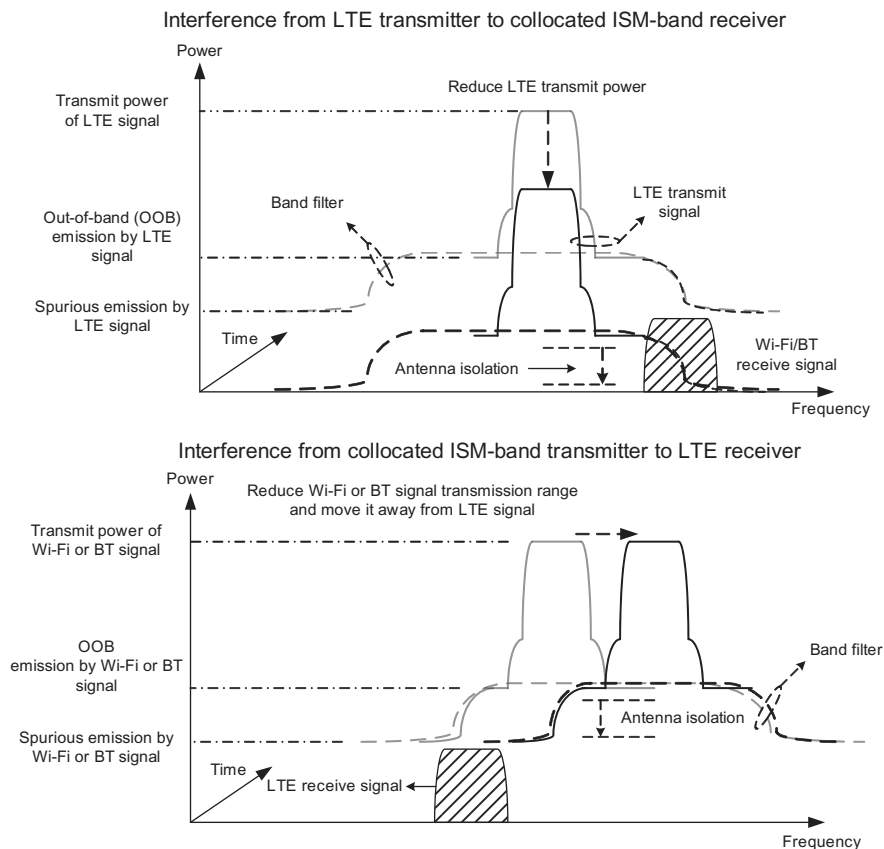


FIGURE 14.10

Illustration of IDC issues and some remedies [1].

common services under this scenario, the scheduling periods and unscheduled periods should be typically not more than 20–60 ms.

4. *LTE + Wi-Fi off-load*: In this scenario, an LTE UE can also connect to Wi-Fi to off-load traffic, and the Wi-Fi transceiver operates as a terminal in the infrastructure mode. It is difficult for the Wi-Fi transceiver to change the configured frequency channel in this case. In addition, the Wi-Fi radio is required to scan for the beacon signal transmitted from the Wi-Fi access point every 102.4 ms to maintain connection. The scheduling/unscheduled period requirements pertaining to this scenario differ from the previous scenario. One difference is about Wi-Fi beacon reception by the UE in Wi-Fi client mode, which implies alignment of the LTE unscheduled period with the Wi-Fi beacons. Furthermore, the scheduling period of LTE should be less than 100 ms in order to facilitate beacon reception. In this case, the packets only go through one radio link (either Wi-Fi for off-load packets or LTE for normal packets), resulting in somewhat larger scheduling/unscheduled intervals that can meet the latency requirements. The ratio of the scheduling/unscheduled intervals should correspond to the traffic volume of the normal and offloaded traffic.
5. *LTE + GPS receiver*: In this scenario, the LTE UE is also equipped with a GPS receiver to support location-based services.

14.4.3 In-device coexistence and interference avoidance

The LTE network-controlled UE-assisted solutions which were studied during LTE Rel-10 can be categorized as follows [1]:

- Frequency division multiplexing (FDM) based solutions include moving the LTE signal away from the ISM band, or moving the ISM signal away from the LTE frequency band (see Figure 14.10).
- Time division multiplexing (TDM) based solutions include DRX mode, HARQ process reservation, and uplink scheduling restriction.
- Power control-based solutions include LTE power control or ISM-band radio power control (see Figure 14.10).
- UE autonomous solutions include time-domain remedies such as LTE denials for infrequent short-term events, LTE denials for ISM data packets, and ISM denials for LTE important signals reception.

The RF filtering in the transmit side reduces the out-of-band (OOB) spurious emissions of the aggressor leaking into the receive band of the victim. The receive filter reduces the blocking effect due to the transmissions in the band of the aggressor technology. When two radios operate in adjacent bands, there can be limited attenuation of each filter in the transition band that overlaps with the designated band of the other technology. This can lead to a large interference to the victim, due to spurious emissions and imperfect blocking performance. In some cases, such as LTE Band 40 and the ISM band starting at 2400 MHz, there is no guard

band between the frequencies of the two technologies. There are further challenges in RF design due to variations in filter response across manufacturing processes, as well as a wide temperature range over which the terminal must operate [18].

As shown in Figure 14.11, in a typical UE implementation, the baseband processing modules of UMTS/LTE and ISM-band radios are separated, whether within the same chip from the same vendor or different chips from the same or different manufacturers. In either case, the two chips may exchange handshake signals, referred to as inter-chip handshaking and signaling, to convey real-time status and control information including advanced notice of future activities. This advanced notification signal can be used as a trigger to notify the serving eNB of forthcoming IDC conditions. The eNB can suspend normal UE LTE operation during the ISM-band radio activities and resume normal operation once the IDC condition is resolved. The IDC coordination module (typically proprietary) resides in the UE, as shown in Figure 14.11, and is responsible for coordination and prioritization among different collocated radios, obtaining and interpreting the coordination information from different radios, and generating control commands to different radio modules including but limited to generation of the IDC trigger messages in the uplink (to be transmitted via LTE transceiver module), interpretation of the IDC acknowledgment messages, and so on.

The IDC solutions for interference avoidance are mainly considered for the UE in RRC connected mode. The idle mode operation itself is not considered a problem since the UE can just stop ISM-band radio transmissions at important LTE events such as paging. There are three interference avoidance approaches that can be taken to address the IDC issues: (1) uncoordinated, where different radio technologies within the same UE operate independently without any internal coordination; (2) UE only, where there is an internal coordination between different radio technologies within the UE, which means that the activities of one radio are known by other radios. However, in this case the network is not

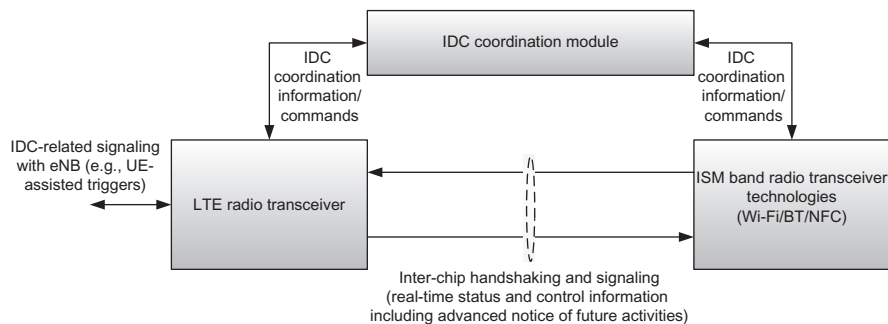


FIGURE 14.11

Example block diagram of the UE internal IDC signaling and coordination module.

aware of the coexistence issues experienced by the UE and is not involved in the coordination; and (3) network-coordinated with UE assistance, where different radio technologies within the UE are aware of possible coexistence problems and the UE can inform the network about such problems. The latter method is illustrated in Figure 14.11, and has become the basis for the solutions that have been developed in LTE Rel-11 for collocated multi-radio coexistence problems.

Based on the above assumption that different collocated radio modules can handshake and exchange (advance) information/notification about their current or upcoming activities, we now study the solutions that were developed in 3GPP to mitigate collocated multi-radio coexistence issues. It must be noted that other standardization organizations such as Wi-Fi Alliance [21] and Bluetooth Special Interest Group [20] have also taken steps on their side to find solutions that can alleviate or ideally resolve the in-device coexistence and interference problems. For example, BT devices may by default configure themselves as masters; thus, in-device BT may only behave as a BT slave under certain scenarios. On the 3GPP side, the standard solution in LTE Rel-11 enables the UE, with the assistance from the serving eNB, to resolve the IDC interference issues in situations where the actions taken by BT/Wi-Fi radios are not sufficient to solve the problem [18].

Based on RF analysis results, one straightforward solution to effectively mitigate or reduce the IDC interference is to let radio transceivers work in different frequency bands with sufficient frequency separation. The basic concept of an FDM-based solution is to move the victim (or aggressor) signal farther away from the aggressor (or victim) signal and increase the frequency separation for better filtering performance. An LTE FDM-based solution is to move the LTE signal farther away from the ISM band by performing inter-frequency handover within LTE according to the existing procedure specified in [3,4]. On the contrary, in the ISM FDM-based solution, the ISM radio signal is moved away from the LTE frequency band in the frequency-domain by switching the Wi-Fi channel in the portable router scenario, or by making use of the BT adaptive frequency hopping (AFH) feature to select a set of BT channels away from the LTE operating band (see Figure 14.9). The LTE FDM-based solution is applicable to all usage models as long as an alternative LTE frequency channel is available. In some deployments, using the FDM-based solution to resolve IDC interference problems may not be possible or desirable. As an example, the LTE FDM-based solution may not be applicable when all available LTE bands are impacted by ISM radio activities, the UE is in an area with only one LTE frequency band, or the UE does not have good channel quality in the alternative bands. It is also possible that the operator has alternative frequency bands, but those bands are congested due to a large number of active UEs. To ensure efficient network operation, it can be beneficial to balance load between RF bands and retain the UE in the current frequency, even if the LTE receiver is disturbed by the ISM signals. In that case, time multiplexing of LTE and ISM-band radios is more desirable [18].

In LTE TDM-based solutions, the basic idea is to time-multiplex the transmission or reception of different radios by either adapting the LTE transmission/reception timing to that of ISM-band radios, or vice versa. In LTE, DRX was adopted as a TDM-based solution for IDC interference avoidance. In the DRX mode, the UE is allowed to switch its LTE receiver off and stop monitoring the PDCCH. Since uplink transmissions are scheduled on the PDCCH, the gaps in PDCCH reception imply that uplink transmissions cannot be scheduled when the UE is in DRX mode. As a result, the time is divided into scheduled and unscheduled periods from the LTE device perspective. Unscheduled time can be used for ISM-band communication. To facilitate the DRX solution for coexistence of LTE and other radios, the UE should provide assisting information to the eNB.

The UE provides the eNB with a desired TDM pattern. For example, the parameters related to the TDM pattern can consist of periodicity of the TDM pattern and scheduling period (or unscheduled period), as shown in Figure 14.12. It is up to the eNB to decide and signal a suitable DRX configuration to the UE based on a UE suggested TDM pattern and other criteria. The scheduling period corresponds to the active time of DRX operation, while unscheduled period corresponds to the inactive time. The eNB would attempt to guarantee the unscheduled period using appropriate downlink/uplink scheduling, sounding reference signal transmission configuration, DRX command MAC control element usage, and so on. During the inactive time, the UE is allowed to delay the initiation of dedicated

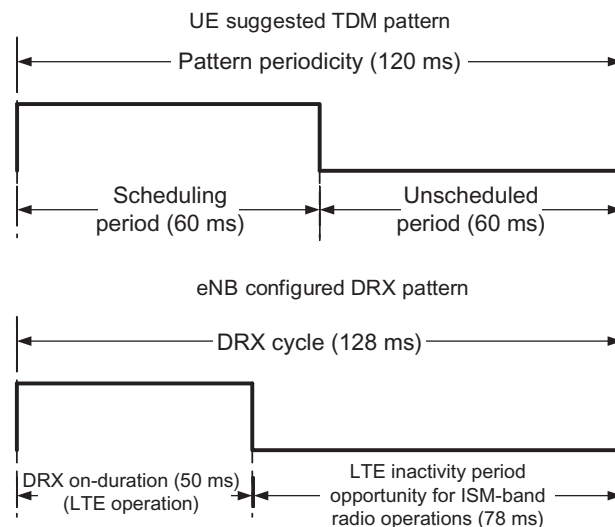


FIGURE 14.12

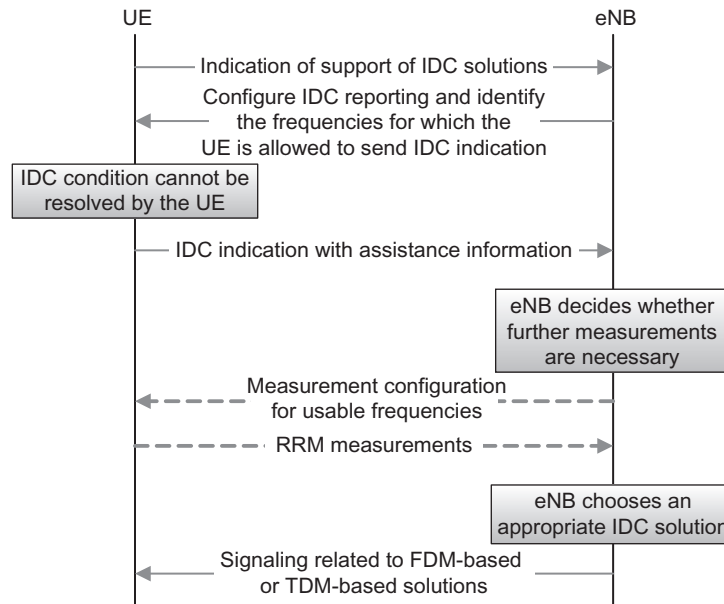
Example UE suggested TDM pattern and eNB configured DRX pattern [1].

scheduling request and/or random access procedure. Figure 14.12 illustrates an example where the eNB signals a DRX configuration based on a UE suggested pattern [1].

