

An SS must maintain the same power spectral density when changing between transmissions with different numbers of subchannels. In other words, if the number of subchannels is double that of the previous allocation, the total transmit power, when feasible, must be doubled. Reciprocally, if the number of subchannels is halved compared to the previous allocation, the total transmit power, when feasible, must be halved.

Chapter 12 PHY: WirelessMAN-OFDMA

Multicarrier PHY for frequencies below 11 GHz

WirelessMAN-OFDMA is one of the three PHY specifications defined in IEEE Std 802.16 for applications below 11 GHz. This PHY has attracted much attraction in the past few years, particularly because of the expansion of the scope of the IEEE 802.16 standard, through the IEEE 802.16e amendment, to include mobile stations (MSs). IEEE Std 802.16e includes the expansion of all three of the lower frequency PHY specifications into the mobile arena (WirelessMAN-SC is excluded due to the IEEE 802.16e upper limit of 6 GHz). However, the primary interest has centered around WirelessMAN-OFDMA, which is abbreviated as the "OFDMA PHY."

WirelessMAN-OFDMA uses orthogonal frequency-division multiple access (OFMDA), which is an extension of orthogonal frequency-division multiplexing (OFDM). The multiple access feature makes OFDMA considerably more complex. In OFDM, all of the transmitter's subcarriers are, at any given time, addressed to a single receiver; multiple access is provided solely by TDMA time slotting. OFDMA divides the subcarrier set into subsets, each of which can address a different receiver at any given time. This provides for a number of performance advantages, as discussed below, at the cost of considerable complexity. The complexity comes not only in the air interface, as defined in the IEEE 802.16 standard, but also in the control functionality outside the standard. For example, the design and optimization of an efficient scheduler will prove an interesting engineering challenge.

The description of WirelessMAN-OFDMA here is less comprehensive than those of the other PHYs. This is due to the large number of features and options present in the specification, as well as by the substantial changes and additions that have recently been added through IEEE Std 802.16e (which, as published, also includes an approved corrigendum to the base standard). This book is not intended to thoroughly cover IEEE Std 802.16e, but, on the other

hand, neither do we wish to spend time explaining features that have changed significantly by virtue of that amendment. Therefore, while this chapter excludes a substantial number of features, mainly optional and mobility features added in IEEE Std 802.16e, care has been taken to ensure that the features described here are consistent with the changes in IEEE Std 802.16e.

INTRODUCTION

Selection of OFDMA waveform

As compared to the OFDM case discussed in the previous chapter, OFDMA involves different considerations regarding the complexity and implementation cost tradeoffs. Although WirelessMAN-OFDM has a limited capability for OFDMA through its subchannelization feature, its basic premise is TDMA with fairly large intercarrier spacing, which allows for an implementation hardly more challenging than the well-known Wi-Fi IEEE 802.11a or IEEE 802.11g OFDM products that have been readily available in the market since 2001. Those IEEE 802.11 amendments are based on a 64-FFT. Recall that WirelessMAN-OFDM uses a 256-FFT. WirelessMAN-OFDMA, as defined in IEEE Std 802.16-2004 [B20], uses a 2048-FFT. Therefore, for a given channel bandwidth, the OFDMA PHY presumes smaller intercarrier spacing and places more stringent demands on the hardware.

The issue of intercarrier spacing is made more complex by the decision, embedded in IEEE Std 802.16e, to move toward a “scalable” OFDMA providing for multiple FFT sizes: 2048, 1024, 512, and 128 (leaving out 256 presumably to maintain distinctiveness from WirelessMAN-OFDM). The idea of scalability is to match the FFT size to the channel bandwidth (i.e., larger FFT size with larger bandwidth), optimizing the subcarrier spacing. This idea of scalability was discussed earlier in the IEEE 802.16 Working Group, during the early Task Group 3 development of IEEE Std 802.16a-2003, but was rejected in order to simplify the interoperability problem. The IEEE 802.16 standard is rather ambiguous about channel bandwidth, as it is about carrier frequency, because of the lack of specific, harmonized worldwide spectrum in which to deploy.

In the remainder of this chapter, the 2048-FFT will be assumed, unless stated otherwise.