In the LTE + Wi-Fi off-load usage model introduced earlier, long scheduling and unscheduled periods are desired to enable completion of pending data transmissions. However, long periods would increase the latency of packet transmission. In addition, since in this scenario Wi-Fi acts as a terminal, it should be able to receive a beacon signal transmitted once every 102.4 ms. As a result, a suitable TDM pattern suggested by the UE should be 128 ms, where LTE occupies the first 60 ms. However, due to a limited number of DRX patterns in LTE, the eNB may configure the UE with a long DRX cycle of 128 ms and “on duration” of 40 ms. It should be noted that because of pending HARQ retransmissions in the LTE side, transition from scheduling time to unscheduled time is not unexpected. Therefore, LTE transmissions may stop before expiration of the on duration timer.

In an LTE + BT voice scenario, scheduling and unscheduled periods for each radio alternate much faster than in the Wi-Fi coexistence scenario. In enhanced synchronous connection oriented (eSCO) mode in BT [20], the transmission interval is 3.75 ms having six transmit/receive slots; thus, in order to maintain the minimum QoS requirements for voice conversation, the network should ensure at least a pair of correct BT transmit/receive instances in each BT interval of 3.75 ms. The remainder of the time can be allocated to LTE radio activities. The UE indicates to the network the desired subframes reservation bitmap (10 bits, one for each subframe). For short-term subframe reservation patterns, it is desirable that the pattern is consistent with uplink/downlink HARQ timing so that none of the HARQ processes is interrupted. Based on the assisting information, the network configures suitable DRX parameters.

In certain cases where the IDC interference condition cannot be predicted in advance, it is impossible to perform inter-frequency handover, or to provide unscheduled periods via DRX configuration. For example, one such condition may be the case where an unpredicted BT connection setup occurs and the DRX cannot be configured early enough to accommodate this critical communication. In another scenario, some critical signaling may occur irregularly where the UE can neither perform handover to an alternative band or be configured with a specific DRX configuration. Therefore, there are conditions where FDM-based or TDM-based schemes may not be applicable, and the UE has to deny LTE uplink transmissions autonomously to protect important signaling on other radios. However, the denial rate should be very low so that it does not significantly impact LTE operation. In addition to the TDM-based solution performed under the control of an LTE network, the UE may also use time-multiplex solutions through internal coordination. For example, the UE may terminate Wi-Fi or BT transmission when the LTE is receiving critical downlink signals. This would be useful to prevent disruption in the LTE signaling procedure as a result of unpredictable IDC interference from the ISM-band radios. Consequently, the

**FIGURE 14.13**

Signaling procedure for network-coordinated UE-assisted IDC resolution [18].

UE must carefully assess the IDC conditions before deciding on the best mitigation strategy in order not to compromise the performance and normal operation of the collocated radios.

Figure 14.13 illustrates the signaling procedure in network-coordinated UE-assisted IDC interference mitigation solution. When a UE experiences an IDC condition that cannot be locally resolved and network assistance is required, the UE sends an IDC indication via dedicated RRC signaling to report the problem [3]. The detail of the IDC indication trigger is left to UE implementation. The UE may rely on the existing LTE measurements and/or UE internal coordination. The IDC indication should be triggered based on ongoing IDC interference on the serving or non-serving frequencies, instead of assumptions or predictions of potential interference. A UE that supports IDC functionality indicates this capability to the network, and the network can then configure the UE through dedicated signaling whether the UE is allowed to send an IDC indication. The UE may only send an IDC indication for E-UTRA uplink/downlink RF carriers for which a measurement object is configured [4].

The term “ongoing IDC interference” should be treated as a general guideline by the UE. For the serving frequency, the ongoing interference may be related to the interference caused by an aggressor radio to a victim radio during either active data exchange or upcoming data activity which is expected in

a few hundred milliseconds. For a non-serving frequency, the ongoing interference may be an anticipation of the LTE radio becoming an aggressor or a victim, if it makes handover to a non-serving frequency. Similarly, concerning activation of secondary cells in the case of carrier aggregation, the ongoing interference may be an anticipation of the LTE radio becoming an aggressor or a victim. Ongoing interference may affect several subframes/slots. When the eNB is notified of an IDC condition through an IDC indication from the UE, the eNB can choose to apply an FDM-based or a TDM-based solution. To assist the eNB in selecting an appropriate solution, all necessary/available assisting information for both methods is sent together as part of IDC indication message to the eNB. The IDC assisting information contains the list of E-UTRA carriers suffering from ongoing interference, the direction of the interference and depending on the scenario; it may also contain preferred time-multiplex patterns or parameters to enable appropriate DRX configuration for the UE on the serving E-UTRA carrier. The IDC indication is also used to update the IDC assistance information, including the cases when the UE no longer encounters the IDC condition. In the case of inter-eNB handover, the IDC assisting information is transferred from the source eNB to the target eNB. The UE should only indicate that the IDC condition is over when it is not experiencing an IDC condition any more. The UE should not resend the same IDC indication message to the network, but it may resend the same IDC indication after handover. The IDC condition can be divided into three phases: (i) the UE detects the start of IDC condition but does not initiate the transmission of the IDC indication to the eNB; (ii) the UE has initiated the transmission of the IDC indication to the eNB and no solution is configured by the eNB to resolve the IDC issue; (iii) the eNB has provided the UE with a solution that resolves the IDC issue (Table 14.2) [3].

In addition, once configured by the network, the UE can autonomously deny LTE uplink transmission in all phases to protect ISM-band transmission in special circumstances, if other solutions cannot be used. On the other hand, it is assumed that the UE also autonomously denies ISM-band transmission to ensure LTE connectivity to the eNB in order to perform LTE procedures, e.g., RRC connection reconfiguration and paging. The network may configure a long-term denial rate by dedicated RRC signaling to limit the amount of LTE uplink autonomous denials. Otherwise, the UE must not perform any LTE uplink autonomous denials [3].

In summary, the IDC interference level and its impact on the receiver performance depends on transmit power and receiver blocking characteristic of each radio and physical characteristics of transceivers (e.g., filter responses, antenna isolation). The following conclusions were drawn from the analyses performed in 3GPP related to this work item:

- For most cases, we observe that frequency-domain solutions, i.e., moving to other frequencies, and RF filtering can sufficiently suppress the coexistence interference.

Table 14.2 RRM, RLM, CSI Measurements in Different Phases of IDC Interference [3]

Phases of IDC Interference	RRM Measurements	RLM Measurements	CSI Measurements
Phase 1	It is up to the UE implementation and RRM measurement requirements	It is up to the UE implementation and RLM measurement requirements	It is up to the UE implementation and CSI measurement requirements
Phase 2 (If the UE determines that the network does not provide a solution that resolves its IDC problem, it performs measurements)	The UE is required to ensure that the measurements are free of IDC interference	The UE is required to ensure that the measurements are free of IDC interference effects. The UE should maintain LTE connectivity in this phase, meaning that RLM measurements are not impacted by IDC interference. If no solution is provided within a time, which is up to UE implementation, the UE may declare RLF or it may continue to deny the ISM transmission	—
Phase 3 (If the IDC indication message reports the IDC condition on a neighbor frequency, the UE performs RRM measurements for that frequency)	The UE is required to ensure that the measurements are free of IDC interference	The UE is required to ensure that the measurements are free of IDC interference effects	—

Table 14.3 LTE Blocking Levels for Bluetooth and Wi-Fi Receivers for Different LTE Transmit Powers and Operating Bands [1]

LTE Transmit Power (dBm)	Blocking with FBAR Filter (dBm)				
	2300–2370 MHz	2360–2380 MHz	2380–2400 MHz	2500–2520 MHz	2520–2570 MHz
23	–34	–28	7	–37	–40
21	–36	–30	5	–39	–42
19	–38	–32	3	–41	–44
17	–40	–34	1	–43	–46
15	–42	–36	–1	–45	–48
13	–44	–38	–3	–47	–50
11	–46	–40	–5	–49	–52
9	–48	–42	–7	–51	–54
7	–50	–44	–9	–53	–56
5	–52	–46	–11	–55	–58
3	–54	–48	–13	–57	–60
1	–56	–50	–15	–59	–62
–1	–58	–52	–17	–61	–64
–3	–60	–54	–19	–63	–66
–5	–62	–56	–21	–65	–68
–7	–64	–58	–23	–67	–70
–9	–66	–60	–25	–69	–72

- For the uppermost region of LTE Band 40 (2380–2400 MHz), LTE transmitting with the maximum power of 23 dBm can block the Wi-Fi or BT signal in the entire ISM band, thus limiting the maximum LTE transmit power below 23 dBm, moving LTE signal away from ISM, or TDM-based solution needs to be considered (Table 14.3).
- For 2300–2380 MHz in LTE Band 40, Wi-Fi or BT desense due to the LTE interference may be acceptable except for the lower 20 MHz of the ISM band, since the performance of the state-of-the-art film bulk acoustic resonator (FBAR) filtering²,

²FBAR filters are a form of bulk acoustic wave (BAW) filter that have superior performance with steeper rejection curves compared to surface acoustic wave (SAW) filters. The FBAR filters also feature 0.3–0.5 dB less insertion loss, resulting in up to 50 mA less current consumption, thereby improving battery life and talk time of the mobile devices. A thin-film bulk acoustic resonator is a device consisting of a piezoelectric material contained between two electrodes and acoustically isolated from the surrounding medium. The FBAR devices using piezoelectric films with thicknesses ranging from several micrometers down to tenths of micrometers resonate in the frequency range of approximately 100 MHz to 10 GHz. Aluminum nitride and zinc oxide are two common piezoelectric materials used in FBARs [19].

device OOB/spurious emissions, sensitivity, and blocking of implementations are typically better than specification limits. Additionally, limiting the number of data/control bearing resource blocks and assigning resources away from the ISM band, which directly impact the OOB emissions, can help reduce desensitization to the lower 20 MHz of the ISM band.

Table 14.3 shows LTE blocking for Wi-Fi and BT receivers for different LTE transmit powers and operating bands in E-UTRA Band 40 and Band 7. As shown in Table 14.3, a cell-edge UE with maximum transmitting power of 23 dBm in the uppermost 20 MHz segment of Band 40 can result in a maximum of 7 dBm OOB blocking interference³ in the Wi-Fi/BT receiver. The LTE transmit power level needs to be limited for the simultaneous operation with ISM-band reception, if the LTE transceiver is operated in the upper 20 MHz of Band 40. The maximum allowed LTE transmit power for coexistence varies depending on the blocking characteristics of the Wi-Fi/BT receivers [1].

The RF analyses conducted in 3GPP related to the IDC interference between ISM-band and LTE technologies, and the conclusions that were made and documented as a result of those analyses were mainly based on four information sources. The analyses and measurements presented in 3GPP TR 36.816 [1] indicate that for some IDC scenarios, significant degradation on both LTE and ISM-band radios can occur despite the use of state-of-the-art RF filtering technology. The precise quantitative results differed from one source to another due to different assumptions in the analyses or the measurement approaches. Nonetheless, the conclusions were consistent in that at least a significant fraction of spectrum is highly desensitized when the other technology is transmitting. The assumptions used by those sources in the simulation or measurements presented to 3GPP are summarized in Table 14.4.

³Radio receiver blocking or receiver desensitization is an important parameter for any radio receiver. A good radio receiver blocking or desensitization performance is particularly important in the scenarios where a number of radios of various forms are used in close proximity to each other. With wireless communications being used for everything from Wi-Fi to cellular communications and Bluetooth, as well as many more traditional applications, there are many instances where two radios operate very close to each other, and the receiver blocking performance will be very critical. Blocking rejection is the ability of a receiver to tolerate an OOB signal and avoid blocking. A good automatic gain control design is part of achieving good blocking rejection. When a very strong OOB signal appears at the input of a receiver, it is often found that the sensitivity is reduced. The effect arises because the front-end amplifiers are saturated as a result of the strong OOB signal. This often occurs when a receiver and transmitter are operated from the same site and the transmitter signal is exceedingly strong. When this occurs, it has the effect of suppressing all the other signals trying to pass through the amplifier, giving the effect of a reduction in gain. Blocking is generally specified as the level of the unwanted signal at a given offset, which will give a 3-dB reduction in gain. Depending on the type of receiver, the values for blocking will vary considerably. As a reference point, a good radio receiver should be able to withstand blocking signals of about 10 dBm before this effect becomes noticeable.

Table 14.4 Assumptions for the RF Analyses in 3GPP IDC Studies [1]

Parameter	Analysis 1	Analysis 2	Analysis 3	Analysis 4
LTE frequency band	40 and 7	40 and 7	40	40 and 7
ISM radio	BT, Wi-Fi	Wi-Fi	Wi-Fi	BT, Wi-Fi
Interference directions considered for B and 40	LTE to BT/ Wi-Fi; BT/Wi-Fi to LTE	LTE to Wi-Fi; Wi-Fi to LTE	LTE to Wi-Fi	LTE to BT/ Wi-Fi; BT/Wi-Fi to LTE
Interference mechanisms	Spurious emission and blocking	Spurious emission and blocking	Spurious emission	Spurious emission and blocking
RF filtering method	FBAR	No filters external to test setup	Commercially available filter (typical/minimum)	FBAR
Antenna isolation (dB)	12	15, 20, 25	12	12
LTE transmitter power (dBm)	23	23	N/A	0, 15, 23
Wi-Fi transmitter power (dBm)	20	20	20	20, 14.5
BT transmitter power (dBm)	10	N/A	N/A	4, 0
LTE RSSI as victim (dBm)	−94	−70	−94	−94 (Band 40) −92 (Band 7)
Wi-Fi RSSI (dBm)	−79	−50	N/A	−89, −76
BT RSSI (dBm)	−90	N/A	N/A	−70
LTE bandwidth (MHz)	20	25–100 resource blocks (over 20)	20	20
Wi-Fi bandwidth (MHz)	22	22	22	22
BT bandwidth (MHz)	1	N/A	N/A	1
Performance measure	Desensitization (dB)	EVM	Desensitization (dB)	Desensitization (dB)

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Positioning and Multimedia Broadcast/Multicast Services

15

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In this chapter, we take a top-down systems approach to describe two important service enablers of LTE/LTE-Advanced that both started in LTE Rel-9 and have been enhanced in the later releases. The UE positioning and location-based services, as well as the evolved multimedia broadcast/multicast services (E-MBMS), are considered the key enablers of various services in modern cellular systems. There are numerous applications that rely on these functionalities to provide the

users with the best quality of experience and ease of access to location-optimized and customized content.

This chapter begins with the description of the positioning standard for LTE/LTE-Advanced systems. We review the positioning requirements, positioning architectures, and signaling. The coordinate systems and the transformations used in positioning systems are described in detail. There are many different use cases for positioning information. The positioning functions may be used internally by the EPS, value-added network services, the UE itself, or through the network by a third party. While the location-based services may be used for emergency services (which may be mandated), the feature has not been exclusively developed for emergencies.

We will then describe the E-MBMS feature in LTE/LTE-Advanced. The E-MBMS bearer service is the service provided by the packet-switched domain to E-MBMS user services in order to deliver IP multicast¹ datagrams to multiple receivers using minimal network and radio resources. An E-MBMS user service is a service provided to the end user by means of the MBMS bearer service, and possibly other EPS bearers. The E-MBMS is a point-to-multipoint service in which data is transmitted from a single source entity to multiple recipients. Transmitting the same data to multiple recipients allows the sharing of network resources. The E-MBMS for EPS bearer service supports broadcast mode over E-UTRAN and UTRAN. The E-MBMS is realized by the addition of a number of new features and new functional entities to the 3GPP network architecture.

An E-MBMS counting function was introduced that allows counting the number of connected mode users that are either receiving or are interested in receiving particular MBMS services. In LTE Rel-11, E-UTRAN MBMS is enhanced to ensure service continuity when multi-carrier functionality is deployed in an MBMS service area. The MBMS services may be deployed on different frequencies over different geographic areas. LTE Rel-11 enhancements allow the network to inform MBMS-capable devices of information related to MBMS deployment, such as carrier frequencies and service area identities (SAIs). In LTE Rel-11, an MBMS-capable device can inform the network of its interest in MBMS services by indicating the carrier frequencies associated with the MBMS services of interest. The MBMS interest indication by the device also allows the device to indicate the priority between MBMS service and unicast service. The network uses the MBMS interest indication provided by the device for mobility management decisions so that the device is always able to use its receiver at the appropriate carrier frequency to ensure continuity of MBMS services. In idle mode, an MBMS-capable device can prioritize a particular carrier frequency during cell reselections depending on the availability of the MBMS service of interest on that carrier frequency. To ensure

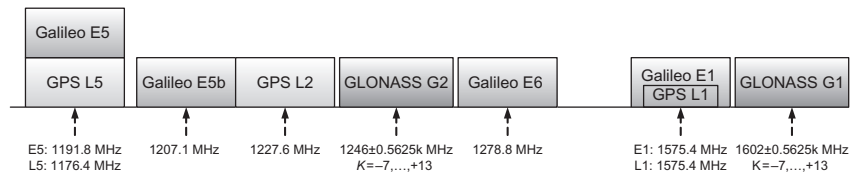
¹IP multicast is a method of transmitting IP datagrams to a group of interested receivers in a single transmission. It is often employed for streaming media applications on the Internet and private networks. The method is the IP-specific version of the general concept of multicast networking. It uses especially reserved multicast address blocks in IPv4 and IPv6. In IPv6, IP multicast addressing replaces broadcast addressing as implemented in IPv4. IP multicast is described in IETF RFC 1112 [20].

MBMS service continuity in connected mode, the MBMS interest indications received from the device are signaled to the target cell as part of handover preparation procedure [4].

15.1 Positioning and location-based services

Positioning defines the process of determining the position and/or velocity of a device using radio signals. Location-based services are considered a significant feature of the modern cellular networks which allow the users to locate themselves and each other, as well as enable the mobile applications to offer services and information customized to the current users' locations. In addition to the commercial usage, there are also public safety applications for positioning. As an example, an emergency call made from a mobile device can be tracked and sufficiently accurate location of the caller can be determined, even though the caller may not know where he/she is. Many government regulatory organizations around the world have made support of accurate positioning functionality mandatory for all mobile devices. In the United States, it is mandatory for network operators to support FCC's Enhanced 911², making the location of a cell phone available to emergency call dispatchers. With this mandate, the FCC has defined accuracy requirements for different position estimation methods. Cellular network operators are responsible for positioning wireless terminals with an accuracy of 50 and 150 m in 67% and 95% of all positioning attempts, respectively. These figures are valid for UE-based positioning methods, i.e., where the positioning method involves functionality located in the UE such as global positioning system (GPS) receiver hardware. The requirements for network-based methods, without such UE functionality, are 100 m (67%) and 300 m (90%) [17]. These are stringent accuracy requirements that need to be fulfilled and guaranteed no matter what position estimation technology is used, or in which environment the position

²The FCC's wireless Enhanced 911 (E911) requirements seek to improve the effectiveness and reliability of wireless 911 services by providing the dispatchers with additional information on wireless 911 calls. The FCC's wireless E911 rules apply to all wireless licensees, broadband personal communications service (PCS) licensees, and certain specialized mobile radio (SMR) licensees. The FCC has divided its wireless E911 program into two phases: Phase I and Phase II. Under Phase I, the FCC requires carriers, within 6 months of a valid request by a local public safety answering point (PSAP) to provide the PSAP with the telephone number of the originator of a wireless 911 call and the location of the cell site or base station transmitting the call. Under Phase II, the FCC requires wireless carriers, within 6 months of a valid request by a PSAP to begin providing information that is more precise, specifically, the latitude and longitude of the caller. This information must meet FCC accuracy standards, generally within 50–300 m, depending on the type of technology used. The deployment of E911 requires the development of new technologies and upgrades to local 911 PSAPs, as well as coordination among public safety agencies, wireless carriers, technology vendors, equipment manufacturers, and local wireline carriers [17].

**FIGURE 15.1**

Frequency bands used by prominent positioning methods [15].

is estimated (i.e., indoor or outdoor). Determining a user's device position is traditionally based on satellite-based position estimation using Global Navigation Satellite Systems (GNSS) such as GPS. Figure 15.1 provides the frequency bands of the prominent global positioning systems.

The majority of modern mobile devices have an integrated GNSS receiver. To properly estimate the position, the receiver needs to have an unobstructed line of sight to at least four satellites, and this is one of the main drawbacks of GNSS-based methods. In indoor environments, line of sight reception of the low-power radio signals transmitted from the medium-earth-orbit satellites is not guaranteed, if not impossible. To overcome this limitation, especially in an environment with poor signal conditions, Assisted-GNSS (A-GNSS) methods have been developed, e.g., Assisted-GPS. In A-GPS, a cellular network uses network resources to provide assistance data that helps the device to locate and utilize the available GPS satellites faster. A-GNSS reduces start-up and acquisition times, increases sensitivity, and reduces the UE's power consumption. While there is often an acceptable coverage by a cellular network to determine the A-GPS information, this does not help if the satellites cannot be detected due to extremely weak reception of GPS signals inside a building. In that case, position estimation using radio signals is more feasible. In GSM, position estimation based on radio signals has been around for many years. As mobile broadband technology advances and the demand for more accurate positioning and location-based services increases, more sophisticated and accurate positioning methods have been developed. In this section, we will only focus on the positioning methods developed for E-UTRA.

The positioning methods supported in LTE mainly rely on the high-level network architecture as shown in Figure 15.2. The positioning network architecture has been defined in such a way that it is generally independent from the underlying network. There are three main entities in this architecture, location service (LCS) client, LCS server, and LCS target. An LCS client is the entity requesting the service and in the majority of the cases is located in the LCS target. This service obtains the location information by sending a request to the server. The location server is a physical or logical entity that collects measurements and other location information from the device and base station, and assists the device with measurement and estimation of its position. The server processes the request from the client and provides the client with the requested information [15,18].

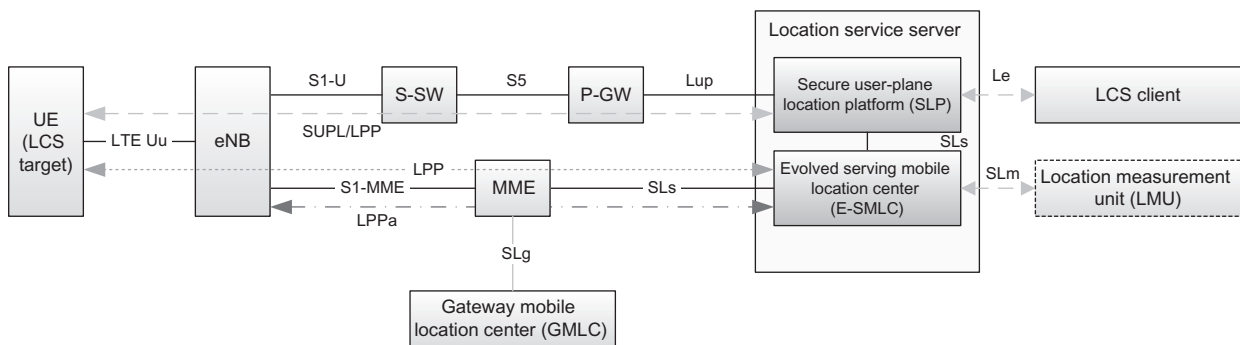


FIGURE 15.2

E-UTRA location service architecture [7,15].

15.1.1 E-UTRA positioning network architecture

Some location-based services are targeted at individual users, while others are focused on aggregated user behavior that will be of value to enterprises and application and content providers. In general, the services can be grouped into the following categories [12]:

- Regulatory-based applications such as emergency call services.
- Consumer applications, such as social networking, service finder, and navigation services.
- Business applications such as fleet management or social networking tailored to business needs.
- Third-party applications that enable merchants or application and content providers to target specific end users for their advertising or services.
- Network operator applications that help detect internal problems, or optimize networks and business capabilities.

Given that location-based services have generally diverse requirements, the communication service providers must carefully identify and prioritize a particular service's requirements before choosing methods of gathering and delivering location information. The following list summarizes some of the most important general requirements [12]:

- Providing the required degree of location accuracy.
- Promptness of response to a location request.
- Scalability to support a large number of user locations.
- Support for real-time, periodic, or event-triggered location updates.
- Ease of implementation.
- Battery consumption for mobile devices.
- Impact on network resources.
- Differentiation of the network provider service from application and content providers offerings.

The EPS provides several methods for delivering location information when it is determined. Each method has certain capabilities, strengths, and constraints, which necessitate satisfaction of the unique requirements of each specific service.

The user-plane method requires minimal interaction with the underlying wireless access technologies; thus, this method can be used ubiquitously across LTE and the legacy networks. It is also scalable, which makes it well suited to support commercial location-based services with less complexity, cost, and impact on the network than the control-plane solution. This solution relies on user-plane data bearers to transfer location-assistance and positioning-related messages between the secure user-plane location³ (SUPL)-enabled terminal (SET) and the SUPL location platform

³SUPL is an IP-based protocol for assisted-GPS in order to receive positioning information of GPS satellites faster via IP connections instead of slow GPS satellite links.

(SLP). An SUPL client is required on the user device. Lack of direct connection to the access network is a disadvantage for supporting positioning methods, which require assistance data from the network. In addition, because this solution can only enable single-user location requests, it is not suitable for applications that need periodic reporting on all user locations within a cell or zone. Depending on the location technology used, the user-plane solution can support a high level of accuracy to meet the needs of the majority of location-based services targeted at the individual user, such as turn-by-turn navigation and fleet management.

In the control-plane method, which was specified in LTE Rel-9, positioning data is transferred over the control-plane, between the UE, the eNB, and the positioning elements, i.e., evolved serving mobile location center/gateway mobile location center (GMLC). This method provides convenient access to assistance data from the network, and enables more reliable service performance than the user-plane solution. Since the control-plane method does not require a client on the UE, it can be used to support emergency services on LTE networks for limited service devices. On the other hand, this solution has less scalability than the user-plane, only supports single-user location requests, and is more difficult to interwork with legacy networks.

The 3GPP legacy technologies (GSM and UMTS) have supported LCS network architecture for the purpose of positioning mobile devices since 3GPP Rel-4. With the introduction of EPS in 3GPP Rel-8, control-plane location-service architecture for the EPS was introduced in 3GPP Rel-9. Figure 15.2 illustrates the control-plane location service architecture for the EPS, which introduced new interfaces SLg and SLs, and allowed the EPS control-plane element mobility management entity to interconnect with the location service core network elements, making location services using the positioning functionality provided by the E-UTRAN possible.

The location service architecture follows a client/server model with the GMLC acting as the location server providing location information to location service clients. The GMLC sends location requests to the evolved serving mobile location center (E-SMLC) through the MME to retrieve this location information. The E-SMLC is responsible for interaction with the UE through E-UTRAN to obtain the UE position estimate or to obtain position measurements that help the E-SMLC to estimate the UE position. Note that the GMLC interaction over the interfaces connected to it other than SLg was already available before 3GPP Rel-9 for GSM and UMTS access.