The OFDMA PHY using 2048-FFT is slightly more efficient than the OFDM PHY under the same conditions because the larger FFT size allows for a relatively smaller cyclic prefix (T_g/T_s).

The number of subchannels within the OFDMA PHY depends both on the FFT size and the time-frequency mapping (discussed below). As shown in Table 12-1, the number of data carriers per subchannel (per OFDM symbol) varies with the permutation method (discussed later in this chapter) and is 48 for full usage of subchannels (FUSC), optional full usage of subchannels (O-FUSC), and adaptive modulation and coding (AMC) and on average 24 and 16 for partial usage of subchannels (PUSC) and optional partial usage of subchannels (O-PUSC).

Table 12-1: Subchannel allocations

Method / FFT size	2048	1024	512	128
DL PUSC	60	30	15	3
UL PUSC	70	34	17	4
UL O-PUSC	96	48	24	6
DL FUSC	32	16	8	2
DL O-FUSC	32	16	8	2
AMC	32	16	8	2

As can be seen from Table 12-1, the power concentration that can be achieved, which is easily computed as $10 \cdot \log_{10}(\text{subchannels})$, varies widely with the time-frequency mapping and FFT size selected.

Time-frequency mapping

In the OFDMA PHY, the mapping of data to physical subcarriers occurs in two steps. In the first step, dictated by the scheduler, data are mapped to one or more data slots (in the time domain) on one or more logical subchannels. In the second step, for each data slot, each logical subchannel is then mapped to a number of physical subcarriers (in the frequency domain), with a mapping that may vary from one OFDM symbol to the next.

The first step, the logical mapping, makes use of certain basic terms in its description:

- **Slot:** The smallest unit of allocation in the time-frequency domain (except for mini-subchannels, which split a UL subchannel allocation further into two, three, or six pieces in the frequency domain). A slot always consists of a single subchannel, but, depending on the physical mapping, consists of one to three OFDM symbols.
- **Data region:** A contiguous allocation of slots in the time-frequency domain.
- **Subchannel group:** A single set of contiguous subchannels. The allocation of subchannels to subchannel groups is fixed.
- **Segment:** One or more subchannel groups that are controlled by a single instance of the BS MAC. As an example, a BS might segment the available subchannels among different sectors. There can be up to three segments where segment 0 must always contain subchannel group 0; segment 1, when present, must always contain subchannel group 2; and segment 2, when present, must always contain subchannel group 4.

Figure 12-1 displays these concepts in an example for 1024-FFT DL PUSC with three segments.