The location service clients can be part of the core network or external to the core network, and can also reside in the UE or be attached to the UE. Depending on the location of the location service client, the location request initiated by the location service client may be a mobile-originated, mobile-terminated, or network-induced location request. Emergency location service is possible even if the UE does not have a valid service subscription due to regulatory mandates. Support of location service-related functionality in the E-UTRAN, MME, and UE are optional. The location service is applicable to any target UE, no matter

whether the UE supports location service. The following is a description of various LCS architectural elements and interfaces shown in [Figure 15.2 \[18\]](#):

- *Gateway mobile location center*: This entity receives and processes location requests from location service clients; obtains routing information from the home subscriber server; performs registration authorization; communicates information needed for authorization, location service requests, and location information with other GMLC; checks the target UE privacy profile settings; and depending on roaming support, it may assume the role of requesting GMLC, visited GMLC, or home GMLC.
- *Evolved serving mobile location center*: This entity manages the overall coordination and scheduling of resources required for the location determination of a UE that is attached to E-UTRAN. It calculates the final location and estimates velocity, as well as the location accuracy. It interacts with the UE to exchange location information applicable to the UE-assisted and the UE-based positioning methods. It interacts with the E-UTRAN to exchange location information applicable to the network-assisted and the network-based positioning methods.
- *Mobility management entity*: This entity is responsible for UE subscription authorization. It coordinates location services and positioning requests. It handles charging and billing, and performs E-SMLC selection (e.g., based on network topology to balance the load on E-SMLC, location service client type, and requested QoS). It is further responsible for authorization and operation of the location service.
- *Home subscriber server*: This entity is used for storage of location services subscription data and routing information.
- *Location measurement unit*: The location measurement unit (LMU) conducts measurements and communicates the measurements to an E-SMLC. All positioning measurements obtained by an LMU are supplied to the E-SMLC that made the request. A UE positioning request may involve measurements by multiple LMUs. The SLM interface between the E-SMLC and the LMU is used for uplink positioning. It is used to transport SLM-application protocol (AP) messages over the E-SMLC-LMU interface. Both stand-alone LMU and LMU integrated into an eNB are supported in LTE Rel-11.

Two protocols are used for the overall information exchange concerning location services: (i) LTE positioning protocol (LPP); and (ii) LTE positioning protocol annex (LPPa). The latter protocol is used for communication between the location server and the eNB. The base station (when using the observed time difference of arrival (OTDOA) method) is in charge of properly configuring the radio signals that are used by the terminal for positioning measurements, i.e., positioning reference signals (PRSs). It further provides information to the E-SMLC; it enables the device to conduct inter-frequency measurements, if required; and based on the E-SMLC request, it conducts measurements and sends the results to the server. The LPP can be used in the user-plane and control-plane methods. The LPP is a

point-to-point protocol that allows multiple connections to different devices. The exchanged LPP messages and information can be divided into four categories:

1. UE positioning capability information transfer to the E-SMLC.
2. Positioning assistance data delivery from the E-SMLC to the device.
3. Location information transfer.
4. Session management.

The SLm-AP (application protocol), terminated between the E-SMLC and the LMU, is used to support the following functions: (i) delivery of target UE configuration data from the E-SMLC to the LMU; and (ii) request of positioning measurements from the LMU and delivery of positioning measurements to the E-SMLC. The SLm-AP is directly used between the E-SMLC and the LMU.

The MME receives a request for location service associated with a particular target UE from another entity (e.g., GMLC, eNB, or UE), or the MME by itself decides to initiate some location service on behalf of a particular target UE (e.g., for an IP multimedia subsystem (IMS) emergency call from the UE). The MME then sends a location service request to the E-SMLC. The E-SMLC processes the location service request, which may include transferring assistance data to the target UE to help UE-based and/or UE-assisted positioning. The E-SMLC then returns the result of the location service to the MME, e.g., a position estimate for the UE and/or an indication of any assistance data transferred to the UE. In the case of a location service requested by an entity other than the MME (e.g., UE, eNB, or E-SMLC), the MME returns the location service result to this entity.

The UE positioning is an access network function (e.g., GERAN, UTRAN, and E-UTRAN). An access network may support one or more UE positioning method, which may be the same or different from another access network. In E-UTRAN, the following UE positioning methods are supported: Cell ID (CID)-based; enhanced Cell ID (E-CID)-based; downlink OTDOA; and network-assisted GNSS positioning methods. Determining the position of a UE involves two main steps: (i) radio signal measurements; and (ii) position and optionally velocity estimation based on the measurements. The signal measurements may be conducted by the UE or the E-UTRAN. Both TDD and FDD radio interfaces will be supported in E-UTRAN positioning methods. The basic signals measured for terrestrial position methods are typically the E-UTRA radio transmissions. Other transmissions such as general radio navigation signals, including those from global navigation satellites systems, can also be measured. The position estimation may be performed in the UE or in the E-SMLC. In UE-assisted positioning, the UE performs the downlink radio measurements and the E-SMLC estimates the UE position, while in UE-based positioning, the UE performs both downlink radio signal measurements and position estimation. The UE may require some assistance from the network in the form of assistance data in order to perform the downlink measurements, and these are provided by the network either autonomously or upon UE request. The E-UTRAN positioning capabilities are intended to be forward compatible to other access types and

other positioning methods, in an effort to reduce the amount of additional positioning support needed in the future [7].

15.1.2 Network-based and UE-based positioning methods

A network service provider needs to select an appropriate method for determining the location of a user device, based on the service requirements that have been identified. There are three primary network-enabled modes of operation for determining a user's location. In the UE-based mode, the user device obtains location measurements with assistance from the network and calculates the user's position. In the device-assisted mode, the user device provides positioning measurements, which the network uses to calculate the user's location. In the network-based mode, the network calculates the user's position without involving the device. The following location technologies support one or more of the above modes.

The differentiation between supported positioning methods is based on two facts. First, what the “measurement entity” is, which could only be the device or the base station. Second, what the “position estimation entity” is. The terms “-based” and “-assisted” refer to the node that is responsible for performing the positioning calculation (which may also provide measurements), and a node that provides measurements (but does not perform the positioning calculation), respectively. Thus, an operation in which measurements are provided by the UE to the E-SMLC to be used in the calculation of a position estimation is described as “UE-assisted” (and alternatively “E-SMLC-based”), whereas one in which the UE calculates its own position is described as “UE-based.” With that knowledge, the positioning methods supported in LTE can be further categorized. Table 15.1 provides an overview of supported positioning methods in LTE.

In Table 15.1, A-GPS refers to the case where the network assists GPS-enabled mobile devices to improve the performance of their GPS receivers by providing assistance information such as reference time, visible satellite list, reference position, and satellite ephemeris. In general, A-GPS provides the highest accuracy of any network-enabled technique. However, it is not reliable in indoor or in dense urban or high-rise building environments, in which case A-GPS can be supplemented with other techniques such as downlink OTDOA or E-CID. In CID-based methods, a user device is located within the coverage area of its serving eNB, typically to the specific cell/sector within the eNB. Although this method is the least accurate one, it is the easiest to implement, and highly scalable. In E-CID-based methods, the position of the UE is determined to a finer level compared to the CID-based method, using additional radio signal measurements. This method has low accuracy (50–1000 m) depending on the size of the cell, but it is easier to implement than other methods, and is generally available across diverse vendor products and networks. Downlink OTDOA uses the measured timing of downlink signals received from multiple eNBs to locate the user device in relation to neighboring eNBs. In dense urban and indoor environments, OTDOA can be used to supplement A-GPS, provided that the user device can

Table 15.1 E-UTRA UE Positioning Methods [7]

3GPP Release	Method	UE-based	UE-Assisted (E-SMLC-Based)	LMU-Assisted/ E-SMLC-Based	eNB-Assisted	Secure User-Plane Location
9	A-GNSS	Yes Measurement: UE Estimation: UE	Yes Measurement: UE Estimation: LCS server	No	No	Yes (UE-based and UE-assisted)
9	Downlink OTDOA	No	Yes Measurement: UE Estimation: LCS server	No	No	Yes (UE-assisted)
9	Enhanced Cell-ID	No	Yes Measurement: UE Estimation: LCS server	No	Yes Measurement: eNB Estimation: LCS server	Yes (UE-assisted)
11	Uplink TDOA	No	No	Yes	No	No

detect PRSs transmitted from three or more eNBs. The uplink time difference of arrival (UTDOA) has been specified as part of LTE Rel-11, and has minimal impact on air-interface resources. This uplink positioning method makes use of the measured timing at multiple LMUs of uplink signals transmitted from the UE. The LMU measures the timing of the received signals using assistance data received from the positioning server, and the resulting measurements are used to estimate the location of the UE.

15.1.3 Positioning methods in LTE/LTE-Advanced

The positioning feature provides a means to determine the geographic location and/or velocity of the UE based on measuring radio signals. The position information may be requested by and reported to a client (e.g., an application) associated with the UE, or by a client within or attached to the core network. The position information is reported in standard formats such as those for cell-based or geographical coordinates, together with the estimated errors (uncertainty) in the position and velocity estimation as well as the positioning scheme(s) used to obtain the position estimate.

The uncertainty of the position measurement is dependent on network implementation and is controlled by the network operator. The uncertainty may vary between networks, as well as from one area within a network to another. The uncertainty may be hundreds of meters in some areas and only a few meters in others. In the event that a particular position measurement is provided through a UE-assisted process, the uncertainty may also depend on the capabilities of the UE. The uncertainty of the position information is dependent on the method used, the position of the UE within the coverage area, and the activity of the UE. Several design options of the E-UTRAN system (e.g., size of cell, adaptive antenna technique, path loss estimation, timing accuracy, and eNB surveys) allow the network operator to choose a suitable and cost-effective UE positioning method. The following assumptions are made for the operation of UE positioning in E-UTRAN [7]:

- The positioning method is equally applicable to TDD and FDD systems.
- The provision of the UE positioning function in EPS is optional through support of the specified methods in the eNB and the E-SMLC.
- UE positioning is applicable to any target UE, no matter if the UE supports location service, but with restrictions on the use of certain positioning methods depending on UE capability [6].
- The positioning information may be used for internal system operations to improve system performance.
- The location service architecture and functions include the option to accommodate several techniques of measurement and processing to ensure adaptability to the future technologies and service requirements.
- The LMU aspects are implementation-specific.

The following sections describe the specific positioning methods that are specified in E-UTRAN specifications as of LTE Rel-11.

15.1.3.1 Principles of GPS

The GPS is a space-based satellite navigation system that provides location and time information in all weather conditions, anywhere on or near the earth where there is an unobstructed line of sight to four or more GPS satellites. The system provides critical capabilities to military, civil, and commercial users around the world. It is maintained by the United States government, and is freely accessible to anyone with a GPS receiver.

A GPS receiver calculates its position by precisely timing the signals sent by GPS satellites in medium earth orbits. Each satellite continuously transmits messages that include the time at which the message was transmitted, and the satellite position at the time of message transmission. The receiver uses the messages it receives to determine the transit time of each message and computes the distance to each satellite. Each of these distances and satellites' locations define a sphere. The receiver is on the surface of each of these spheres when the distances and the satellites' locations are correctly calculated. These distances and satellites' locations are used to compute the location of the receiver using the navigation equations. This location is then displayed, perhaps with a moving map display or latitude and longitude; elevation information may be included. Many GPS units show derived information such as direction and speed, calculated from position changes.

In typical GPS operation, four or more satellites must be visible to obtain an accurate result. Four sphere surfaces typically do not intersect; thus, we can confidently conclude that when we solve the navigation equations to find an intersection, this solution gives us the position of the receiver along with accurate time, thereby eliminating the need for a very large, expensive, and power-consuming clock. The very accurately computed time is mainly used only for display and is not utilized in many GPS applications, which use only the location. However, a number of applications for GPS do use this highly accurate timing.

The receiver uses the messages received from satellites to determine the satellites' positions and the transmission times. Let (x_i, y_i, z_i, t_i) denote the coordinates of the i th satellite position and the transmission time, where the subscript $i = 1, 2, 3, \dots, N$ is the satellite number, assuming $N \geq 4$. When the transmission time of message reception is indicated by the local clock t_r , the true reception time is going to be $t_r + t_{\text{bias}}$, where t_{bias} denotes the receiver's clock bias. The message transit time is $t_r + t_{\text{bias}} - t_i$. Assuming the message is traveling at the speed of light, the distance traveled is calculated as $(t_r + t_{\text{bias}} - t_i)c$. Having the knowledge of the distance between the receiver and the satellite, and the satellite's position, implies that the receiver is on the surface of a sphere centered at the satellite's position with radius equal to this distance. Thus, the receiver is at or near the intersection of the surfaces of the spheres if it receives signals from more than one satellite. In the

ideal case with no errors, the receiver is at the intersection of the surfaces of the spheres [13].

The clock error or bias t_{bias} is the amount that the receiver's clock is off. The receiver has four unknowns, the three coordinates of the GPS receiver position, and the clock bias $(x, y, z, t_{\text{bias}})$. The equations of the sphere surfaces are given by $(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = (t_r + t_{\text{bias}} - t_i)^2 c^2 \quad i = 1, 2, 3, \dots, N$. These equations can be solved by algebraic or numerical methods.

Each GPS satellite continuously broadcasts a navigation message on the L1 C/A and L2 P/Y frequencies (see Figure 15.1) at a rate of 50 bps. Each message takes 750 s to be completely received. The message structure has a basic format of a 1500-bit long frame comprising five subframes, each subframe having 300 bits (6 s) long. Subframes 4 and 5 are sub-commutated 25 times each, so that a complete data message requires the transmission of 25 full frames. Each subframe consists of 10 words, each 30 bits long. Thus, with 300 bits in a subframe, times 5 subframes in a frame, times 25 frames in a message, each message is 37,500 bits long. At a transmission rate of 50 bps, it would take 750 s to transmit the entire almanac message. Each 30-s frame begins precisely on the minute or half-minute as indicated by the atomic clock on each satellite [13].