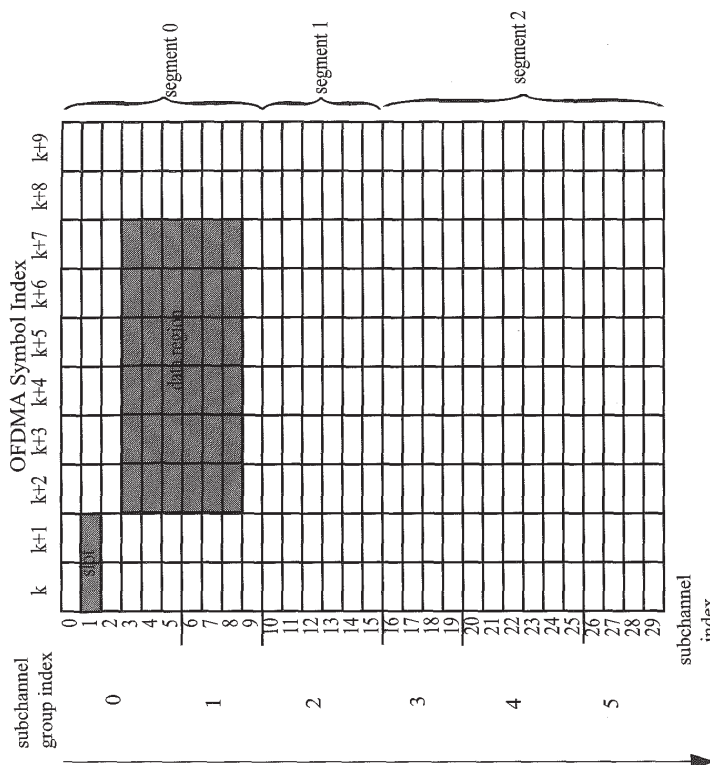


Figure 12-1: Schematic indication of logical mapping elements

The second step, the mapping of logical subchannels to physical subcarriers, is termed *permutation*. The OFDMA PHY specifies seven permutation mechanisms: FUSC, PUSC, O-FUSC, O-PUSC, AMC, TUSC1, and TUSC2. A set of OFDM symbols over which the same permutation method is used (using more than one method in an OFDM symbol is not possible) is termed a *permutation zone*. A single frame may contain one or more permutation zones. These permutation alternatives are described below.

- **FUSC (DL only):** FUSC consists of a single segment containing all subchannel groups. Each subchannel is mapped onto physical subcarriers distributed throughout the entire physical channel as a function of IDCell (a number specific to the sector or cell). This mapping changes with each OFDM symbol. An example of this mapping is shown in the next section. Besides IDCell, which is used for the first DL zone in a frame, the BS may alter the permutations through the use of the PermutationBase parameter. A data slot consists of one subchannel over one OFDM symbol.

The concept behind this method is that of interference mitigation through classical frequency hopping. Under light load, this allows the FEC to correct the few subcarriers on which a collision has occurred. As with classical frequency hopping, this scheme starts to lose its effectiveness if roughly one-third or more of the subchannels become occupied. The efficiency is hence roughly equal to that of system with frequency reuse of 3 (although some claim that it is comparable to a frequency reuse of 1), but the allocation of the instantaneous capacity (i.e., subchannels) to the individual sectors is more flexible. The disadvantage is that the BS needs to obtain a reasonable understanding (through network intelligence or channel measurements) of instantaneous load on other BSs, as throughput degradations are not a measure of only system load, but also of many other factors.

- **PUSC:** On the DL, each physical channel is split into clusters of fourteen subcarriers, which are then mapped to six major groups as a function of the IDCell. Subsequently, up to three segments are created out of these major groups. Within each group, pilots are allocated to each cluster in fixed locations that differ for odd and even symbols. The mapping of the remaining physical subcarriers within each major group to subchannels is similar to that of the FUSC case. A DL slot is defined as one subchannel over two OFDM symbols. On the UL, the subcarriers are split into groups of four consecutive physical subcarriers over a period of three OFDM symbols. Such a group is termed a *tile*. Six of those tiles are allocated to one subchannel, after which a UL slot is defined as one subchannel over that period of three OFDM symbols. The corners of each time-frequency tile are fixed for use as pilots. Except for subchannels allocated to UTUC 12 (CDMA BW request/CDMA ranging) and UTUC 13 (PAPR

reduction allocation/safety zone), the mapping between subchannels and slots on the UL is rotated by a fixed number of slots every slot duration within each segment. A UL mini-subchannel is mapped to either one, two, or three tiles for the duration of the slot.

PUSC is in effect a compromise between the above, completely flexible subchannel allocation and the traditional frequency reuse schemes. It has as disadvantages both the load-balancing intelligence requirement and a somewhat large granularity in capacity allocation. This flexible method is hence valuable mostly when frequent, large shifts in capacity demand from one sector to the next are expected (which for WirelessMAN systems may not be typical) or when the deployment necessitates permanent unequal capacity per segment. PUSC is also claimed by some to be equivalent to a frequency reuse of 1, but segmenting the channel in three is similar in deployment to having a traditional reuse of 3 with one-third of the channel size. PUSC is, however, substantially advantageous over such a scheme due to the lack of need for guard bands between the segments.