The first subframe of each frame encodes the week number and the time within the week, as well as the data about the condition of the satellite. The second and the third subframes contain the ephemeris or the precise orbit for the satellite. The fourth and fifth subframes contain the almanac, which contains coarse orbit and status information for up to 32 satellites in the constellation, as well as data related to error correction. Thus, in order to obtain an accurate satellite location from the transmitted message, the receiver must demodulate the message from each satellite it includes in its solution for 18–30 s. In order to collect the transmitted almanacs, the receiver must demodulate the message for 732–750 s [13].

All satellites broadcast at the same frequencies. Signals are encoded using code division multiple access (CDMA) codes, allowing messages from individual satellites to be distinguished from each other based on unique encodings for each satellite that the receiver must be aware of. Two distinct types of CDMA encodings are used: the coarse/acquisition code, which is accessible by the general public; and the precise code, which is encrypted so that only the US military can access it. The ephemeris is updated every 2 hours and is generally valid for 4 hours, with provisions for updates every 6 hours or longer in non-nominal conditions. The almanac is updated typically every 24 hours. Figure 15.3 illustrates the overall structure of the GPS frame.

It would take 12.5 min to download the entire almanac, and it would take even longer if the signal quality becomes poor and the receiver fails to correctly decode any portions of this data. To determine the location of the GPS satellites, two types of data are required by the GPS receiver: the almanac and the ephemeris. This data is continuously transmitted by the GPS satellites, and the GPS receiver collects and stores this data. The almanac data is data that describes the

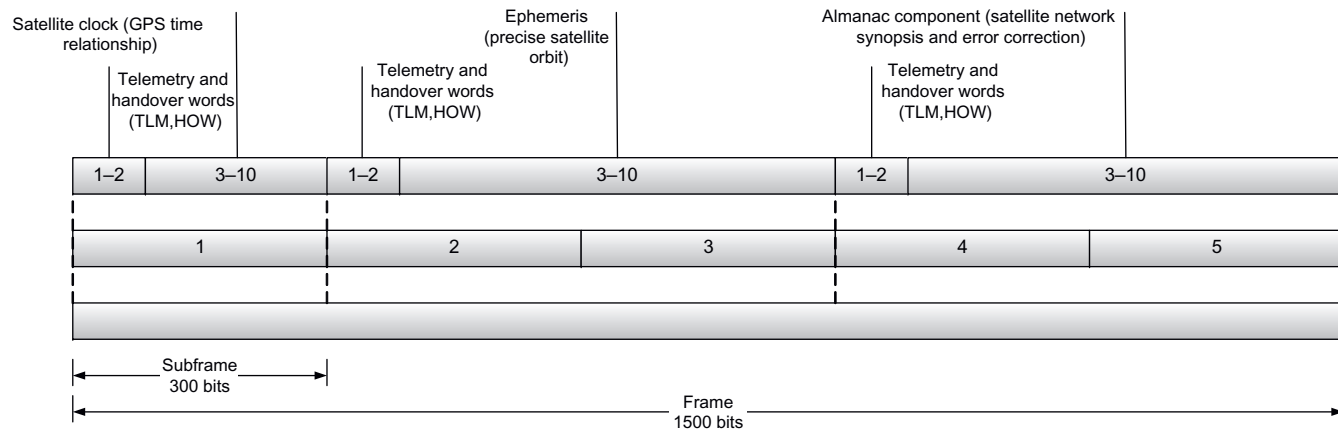


FIGURE 15.3

Overall structure of the GPS frame [16].

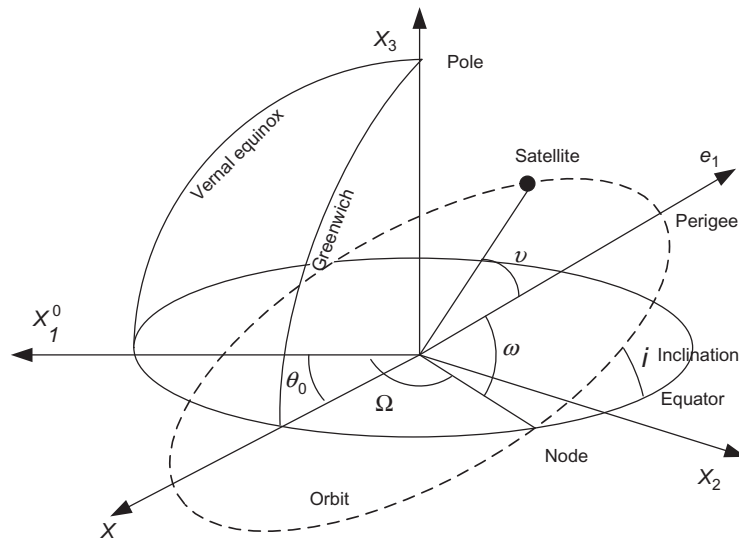
**FIGURE 15.4**

Illustration of almanac parameters [16].

orbital information of the satellites. Each satellite will broadcast almanac data for all satellites. The GPS receiver uses this data to determine which satellites are going to be visible in the sky. It can then determine which satellites should be tracked. With the almanac data, the receiver can focus on those satellites it can see, and exclude those that are over the horizon or out of view. Figure 15.4 illustrates the GPS almanac parameters.

The almanac parameters consist of size and shape of orbit (represented by semi-major axis a and eccentricity e), orientation of the orbital plane in the inertial system (represented by right ascension of ascending node Ω , argument of perigee ω , and inclination i), and position of the satellite in the orbital plane (represented by epoch of perigee T_0).

Ephemeris data provides the GPS receiver with the position of each GPS satellite at any time throughout the day (Figure 15.5). Each satellite will broadcast its own ephemeris data showing the orbital information for that satellite only. Given that the ephemeris data provides very precise orbital and clock correction data necessary for accurate positioning, its validity is much shorter. It is broadcast in three 6-s blocks and repeated every 30 s. The validity of data is implementation-specific and is usually up to 4 hours. The ephemeris data includes the following list [13,16]:

- $\sqrt{a}$ square root of the semi-major axis.
- e eccentricity.
- i_0 inclination angle at the reference time.

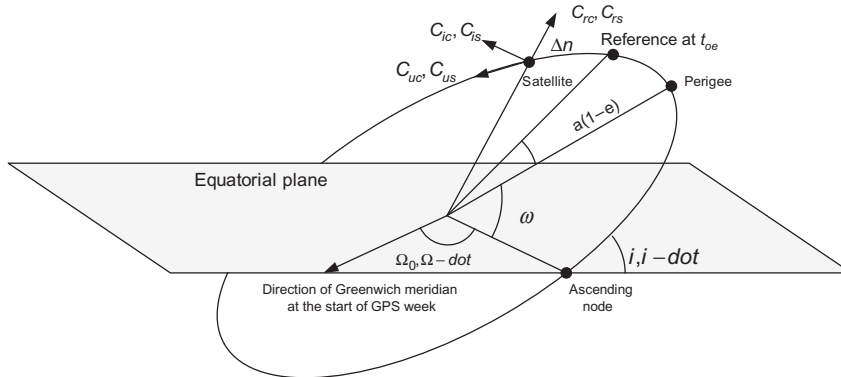
**FIGURE 15.5**

Illustration of ephemeris information [16].

- Ω_0 longitude of the ascending node at the beginning of the GPS week.
- ω argument of perigee.
- M_0 mean anomaly at the reference time.
- Δn correction to the mean motion computed using $\sqrt{a}$.
- $i\text{-dot}$ the rate of change of inclination with time.
- $\Omega\text{-dot}$ the rate of change of the right ascension of the ascending node with time.
- C_{uc}, C_{us} amplitude of the correction terms for the computed argument of latitude.
- C_{rc}, C_{rs} amplitude of the correction terms for the computed orbit radius.
- C_{ic}, C_{is} amplitude of the correction terms for the computed inclination angle.
- t_{oe} ephemeris reference time.

15.1.3.2 A-GNSS positioning

GNSS refers to satellite navigation systems that provide autonomous geospatial positioning with global or regional coverage. Different GNSS methods can be used separately or in combination to determine the location of a UE. In the E-UTRAN, the GNSS is designed to work with assistance data provided by the network. A-GNSS uses signals broadcast by satellites to determine the positions of UEs equipped with GNSS receivers.

Two types of assistance data are provided to improve the positioning speed and accuracy which include data assisting the measurements (e.g., reference time, visible satellite list, satellite signal Doppler, code phase Doppler, and code phase search windows), and data assisting position calculation (e.g., reference time, reference position, satellite ephemeris, and clock corrections). A-GNSS provides improved accuracy relative to the stand-alone GNSS, and it can further reduce the UE GNSS start-up and acquisition times, it can increase the UE GNSS sensitivity, and it can allow the UE to consume less power with the GNSS-capable receiver

put in idle mode when it is not needed. The A-GNSS methods can be operated in UE-assisted mode, where the UE performs GNSS measurements and sends them to the E-SMLC to calculate its position, or the UE-based mode, where the UE performs GNSS measurements and calculates its own location.

15.1.3.3 Observed time difference of arrival positioning

The OTDOA positioning method is based on measuring the time difference of arrival (TDOA) on special reference signals, embedded into the overall downlink signal, received from different eNBs. Each TDOA measurement describes a hyperbola, where the two focal points (F_1, F_2) are at the two measured eNBs. The measurement needs to be conducted at least for three pairs of base stations. The position of the device is the intersection of the three hyperbolas for the three measured base stations (A-B, A-C, and B-C), as shown in Figure 15.6.

The measurement conducted between a pair of eNBs is defined as the reference signal time difference (RSTD). The measurement is defined as the relative timing difference between a subframe received from the j th (neighboring) cell and the corresponding subframe from the i th (serving) cell. These measurements are conducted on the PRSs and the results are reported back to the location server, where the calculation of the position takes place. PRSs were introduced in

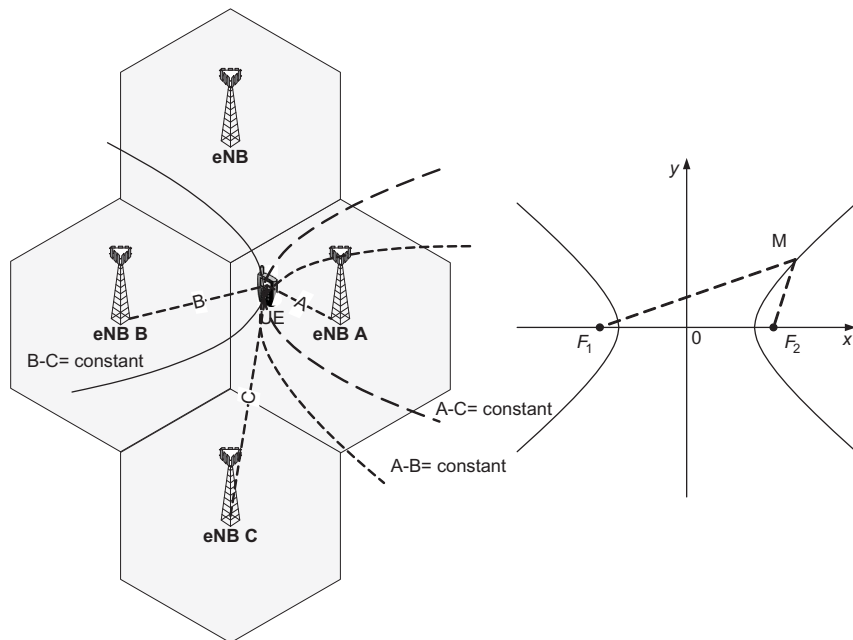


FIGURE 15.6

Illustration of downlink OTDOA positioning method [15].

LTE Rel-9 associated with antenna port 6, since the performance of cell-specific reference signals was not deemed sufficient for positioning. The reason is that the required high probability of detection could not be guaranteed. A neighbor cell with its synchronization signals (primary/secondary synchronization signals) and reference signals is seen as detectable, when the post-processing SINR is at least -6 dB. The results of the simulations performed during standardization of LTE Rel-9 suggested that this could be only guaranteed for 70% of all cases for the third best-detected cell, means second best neighboring cell. This is not enough, and further it assumed an interference-free environment, which cannot be ensured in a realistic scenario. However, PRSs still have some similarities with cell-specific reference signals as defined in LTE Rel-8. It is a pseudo-random QPSK sequence that is mapped in diagonal patterns with shifts in frequency and time to avoid collision with cell-specific reference signals and the control channels. The structure of the PRSs is described in Chapter 9. The PRSs can be muted on certain occasions to further reduce inter-cell interference. Therefore, PRS configuration and PRS muting is provided via the LPP protocol from the location server [15].