- **O(optional)-FUSC (DL only):** O-FUSC differs from FUSC solely in the manner by which pilots are allocated. Whereas FUSC's pilots are distributed in a pseudo-random way throughout the frame (after which the data subcarriers are pseudo-randomly allocated to subchannels), O-FUSC spaces the pilots always eight data subcarriers apart, rotating the locations three subcarriers for each OFDM symbol. After this, the data subcarriers are pseudo-randomly allocated to subchannels with the same algorithm used by FUSC. In synchronized networks, this setup has the effect of completely colliding the pilots when the same logical subchannel is used in nearby sectors.
- **O-PUSC (UL only):** O-PUSC differs from PUSC solely in the size of the tile and the allocation of pilots within it. PUSC in the UL has tiles sized four subcarriers by three OFDM symbols, where the four tile corners are used as pilots. O-PUSC instead uses tiles sized three subcarriers by three OFDM symbols, where only the center is allocated as a pilot.
- **AMC (AAS only):** The abbreviation AMC is not defined in the IEEE 802.16 standard, but it appears to have been derived from *adaptive modulation and coding*. It is also called *adjacent subcarrier permutation*. Using AMC, the entire channel is split in nonoverlapping

groups of nine contiguous physical subcarriers. Subchannels are then mapped to a single such group over six contiguous OFDM symbols or to two such contiguous groups over three contiguous OFDM symbols. The middle subcarrier of each group is used as a pilot in each of the symbols. The allocation of physical subcarriers to these groups is the same on each OFDM symbol. Because AMC is used only with AAS, which inherently provides interference mitigation due to directionality, having such larger groups of carriers susceptible to group collision should not cause any degradation as compared to the use of smaller groups (where group collision would be substantially less recoverable by the FEC).

AMC allows for a somewhat simpler transceiver design than PUSC or FUSC. It is tailored specifically to AAS, where one can easily calculate a single weight per group, rather than having to compute individual weights for each carrier.

- **TUSC1 & TUSC2 (DL AAS only):** TUSC1 and TUSC2 (i.e., variations of tile usage of subchannels) are both optional and are similar to DL PUSC and O-PUSC, respectively. The sole difference is that pseudo-random allocation of subcarriers to subchannels follows a different equation.

The above permutation methods can in principle be combined at random into a single frame by indicating switches between permutation methods in the DL MAP (which, together with the FCH preceding, it is always transmitted with PUSC permutation).

Permutation examples

Because the above permutation mappings may be hard to visualize, a few example allocations are depicted. The allocation is derived for 128-FFT.

FUSC

The example given below assumes $IDCell = 0$, $PermutationBase_0 = [1\ 0]$, and $SymbolNumber = 0$.

1. Map physical carriers to logical data carriers by removing from the physical list all DC carriers, guard carriers, and pilots. Note that the pilots are specified relative to the first nonguard carrier. In Figure 12-2, the mapping of the first 40 physical carriers is shown.

2. Partition logical data carriers into subchannels using the $subcarrier(k,s)$ formula. In Figure 12-2, the mapping is shown for the second subchannel ($s = 1$)
3. Map the logical data carriers k of the subchannels to physical carriers by combining step 1 and step 2. In Figure 12-2, the mapping of the logical indices k of subchannel 1 are shown for the first 40 physical carriers. It shows, for example, that physical subcarrier 12 is the 35th logical subcarrier of subchannel 1 because physical subcarrier 12 is logical subcarrier 0, which is the 35th element of $subcarrier(k,1)$.
4. Repeat step 1 through step 3 for the next OFDM symbol. The different allocation for $SymbolNumber = 1$ is shown as the last subplot in Figure 12-2, which is the result of the variable pilots being located in different places for odd and even symbols.