At least three timing measurements from geographically dispersed base stations with a good geometry are needed to solve for two coordinates of the UE, where the good geometry means that no two branches of the distinct hyperbolas intersect twice so that a unique solution can be found. In practice, a larger number of measurements, typically at least six to seven, are desirable. The position calculation is based on the multilateration approach by which an intersection of hyperbolas is found, where a hyperbola for a pair of cells corresponds to a set of points with the same RSTD for the two cells. The OTDOA positioning method is illustrated in Figure 15.6, where a UE is receiving downlink signals from the eNBs A, B, and C, and performing RSTD measurements τ_{AB}, τ_{AC} , and τ_{BC} which form three intersecting hyperbolic strips, the widths of which correspond to the RSTD measurement uncertainties. The distance equivalents of the RSTD measurements are d_{AB}, d_{AC} , and d_{BC} , respectively. Assuming the UE is located at (x, y) in a Cartesian coordinate system, and eNBs are located at $(x_A, y_A), (x_B, y_B)$, and (x_C, y_C) , respectively, the system of equations to be solved in the least squares sense to find two-dimensional coordinates (x, y) is as follows:

$$\begin{aligned} \sqrt{(x-x_A)^2 - (y-y_A)^2} - \sqrt{(x-x_B)^2 - (y-y_B)^2} &= d_{AB} - \Delta d_{AB} \\ \sqrt{(x-x_A)^2 - (y-y_A)^2} - \sqrt{(x-x_C)^2 - (y-y_C)^2} &= d_{AC} - \Delta d_{AC} \\ \sqrt{(x-x_B)^2 - (y-y_B)^2} - \sqrt{(x-x_C)^2 - (y-y_C)^2} &= d_{BC} - \Delta d_{BC} \end{aligned}$$

Accurate knowledge of the transmitter locations and timing offsets is needed to solve the above equations for the UE's coordinates. Determining transmitter timing is nontrivial at the required accuracy level. The advantage of OTDOA is that synchronization between the eNBs and the UE is not required, unlike when the time of arrival measurement is used. Although RSTD measurements can be

performed on a number of downlink signals, e.g., cell-specific reference signals or synchronization signals, it has been recognized that the existing signals suffer from poor reception, which is critical for OTDOA when multiple remote neighbor cells have to be detected. Therefore, to ensure the possibility of positioning measurements of a proper quality, and for a sufficient number of distinct locations, PRS having transmission patterns with an effective reuse of six has been introduced in LTE Rel-9. The interference to PRS can be further minimized, allowing simultaneous PRS transmissions for groups of cells with either orthogonal PRS patterns or low inter-cell interference. In OTDOA, the UE receiver has to deal with PRS from neighbor cells much weaker than those received from the serving cell. Furthermore, without the approximate knowledge of when the measured signals are expected to arrive in time and what is the exact PRS pattern, the UE would need to search the signals blindly, which would impact the time and accuracy of the measurements. To facilitate UE measurements, the network transmits assistance data to the UE, including a neighbor cell list with CIDs, the number of antenna ports, the number of consecutive downlink subframes per positioning occasion, PRS transmission bandwidth, expected RSTD, and the estimated uncertainty [11]. It should be noted that the detection of at least three eNBs is an absolute minimum. In practice, additional measurements are often necessary to be able to suppress outliers in the measurements. Such outliers may arise due to non-line-of-sight propagation. Thus, the detection capability of a TDOA method can often be the limiting factor, which makes it important to understand how the detection performance is computed.

15.1.3.4 E-CID-based positioning

The downlink OTDOA is the method of choice for dense urban and indoor environments where the A-GNSS method may not be able to provide reliable availability and satisfactory performance. Another method of positioning in LTE is the E-CID based on the cell of origin concept. With cell of origin, the position of the device is estimated using the knowledge of the geographical coordinates of its serving base station. The knowledge of the serving cell can be obtained after performing a tracking area update, or through paging. The position accuracy in this case is linked to the cell size, as the location server is only aware that the device is served by this base station. This method would of course not be able to fulfill the accuracy requirements mandated by the FCC [17]. Therefore, the E-CID method was defined in LTE, mainly for devices with no integrated GNSS receiver. In addition to the use of geographical coordinates of the serving base station, the position of the device is estimated more accurately by performing measurements on radio signals.

The E-CID method can take three approaches, based on different types of measurements: (i) E-CID with estimation of the distance from one base station; (ii) E-CID with measurement of the distance from three base stations; and (iii) E-CID by measuring the angle of arrival (AoA) from at least two base stations. In the first two cases, the possible measurement can be reference signal received

power (RSRP), a standard quality measurement for LTE Rel-8 terminals, TDOA, and the measurement of the timing advance or round-trip time.

In the first case, the position accuracy would be just a circle. The second and third methods can provide position accuracy of a point, when measuring more radio sources. In the first and second cases, the measurements are conducted by the UE; thus, they are considered UE-assisted. In the third case, the measurements are performed by the base station; thus, it is eNB-assisted. Ever since LTE Rel-9 was introduced, the timing advance measurement has been enhanced; as a result, there are now two types of measurements: Type 1 and Type 2. The Type 2 measurement relies on the timing advance estimated from receiving a PRACH preamble during the random access procedure. Type 1 is defined as the sum of the receive–transmit timing difference at the eNB (positive or negative value), and the receive–transmit timing difference at the terminal, which is always a positive value. The base station first measures its own timing difference and instructs the device to adjust its uplink timing using a timing advance MAC command (see Chapter 8). The UE measures and reports the receive–transmit timing difference, as well. Both timing differences allow the calculation of the timing advance Type 1, corresponding to the round-trip time. The round-trip time is reported to the location server, where the distance to the base station is calculated using $d = cT_{\text{RTT}}/2$.

The round-trip time and timing advance can be used for distance estimation; nevertheless, they do not provide any information on direction. This can only be obtained through an AoA measurement. The AoA is defined as the estimated angle of a UE with respect to a reference direction which is geographical north, positive in a counterclockwise direction, as seen from an eNB. The base station can usually estimate this angle on any uplink signal; however, typically, sounding reference signals (SRSs) are used for this purpose. The antenna array configuration has an impact on AoA measurements, the larger the array size, the higher the accuracy. With a linear array of equally spaced antenna elements, the received signal at any adjacent element is phase-rotated by a fixed angle whose value is a function of the AoA as well as the antenna element spacing and carrier frequency [15].

15.1.3.5 UTD OA positioning

In the uplink positioning methods, the UE's position is estimated based on timing measurements of uplink radio signals conducted at different LMUs, along with the knowledge of the geographical coordinates of the LMUs. The time required for a signal transmitted by a UE to reach an LMU is proportional to the length of the transmission path between the UE and the LMU. A set of LMUs are designated to sample the UE's signal at the same time [7].

In order to obtain uplink measurements, the LMUs need to know the characteristics of the SRSs transmitted by the UE for the time period required to conduct the uplink measurement. These characteristics should be static over the periodic transmission of SRS during the uplink measurements. Therefore, the E-SMLC will inform the serving eNB to configure the UE to transmit SRSs for the purpose

of uplink positioning. It is up to the eNB to make the final decision on resources to be assigned, and to communicate this configuration information back to the E-SMLC so that E-SMLC can configure the LMUs. The eNB may decide (e.g., in case no resources are available) to configure no resources for the UE, and to report the empty resource configuration to the E-SMLC [7].

The conceptual difference between the UTDOA and OTDOA positioning methods is that the latter requires multiple transmit points, while the former utilizes multiple receive points at different locations, although the position calculation principle is the same. In order to perform UTDOA timing measurements on user data, one reference receiver decodes the UE signals and forwards the sequence to cooperating receivers. This procedure is relatively complex and requires a significant amount of signaling. Therefore, SRSs have been selected for UTDOA measurements. For UTDOA positioning, periodically transmitted SRSs are scheduled in a non-dynamic manner to allow a sufficiently long time for the measurements. This reduces the need for signaling of the full scheduling information to communicate the SRS configuration parameters. The SRS occupies the last SC-FDMA symbol in an uplink subframe. The bandwidth and the periodicity of SRS transmission can be configured to meet the positioning requirements. The SRS-based measurements for positioning may be performed and processed directly at a base station, or the operation may be performed by specific measurement units that may share the antennas with the base stations. The main disadvantage of the UTDOA method relative to OTDOA is a potential reception problem due to the power control of the UE transmissions. The UEs close to their serving base station transmit at a lower power level to avoid unnecessary interference to other UEs; this is known as the near–far problem. The consequence is that such signals may not be strong enough to reach the required uplink signal strength for UTDOA measurements at neighbor cells.

15.2 Evolved multimedia broadcast/multicast service

As we discussed earlier, the E-MBMS bearer service is the service provided by the packet-switched domain to E-MBMS user services in order to deliver IP multicast datagrams to multiple receivers by minimal use of network and radio resources. An E-MBMS user service is a service provided to the end user by means of the E-MBMS bearer service, and possibly other EPS bearers. The E-MBMS is a point-to-multipoint service in which data is transmitted from a single source entity to multiple recipients over a large geographical area. Transmitting the same content to multiple recipients allows the sharing of network resources. The E-MBMS for EPS bearer service supports broadcast mode over E-UTRAN and UTRAN. The E-MBMS is realized by the addition of a number of new features and functional entities to the LTE network architecture. In the next sections, we describe the E-MBMS network architecture, user-plane and

control-plane protocols, and interfaces, as well as E-UTRAN functions and protocols that support MBMS services in LTE/LTE-Advanced systems.

15.2.1 E-MBMS network architecture

MBMS is a bearer service for simultaneous transmission of content over a large number of synchronized cells to all (or a group of) UEs subscribed to the service over a common bearer. In that case, the resulting signal will appear to the UE as one transmission over a time-disperse radio channel. This concept is known as multimedia broadcast/multicast service single frequency network (MBSFN). A group of cells that transmit the same content to multiple users forms an MBSFN area. Multiple cells can belong to a single MBSFN area, and each cell can be part of up to eight MBSFN areas. There can be up to 256 different MBSFN areas defined in a network, each one with a unique identity. Once defined, MBSFN areas will not change dynamically. It is not required that a terminal simultaneously receive content from multiple MBSFN areas. In other words, an MBSFN area is a geographical area comprising one or several cells that transmit the same content. For example, in Figure 15.7, which illustrates a hypothetical MBSFN network, cells 2 and 3 belong to both MBSFN areas 1 and 2. The MBSFN areas are static and do not vary over time. The usage of MBSFN transmission requires not only time synchronization among the cells participating in an MBSFN area, but also usage of the same set of radio resources in each of the cells for a particular service. This coordination is the responsibility of the multi-cell/multicast coordination entity (MCE), which is a logical node in the radio access network that controls resource allocation and transmission parameters across the cells in the MBSFN area [10].

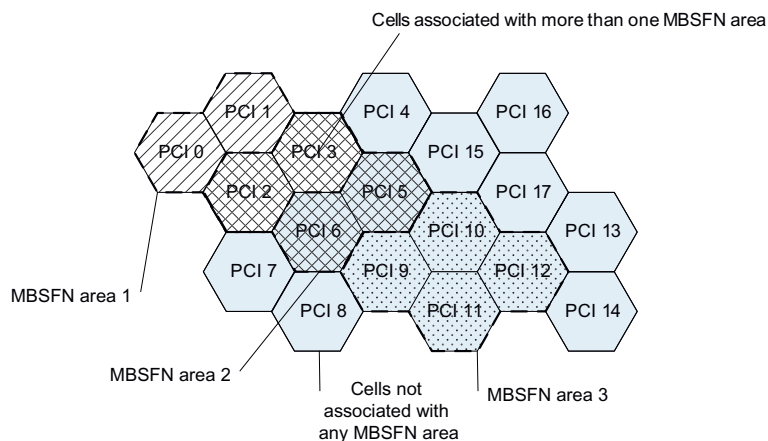


FIGURE 15.7

Illustration of MBSFN areas.

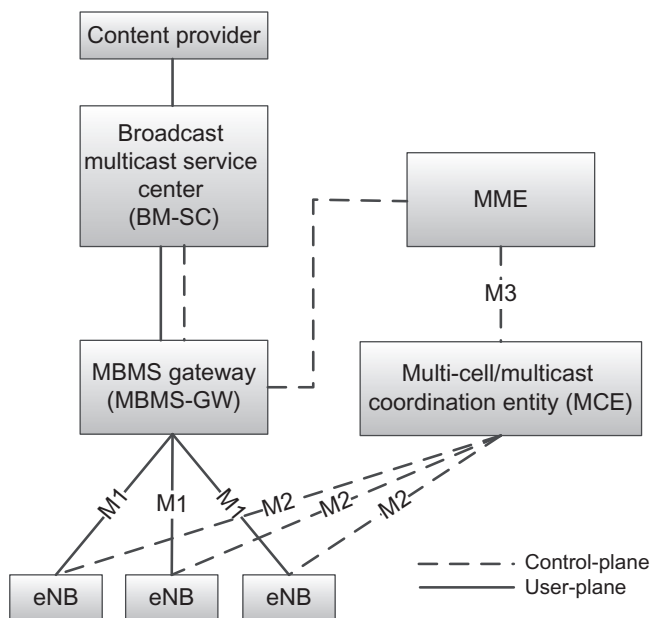


FIGURE 15.8

E-MBMS network architecture [5].

Figure 15.8 illustrates the E-MBMS network architecture. As shown in the figure, the MCE can control multiple eNBs, each controlling one or more cells. The broadcast multicast service center (BM-SC), located in the core network, is responsible for authorization and authentication of content providers, charging, and overall configuration of the data flow through the core network. The MBMS gateway (MBMS-GW) is a logical node handling multicast of IP packets from the BM-SC to all eNBs involved in transmission in an MBSFN area. It also manages session control signaling via the MME. From the BM-SC, the MBMS data is forwarded using IP-based multicast, a method of sending IP packets to multiple receiving network nodes in a single transmission, via the MBMS-GW to the cells. The MBMS is not only efficient from a radio-interface point of view, but it also saves resources in the transport network by avoiding unicast transmission of the same packet to multiple nodes unless necessary. This can lead to significant savings in the transport network.

More specifically, an MBMS-enabled network consists of the following entities and interfaces [5]:

- *Multi-cell/multicast coordination entity*: The MCE is a logical entity whose functions are admission control and allocation of the radio resources used by all eNBs in the MBSFN area for multi-cell MBMS transmissions. The MCE decides whether to establish radio bearer(s) for the new MBMS service(s), if

the radio resources are not sufficient for the corresponding MBMS service(s), or may allocate radio resources from other radio bearer(s) of ongoing MBMS service(s) according to allocation and retention priority (ARP). In addition to allocation of the time/frequency radio resources, the MCE controls the radio configuration, e.g., modulation and coding scheme, counting and acquisition of counting results for MBMS service(s), resumption of MBMS session(s) within MBSFN area(s) based on the ARP and/or the counting results for the corresponding MBMS service(s), suspension of MBMS session(s) within MBSFN area(s) based on the ARP and/or on the counting results for the corresponding MBMS service(s). In the case of distributed MCE architecture, the MCE manages the above functions for a single eNB of an MBSFN area.

- *E-MBMS gateway*: The MBMS-GW is a logical entity that is located between the BM-SC and eNBs whose functions include sending/broadcasting of MBMS packets to each eNB participating in the service. The MBMS-GW uses IP multicast as the method of forwarding MBMS user data to the eNBs. The MBMS-GW performs MBMS session control signaling (i.e., session start/update/stop) toward the E-UTRAN via MME.
- *MCE–MME interface*: The application part of the MCE–MME (M3) control-plane interface allows MBMS session control signaling on E-UTRAN radio access bearer (E-RAB) level (i.e., does not convey radio configuration data). The procedures include MBMS session start and stop. The stream control transmission protocol (SCTP)⁴ is used as the signaling transport method.
- *MCE–eNB interface*: The application part of the MCE–eNB (M2) control-plane interface conveys radio configuration data for the eNBs configured with multi-cell transmission mode and session control signaling. The SCTP protocol is used as signaling transport.
- *MBMS–GW–eNB interface*: The user-plane interface MBMS-GW–eNB (M1) carries IP packets between the two network entities and uses IP multicast for point-to-multipoint delivery of user packets.

There are two MBMS architectures defined in 3GPP. In the “distributed MCE architecture,” the MCE is part of the eNB and the M2 interface is maintained between the MCE and the corresponding eNB, whereas in the “centralized MCE architecture” (shown in Figure 15.8), the MCE is a logical entity and can be deployed as a stand-alone physical entity or collocated in another physical entity

⁴SCTP is a transport layer protocol, performing a similar role as the commonly used protocols transmission control protocol (TCP) and user datagram protocol (UDP). It provides some of the service features of both protocols, i.e., it is message-oriented like UDP and ensures reliable and in-sequence transport of messages with congestion control like TCP. The protocol is defined by IETF RFC 4960 [19]. The SCTP protocol may be characterized as message-oriented, i.e., it transports a sequence of messages comprising a group of bytes, rather than transporting an unbroken stream of bytes as does TCP. As in UDP, a sender sends a message in SCTP in one operation, and that exact message is passed to the receiving application process in one operation. In contrast, TCP is a stream-oriented protocol, transporting streams of bytes reliably and in order.

such as eNB. In both cases, the M2 interface is maintained between the MCE and all eNB(s) belonging to the corresponding MBSFN area [5].

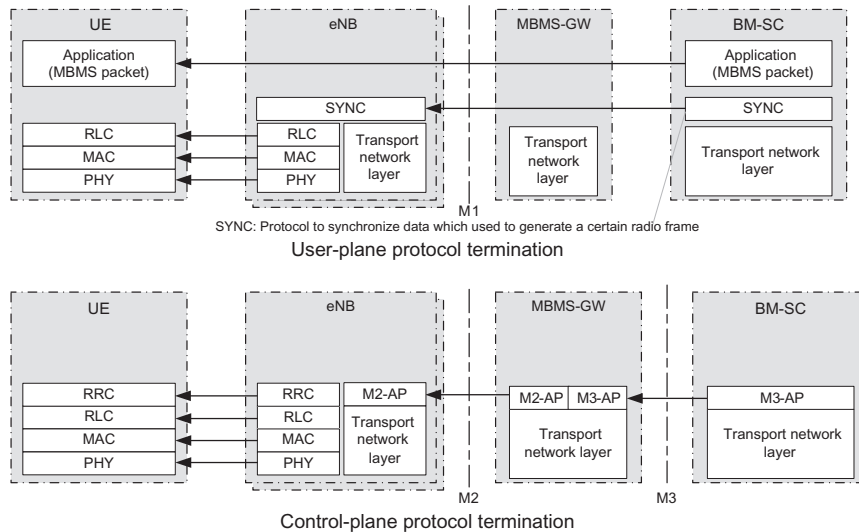
15.2.2 Basic definitions

In the context of MBMS, the following definitions are used [5]:

- *MBSFN synchronization area* is defined as an area of the network where all eNBs can be synchronized and perform MBSFN transmissions. MBSFN synchronization areas are capable of supporting one or more MBSFN areas. On a given frequency layer, an eNB can only belong to one MBSFN synchronization area. MBSFN synchronization areas are independent from the definition of MBMS service areas.
- *MBSFN transmission or a transmission in MBSFN mode* is a simulcast transmission technique realized by transmission of identical waveforms at the same time from multiple cells (macro diversity). An MBSFN transmission from multiple cells within the MBSFN area is considered like a single transmission from a UE point of view.
- *MBSFN area* is defined as a geographical area consisting of a group of cells within an MBSFN synchronization area of a network, which are coordinated to perform an MBSFN transmission. Except for the reserved cells, all cells within an MBSFN area contribute to the MBSFN transmission and advertise its availability. The UE may only need to consider a subset of nodes in the MBSFN areas that are configured to broadcast the desired service.
- *MBSFN area reserved cell* is a cell within an MBSFN area which does not contribute to the MBSFN transmission. The cell may be allowed to transmit for other services, but at restricted power on the resources allocated for the MBSFN transmission.
- Each *Synchronization sequence* (SYNC) protocol data unit contains a time stamp which indicates the start time of the synchronization sequence. For an MBMS service, each synchronization sequence has the same duration which is configured in the BM-SC and the MCE.
- The *synchronization period* provides the time reference for the indication of the start time of each synchronization sequence. The time stamp which is provided in each SYNC PDU is a relative value which refers to the start time of the synchronization period. The duration of the synchronization period is configurable.

15.2.3 E-MBMS user-plane and control-plane protocols

The overall user-plane protocol termination of content synchronization is shown in Figure 15.9. This structure is based on the functional allocation for unicast, and the SYNC protocol is defined additionally on the transport network layer to

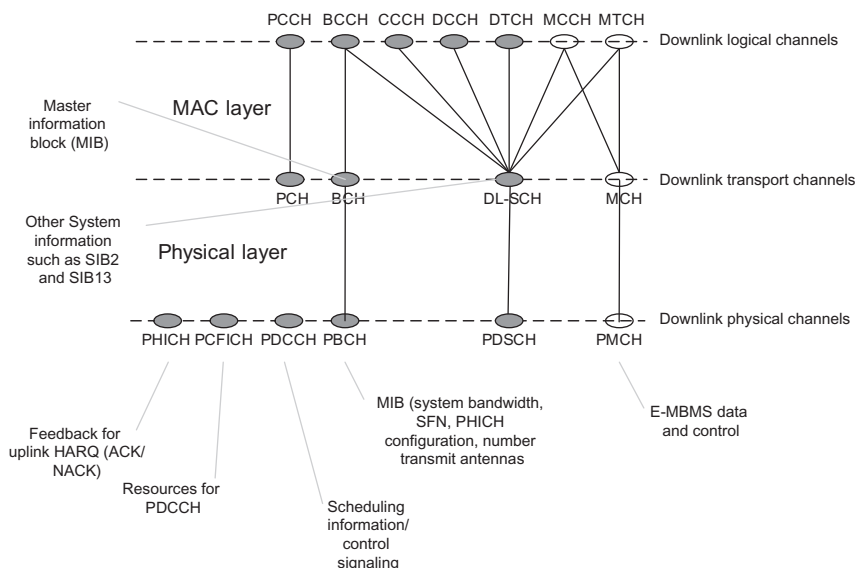
**FIGURE 15.9**

E-MBMS user-plane and control-plane protocol structure [5].

support the content synchronization mechanism. The SYNC is a protocol for transporting additional information that enables eNBs to identify the timing for radio frame transmission and detect packet loss. Each MBMS service uses its own SYNC entity. The SYNC protocol is applicable to downlink and is terminated in the BM-SC. The multicast control logical channel is terminated in the eNB on the network side. The control-plane protocol structure and termination is further shown in Figure 15.9.

15.2.4 Physical and MAC layer aspects of E-MBMS

The MBSFN transmission is made possible through use of a new transport channel known as a multicast channel (MCH). As shown in Figure 15.10, two types of MBMS-related logical channels are multiplexed to MCH, i.e., the multicast traffic channel (MTCH) and multicast control channel (MCCH). The MTCH is a logical channel that is used to carry MBMS data corresponding to a certain MBMS service. If the number of services provided in an MBSFN area is large, multiple MTCHs can be configured. For MBSFN transmission, no acknowledgments are transmitted by the terminals, no RLC retransmissions can be used, and consequently, the RLC unacknowledged mode is utilized. The MCCH is a logical channel that is used to transport control information necessary for reception of a certain MBMS service, including the subframe allocation and MCS for each MCH. There is one MCCH per MBSFN area. Similar to MTCH, the RLC sub-layer uses unacknowledged mode [2].

**FIGURE 15.10**

Logical, transport, and physical channel mapping to support E-MBMS [3,5].

Multiple MTCHs and one MCCH can be multiplexed in the MAC sublayer to form an MCH transport channel. The MAC header contains information about MTCH/MCCH multiplexing, such that the terminal can demultiplex the information upon reception. The MCH is transmitted using MBSFN in one MBSFN area. The transport channel processing for MCH is similar to the downlink shared channel with some exceptions. In the case of MBSFN transmission, the same data is transmitted with the same transport format using the same physical resource from multiple cells typically belonging to different eNBs. Thus, the MCH transport format and resource allocation cannot be dynamically adjusted by the eNB. As described above, the transport format is instead determined by the MCE and signaled to the terminals as part of the information sent on MCCH. As the MCH transmission is simultaneously targeting multiple terminals, and therefore no feedback is used, HARQ is not used for MCH transmission. As already mentioned, multi-antenna transmission (transmit diversity and spatial multiplexing) does not apply to MCH transmission. The physical multicast channel (PMCH) scrambling is unique in each MBSFN area, i.e., identical for all cells participating in MBSFN transmission. The MCH is mapped to PMCH and transmitted in MBSFN subframes (see Chapter 9 for a description of MBSFN subframes). An MBSFN subframe consists of two parts: a control region, used for transmission of non-MBSFN unicast control signaling; and an MBSFN region, used for transmission of MCH. Unicast control signaling may be needed in an MBSFN

subframe, e.g., to schedule uplink transmissions in the next subframe or for MBMS-related signaling [10].

In the case of MBSFN transmission, the cyclic prefix should not only cover the main part of the actual channel time dispersion, but also the timing difference between the transmissions received from the cells involved in the MBSFN transmission. Therefore, MBSFN transmissions, which can take place in the MBSFN regions only, use an extended cyclic prefix. As there are different cyclic prefix lengths and subcarrier spacing defined for LTE, there are different modes for MBMS that take advantage of these configurations. In a mixed mode of MBMS and unicast transmission, the subcarrier spacing is 15 kHz, and resources (subframes) are shared between MBMS data and unicast traffic/control signaling. In a dedicated MBMS mode or single-cell scenario, the RF carrier is only used for MBMS transmission. In this case, a different subcarrier spacing of 7.5 kHz can be used, offering a larger cyclic prefix of 33.3 μ s which leads to a further improved broadcast over large cells (that exhibit larger delay spreads).

If a normal cyclic prefix is used for normal subframes, and also in the control region of MBSFN subframes, there will be a small gap between the two parts of an MBSFN subframe. The reason is to keep the start time of the MBSFN region fixed, irrespective of the cyclic prefix length used for the control region. The MCH is transmitted by means of MBSFN from a group of cells that are part of the corresponding MBSFN area. Thus, from the UE's perspective, the radio channel through which the MBMS content has been propagated is the aggregation of the channels of each cell within the MBSFN area. In order to estimate the channel for coherent demodulation of MCH, the UE cannot rely on the cell-specific reference signals transmitted from each cell; rather, in order to coherently demodulate MCH, dedicated MBSFN reference signals are inserted within the MBSFN part of the MBSFN subframe (see Chapter 9 for a description of MBSFN reference signals). These reference signals are transmitted by means of MBSFN over a set of cells that form the MBSFN area, i.e., they are transmitted in the same time–frequency resources and with the same reference signal values from each cell. As a result, the channel estimation based on these reference symbols correctly reflects the overall aggregated channel corresponding to MCH transmission of all cells that are part of the MBSFN area. The MBSFN transmission in conjunction with specific MBSFN reference signals can be seen as transmission using antenna port 4.

The MBSFN-enabled UE can assume that all MBSFN transmissions within a given subframe correspond to the same MBSFN area. Therefore, the UE may choose to interpolate over all MBSFN reference signals within a given MBSFN subframe when estimating the aggregated MBSFN channel. In contrast, MCH transmissions in different subframes may correspond to different MBSFN areas. The frequency-domain density of MBSFN reference signals is much higher than the corresponding density of cell-specific reference signals, given that the aggregated channel of all cells involved in the MBSFN transmission (due to large coverage area) is equivalent to a highly time-dispersive

or highly frequency-selective channel. There is only a single MBSFN reference signal in MBSFN subframes. Thus, multi-antenna transmission such as transmit diversity and spatial multiplexing is not supported for MCH transmission. The main argument for not supporting any standardized transmit diversity scheme for MCH transmission is that the high frequency selectivity of the aggregated MBSFN channel in itself provides substantial frequency diversity [10].