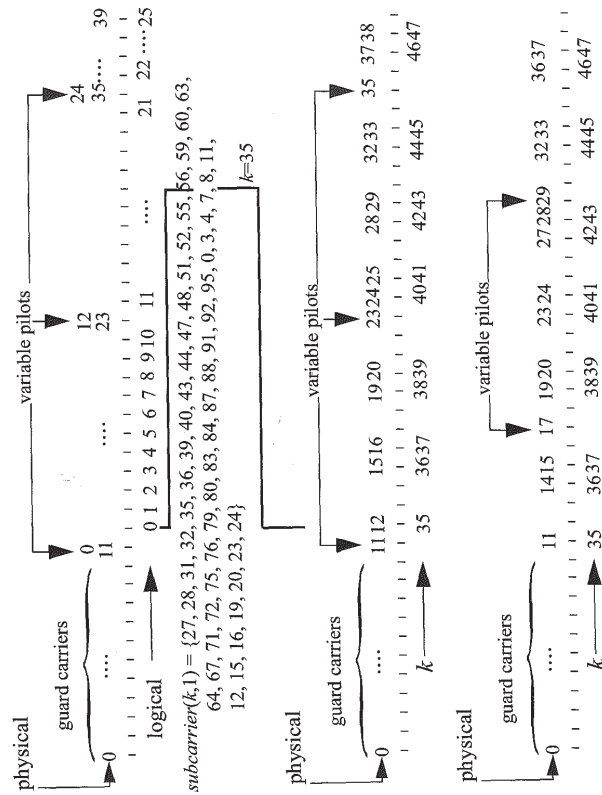


Figure 12-2: FUSC mapping example

PUSC, DL

The example given below assumes that this is the first DL zone and that there is only one segment. It also assumes that the $PermutationBase_3 = [0, 1, 2]$ since this parameter is not specified in the relevant table in the IEEE 802.16 standard.

1. Map the physical clusters consisting of 14 consecutive carriers to logical clusters, which are then assigned to the major groups and from there assigned to segments. The principle is shown in Figure 12-3. However, it is irrelevant to the subsequent mapping, as only one segment is used in this example containing all clusters.
2. Partition logical data carriers within the segment into subchannels, by use of the $subcarrier(k, s)$ formula. In Figure 12-3, the mapping is shown for the second subchannel ($s = 1$).
3. Map the logical data carriers k of the subchannels to physical carriers by combining step 1 and step 2. In Figure 12-3, the mapping of the logical indices k of subchannel 1 is shown for the first 57 physical carriers. It shows, for example, that physical subcarrier 24 is the 11th logical subcarrier of subchannel 1 because physical subcarrier 24 is logical subcarrier 1, which is the 11th element of $subcarrier(k, 1)$.
4. Repeat step 1 through step 3 for the next OFDM symbol. The different allocation for $SymbolNumber = 1$ is shown as the last subplot in Figure 12-3, which is the result of the variable pilots being located in different places for odd and even symbols

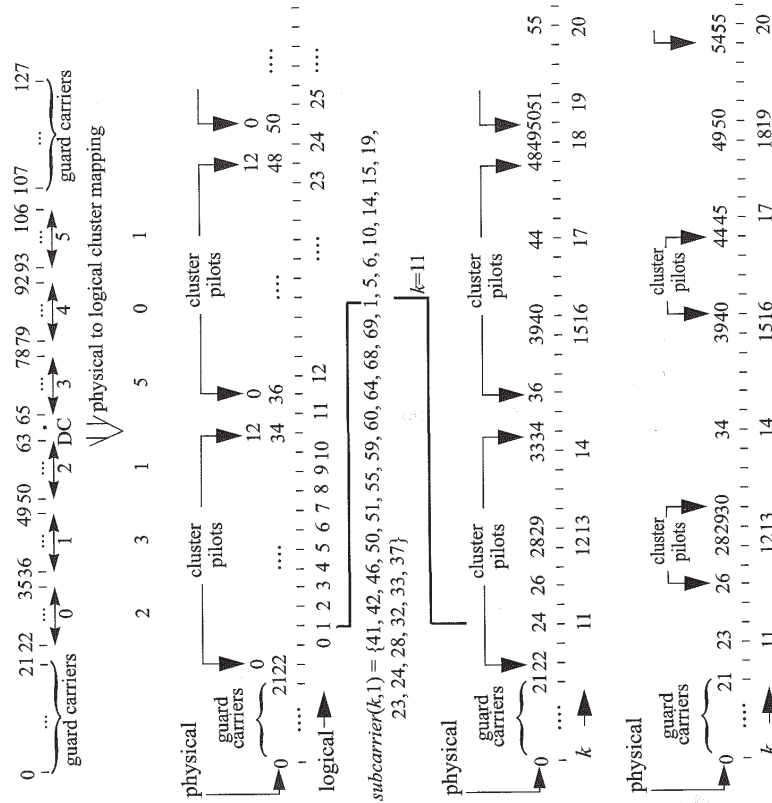


Figure 12-3: PUSC DL mapping example

PUSC, UL

The example given below assumes $UL_PermBase = 0$.

1. Map the physical tiles consisting of four consecutive carriers to per-subchannel logical tiles. The principle is shown in Figure 12-4, in which the carriers belonging to a single physical tile are stacked vertically. As shown, subchannel 1's six logical tile indexes 1 through 5 point to physical tiles 2, 4, 11, 13, 18, and 20, respectively.
2. Allocate the pilots within each tile and sequentially number the logical data carriers, starting with the lowest carrier in the lowest numbered logical tile in the earliest OFDM symbol. Number all carriers within that tile in the same OFDM symbol, and then do the same in the next to lowest logical tile. Repeat until all data carriers within that OFDM symbol for that subchannel have a logical number, and then repeat for the other two OFDM symbols in the slot. The resulting numbering is shown in the second subplot of Figure 12-4, where crossed-out locations are pilot locations.
3. The last step is the mapping of data symbols. Rather than mapping the first data modulation symbol to logical subcarrier 0, an offset of 13 times the subchannel number is applied. This data mapping rotation is shown in the third subplot of Figure 12-4.
4. Repeat step 1 through step 3 for the next slot. The different data mapping for $SymbolNumber = \{3, 4, 5\}$ is shown as the last subplot in Figure 12-4. This is the sole result of the data subchannel rotation mechanism that must be applied on the UL, which in this case results in the previous subchannel 0 being renumbered subchannel 1.

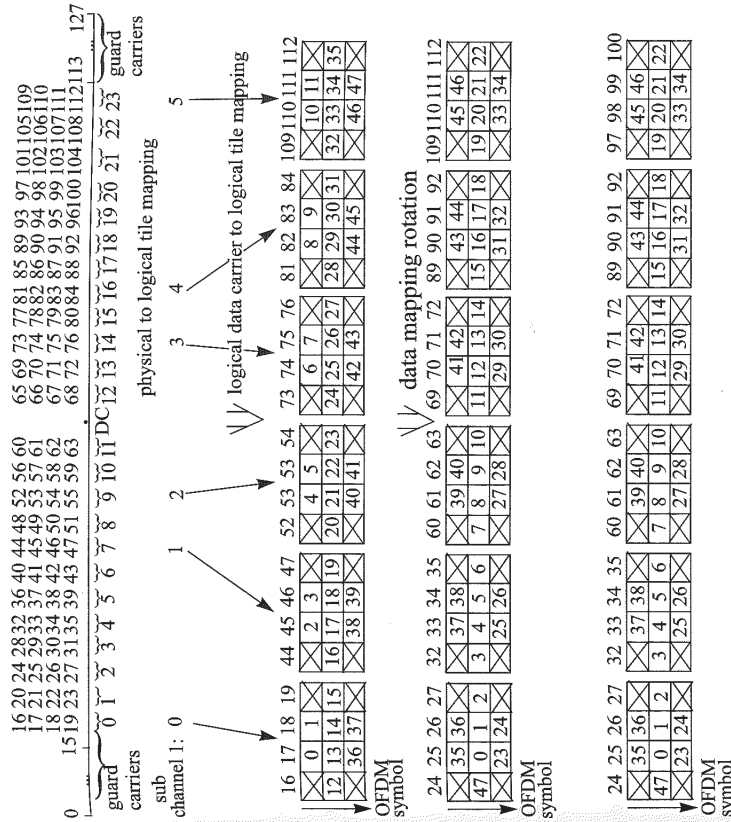


Figure 12-4: PUSC UL mapping example

FRAME STRUCTURE

Point-to-multipoint (PMP)

The only network configuration currently supported for the OFDMA PHY is PMP. It is, however, likely that the amendment project IEEE P802.16j, on mobile multihop relay (see Chapter 9), will target WirelessMAN-OFDMA only.

An example of the logical layout of a frame is shown in Figure 12-5, where the segment spans logical subchannels s through $s + L$. As in the OFDM PHY, the FCH, which has a fixed location and duration in the frame and contains only the DLFP, follows the DL preamble. The DLFP specifies the subchannel groups of which the segment is constructed, the length of the DL MAP, how much repetition coding is used on the DL MAP, and whether there is any change to the ranging allocation from the previous frame.