15.2.5 E-MBMS single frequency network transmission

Multiple MBMS services can be mapped to the same MCH transport channel. One MCH contains data belonging to only one MBSFN area. An MBSFN area contains one or more MCHs. All MCHs have the same coverage area. For MCCH and MTCH, the UE does not perform RLC reestablishment upon cell change between the cells belonging to the same MBSFN area. Within the MBSFN subframes, all MCHs within the same MBSFN area occupy a pattern of subframes, not necessarily adjacent in time, which is common for all of these MCHs and which is referred to as a common subframe allocation (CSA) pattern. As shown in Figure 15.11, the CSA pattern is periodically repeated with the CSA period. The MCH subframe allocation (MSA) for every MCH carrying MTCH is defined by the CSA pattern, the CSA period, and the MSA-end, which are all signaled on MCCH. The MSA-end indicates the last subframe of the MCH within the CSA period. Subsequently, the MCHs are time multiplexed within the CSA period, which ultimately defines the interleaving between the MCHs. It is further possible for MCHs not to use all MBSFN resources signaled as part of the Rel-8 MBSFN signaling. Furthermore, such MBSFN resources can be shared for more than one purpose (e.g., MBMS, positioning). During one MCH scheduling period (MSP), which is configurable per MCH, the eNB multiplexes different MTCHs and (optionally) MCCH for transmission on MCH. The MCH scheduling information (MSI) is provided per MCH to indicate which subframes are used by each MTCH during the MSP [5].

In the example provided in Figure 15.11, the scheduling period for the first MCH is 16 frames, corresponding to one CSA period, and the scheduling information for this MCH is therefore transmitted once every 16 frames. The scheduling period for the second MCH is 32 frames, corresponding to two CSA periods, and the scheduling information is transmitted once every 32 frames. The MSPs can range from 80 ms to 10.24 s.

The MCCH information is transmitted periodically with a fixed repetition period, and changes to the MCCH information can only occur at specific times. Whenever MCCH information is changed, which can only be done at the beginning of a new modification period, as shown in Figure 15.12, the network notifies the UEs about the upcoming MCCH information change in the preceding MCCH modification period. The notification mechanism uses the PDCCCH for this purpose. An 8-bit bitmap, where each bit represents a certain MBSFN area, is

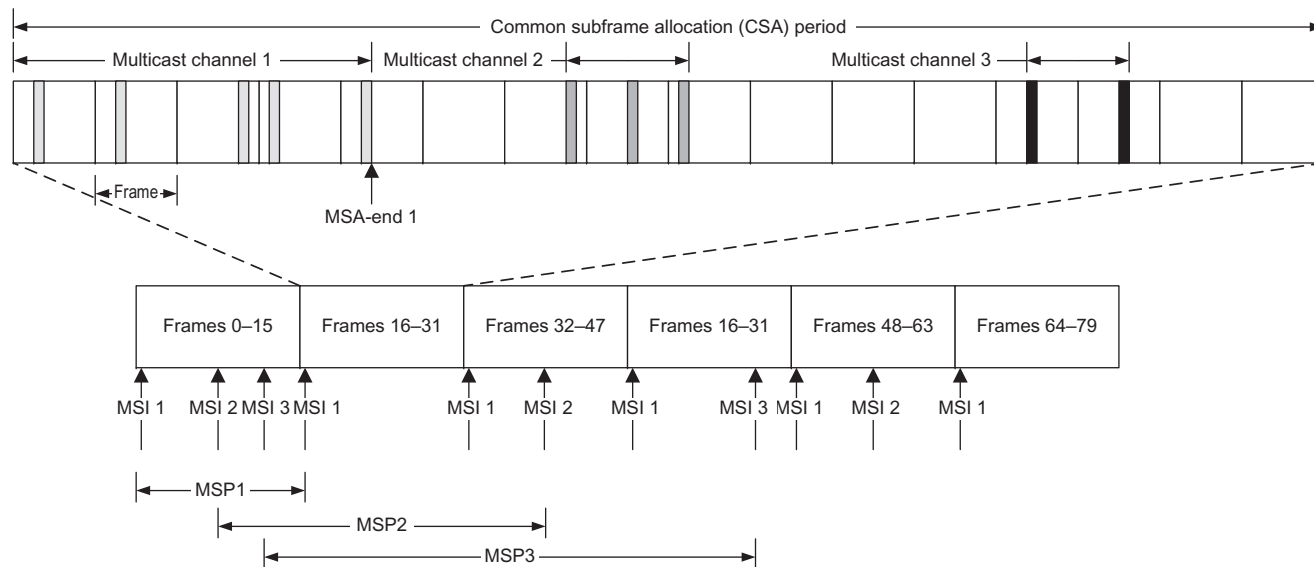
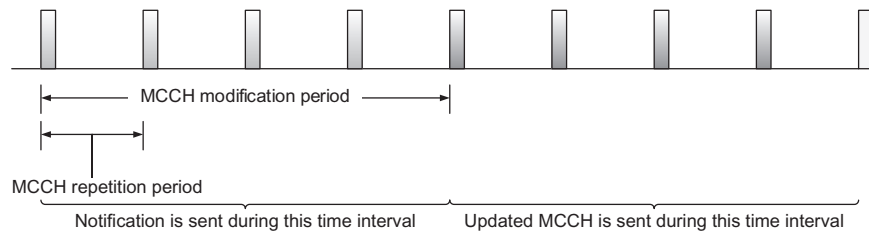


FIGURE 15.11

Example scheduling of MBMS content [10].

**FIGURE 15.12**

Example MCCH transmission schedule [1].

transmitted in the PDCCH in an MBSFN subframe using DCI format 1C and the M-RNTI (see Chapter 8 for a description of multicast RNTI). The notification bit-map is only transmitted when there are changes in the services, as well as to indicate a counting request in an MBSFN area. The purpose of notification indicators and modification periods is to maximize the amount of time the UE may sleep to reduce power consumption. In the absence of any changes to MCCH information, a terminal not subscribed to E-MBMS may enter the DRX mode, and only wake up when the notification indicator is transmitted. The periodic transmission of MCCH is useful in order to support mobility, because a terminal entering a new MBSFN area or a terminal that has missed the first MCCH transmission does not have to wait until the start of a new modification period to receive MCCH information [10].

System information block type 2 (SIB2) carries all relevant information about common and shared channels in LTE. LTE Rel-9 has extended the scope of this information to include MBMS-specific information. The new information element *MBSFN-SubframeConfig* defines which radio frames contain subframes that can be used for MBMS (see the example in Figure 15.13). The MBSFN subframes can be used by all MBSFN areas. The E-MBMS information in SIB2 includes the radio frame allocation period and a radio frame allocation offset, as well as the subframe allocation mode, which can be one or four consecutive radio frames containing MBSFN subframes. A maximum of six subframes in each radio frame can be used for MBMS transmission. This is due to the fact that zero and fifth subframes carry synchronization signals and broadcast channel, and subframes 0, 4, 5, and 9 can be used for paging depending on the paging cycle. A bitmap is used to indicate which of the six possible subframes are used for MBMS transmission.

System information block type 13 (SIB13) provides MBSFN identity (MBSFN ID), non-MBSFN region length (one or two OFDM symbols), and MCCH configuration. The MCCH configuration provides information on the repetition period for MCCH, the MCCH offset as well as the actual subframe where MCCH is transmitted, and the MCS used for MCCH. It is important to note that for MCCH, only four MCSs are allowed: MCS indices 2, 7 (both QPSK); 13 (16QAM); and 19 (64QAM). The MCCH always defines one MBSFN area and carries a single

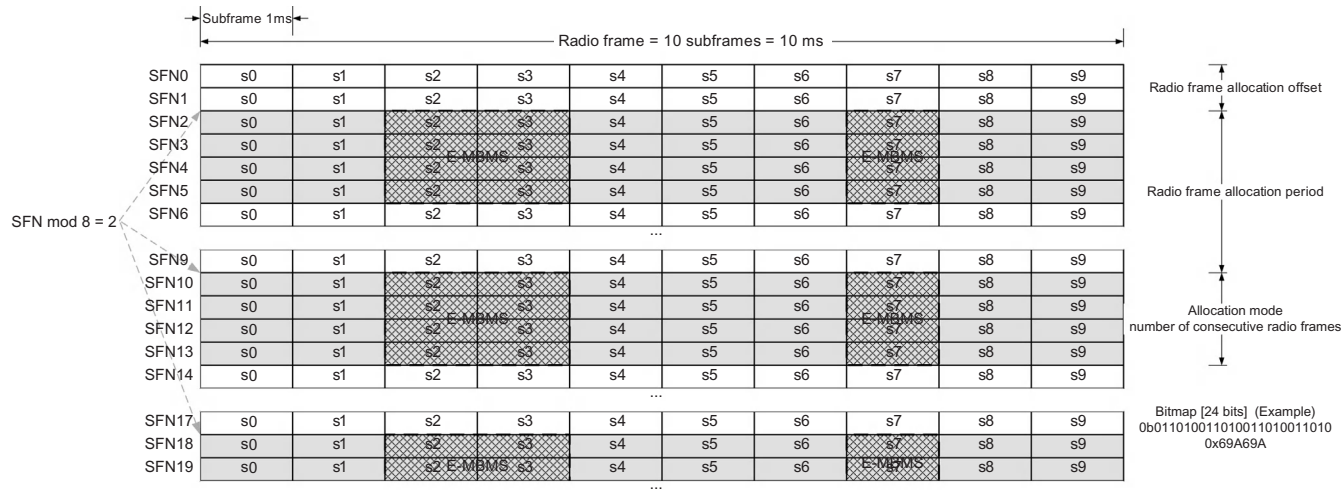


FIGURE 15.13

Example interpretation of E-MBMS information in SIB2 [15].

message, i.e., *MBSFNAreaConfiguration*. This information element provides all required information for scheduling MBMS services, including all PMCH belonging to that particular MBSFN area and the configuration parameters for the sessions that are carried by the corresponding PMCH. There are up to 15 PMCH, where each one has up to 29 MTCHs. For each PMCH, there is information about which MBSFN subframe carries that PMCH (start, end), as well as the MCS that has been utilized.

In general, the control information for the UEs supporting E-MBMS is separated as much as possible from unicast control information. Most of the E-MBMS control information is provided on MCCH. The E-UTRA employs one MCCH logical channel per MBSFN area. In the case where the network configures multiple MBSFN areas, the UE acquires the MBMS control information from the MCCHs that are configured to identify whether the services which the UE is interested to receive are ongoing. The behavior of the UE when it is unable to simultaneously receive MBMS and unicast services depends on the UE implementation. As of LTE Rel-11, an E-MBMS-capable UE is only required to support reception of a single MBMS service at a time, and reception of more than one MBMS service is implementation specific. The MCCH carries the *MBSFN Area Configuration* message, which indicates the ongoing E-MBMS sessions as well as the corresponding radio resource configuration. The MCCH may also carry the *MBMS Counting Request* message, when E-UTRAN needs to count the number of UEs in the RRC_CONNECTED state that are receiving or are interested in receiving specific MBMS services. A limited amount of E-MBMS control information is provided on the broadcast control channel. This is primarily the information needed to acquire the MCCH(s), and is carried via SIB13. An MBSFN area is identified by the *mbsfn-Areaid* in SIB13. During mobility, the UE assumes that the MBSFN area is continuous when the source cell and the target cell broadcast the same value in the *mbsfn-Areaid* [1].

15.2.6 Mobility support in E-MBMS

The E-MBMS mobility is based on the same procedures that are specified for unicast services. There are no additional mechanisms to instruct the E-MBMS-capable UEs to select a carrier frequency providing E-MBMS. Furthermore, there are no provisions to reduce the service interruption time when moving from one MBSFN area to another. Nevertheless, the E-UTRAN can assign the highest cell reselection priority to the carrier frequency that provides E-MBMS to facilitate the transfer of ongoing MBMS service during E-MBMS-subscribed UE mobility. The E-MBMS mobility procedures would allow the UE to start or continue receiving MBMS service(s) via MBSFN when moving across cell(s). The E-UTRAN procedures provide support for service continuity with respect to mobility within the same MBSFN area. Within the same geographic area, MBMS services can be provided on more than one frequency, and the frequencies used to provide MBMS services may change from one geographic area to another within

a PLMN. The E-MBMS-subscribed UEs can be either in the RRC_IDLE state performing cell reselection, or in the RRC_CONNECTED state obtaining target cell MTCH information from the target cell MCCH. To avoid the need for acquiring the E-MBMS related system information and MCCH of neighbor frequencies, the UE is provided with assistance information on the frequency of MBMS services via MBSFN as follows [1,5]:

- *User service description*: The application layer provides temporary mobile group identities (TMGIs) for each service, the session start and end time, the frequencies, and the MBMS SAs belonging to the MBMS service area.
- *System information*: MBMS and non-MBMS cells use *System Information Block Type 15* to provide the MBMS SAs of the current frequency, and of each neighbor frequency. The E-MBMS SAs of the neighboring cells may be provided via X2 signaling.

15.2.7 E-MBMS counting

The MBMS counting in LTE is used to determine if there is a sufficient number of UEs interested in receiving a service to enable the operator to decide whether it would be efficient to deliver the service via MBSFN. It allows the operator to choose between enabling or disabling MBSFN transmission for the service. The MBMS counting applies only to the UEs in the connected mode. Enabling and disabling MBSFN transmission is realized by the MBMS service suspension and resumption function. The counting scheme can be applied to a service already provided by MBSFN in an MBSFN area (an ongoing service), or a service that has not been provided via MBSFN in an MBSFN area (service not started yet), which may be a service provided via unicast bearers [5].

The counting procedure is initiated by the network. Initiation of the counting procedure results in a request to each eNB within the MBSFN area to send a counting request (extended MCCH message), which contains a list of TMGIs, which uniquely identifies an MBMS bearer service. A single globally unique TMGI is allocated by the BM-SC per MBMS bearer service requiring UE feedback. The connected mode UEs which are receiving or are interested in the services will respond with a *Counting Response* message, which includes short MBMS service identities (unique within the MBSFN service area), and may optionally include the information to identify the MBSFN area. The network has the means to disable UE counting per service, and the UE is able to report on multiple MBMS services via a single *Counting Response* message. It is not necessary to retransmit the *Counting Response* message when the UE moves within the same MBSFN area. The network obtains one response from the UE related to one *Counting Request* message, which is broadcast for one modification period. The UE cannot automatically indicate to a network a change of interest in MBMS service(s). The network counts the UE's interest per service [5].

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