The MAPs in this example specify, among other things, that the frame spans two permutation zones on the DL, the first of which (PUSC) is mandatory. The MAPs also specify the location and content of all bursts (including burst profile; destination, if applicable; and so on).

As in the OFDM PHY, UL and DL bursts are separated by RTGs and TTGs to ensure that the transceiver at the BS has the time required to switch between receive and transmit. Furthermore (also as in the OFDM PHY), when establishing the MAPs, the BS must take into account the SSTG and SSRTG, which is the minimum time in which an SS can switch between receive and transmit. Using Figure 12-5 as an example, the BS may be prohibited from providing an allocation to the station addressed in burst #6, as its SSTG may exceed the BS's TTG. Similarly, the BS may be prohibited from addressing, in the next frame's DL, the station addressed in UL burst #1, as its SSRTG may exceed the BS's RTG, making it impossible for the SS to receive the necessary preamble of the following frame. Problems like these may result from the use of inexpensive SSs. The inability to address some SSs in a DL frame must be taken into account when scheduling broadcast messages.

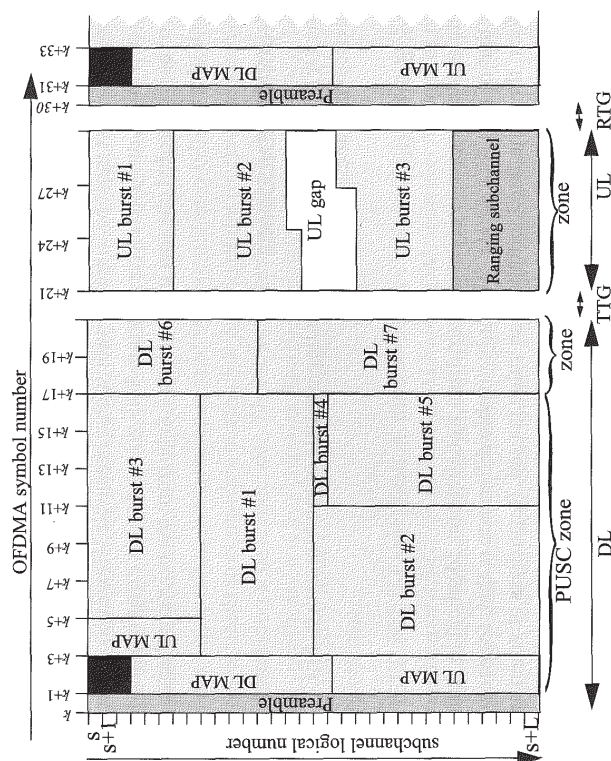


Figure 12-5: Frame structure (TDD)

Preambles

In order to enable channel estimation at the receiver, two steps are taken:

- Preceding each burst with a preamble, as in the OFDM PHY
 - Embedding pilots in the data stream, as in the DVB-RCT standard [B16]
- In comparison to the OFDM PHY, therefore, the OFDMA PHY pilots are more abundant because they are not intended only for phase tracking.

To generate the preambles, the OFDMA PHY uses a series of 114 binary PN sequences of length 568. The sequence to be used is decided by the segment number and the *IDCell*. It is mapped to every third subcarrier except the DC carrier, starting with the subcarrier that equals the segment in number. In each

segment, the SS can derive the complete channel response by interpolation and can augment this by updating the estimate with information derived from the constant and variable location pilots.

Each DL burst must be initiated with such a preamble. However, on the UL, no preambles are used except during AAS zones. In that direction, the BS derives the needed channel information solely from the pilots embedded in each tile.

CHANNEL ENCODING

The OFDMA PHY channel encoding consists of randomization, FEC, interleaving, and modulation.

Randomization

The randomization process is, apart from initialization, identical in definition to that of the OFDM PHY. The only notable difference is that, for each FEC block, the same fixed initialization value is used. Regardless of when and from where it is transmitted, the result for a given input sequence is hence always the same. The remnant value of the randomizer specified in this fashion is, therefore, limited. It is, however, worth noting that the PAPR concerns that stimulate the traditional use of randomizers is substantially mitigated in the OFDMA PHY due to the logical to physical subcarrier permutations and the different time-frequency allocation that may be used when retransmitting the data. Also note that a fixed randomizer seed is necessary with the use of HARQ to allow prandomizer combining. When using chase combining, the transmitted bursts are hence necessarily identical. When incremental redundancy is used, the transmitted bursts are naturally different.

Forward error correction (FEC)

The OFDMA PHY specifies five methods of channel coding: convolutional coding (CC) with tail-biting, block turbo coding (BTC), convolutional turbo coding (CTC), low-density parity check coding (LDPC), and CC with zero-tailing. Tail-biting CC is mandatory; the others are optional.

Convolutional coding (CC)

The CC encoder is identical to that used in the OFDM PHY and the IEEE 802.11a amendment. In the optional zero-tailing case, a single byte 0x00 is appended before encoding, as in the OFDM PHY. In the mandatory tail-biting case, the input data are used cyclically in that the first 6 data bits are fed into the encoder a second time to compute the last 6 output bits. This practice avoids the 1 byte of tail overhead employed by optional zero-tailing; however, the decoder needs to compute a substantial portion of the received sequence twice, mandating a faster decoder. This is an unusual example in that the optional specification is less complex than the mandatory implementation, but requires (slightly more) overhead. The motivation to specify this option is not entirely obvious.

In the IEEE 802.16a specification, the mandatory implementation required concatenation of RS-CC as in WirelessMAN-OFDM. However, it requires the use of tail-biting, rather than the zero-tailing used in the OFDM PHY. The small blocks into which the IEEE 802.16e amendment evolved the OFDMA specification made this concatenation less attractive due to the poor performance of small RS code words.

BTCs and CTCs

The BTC and CTC specifications in the OFDMA PHY are very similar to those in the OFDM PHY, with the minor differences stemming from the need to enable a finer granularity of blocks.

LDPC

The low-density parity check (LDPC) is a coding method that has received substantial attention in the past few years, both academically and in industry. It is no surprise then that LDPC codes were also introduced into the OFDMA PHY through the IEEE 802.16e amendment. Some industry groups, however, appear to be leaning toward the CTC encoder as the primary optional codec.

The LDPC encoding process is the equivalent of the encoding of a data vector of size $n - m$ so that parity check matrix H multiplied by the resultant code word equals an all-zero vector. H is of size $m \times n$, where n is the length of

the code and m indicates the number of parity bits. This results in a code rate of m/n . The matrix $\mathbf{H}$ is constructed out of submatrices of size $(n/24) \times (n/24)$, each of which is identified by a single rotation index. A value of -1 indicates an all-zero submatrix, whereas any larger value indicates an identity matrix right-rotated by the indicated number of times equal to the index. The IEEE 802.16 standard hence provides specifications of the $\mathbf{H}$ matrix by means of the reduced size $(m/24) \times 24$ rotation index matrix, also commonly termed the *shift index matrix*.

Specifically, the standard indicates the shift index matrix for the largest possible block size $n = 2304$. The shift index matrix for smaller block sizes $n^\dagger$ is obtained by replacing each non-negative rotation index $p(i, j)$ by $[p(i, j) \cdot n^\dagger / n]$ for all but one particular index matrix (for rate $2/3$, code A) where $\text{mod}(p(i, j), (n^\dagger / 24))$ is used. The standard specifies five index matrices; one for rate $1/2$ and two each for rate $2/3$ and rate $3/4$. The required dual implementation of index matrices for a particular rate has no technical advantages; it is purely a result of the political process.

The shift index matrix has the general structure shown in Figure 12-6.

[illegible]

Figure 12-6: General shift index matrix structure

Whereas the left side of the matrix may have almost any entries (subject only to column and row weight preferences), the remaining portions are strictly structured. The right side of the matrix consists of a so-called *dual diagonal staircase construction*, where the 0 indexes (which indicate identity submatrices) and the “-1” indexes (which indicate all-zero matrices, as previously explained) create an all-zero section in the $\mathbf{H}$ with two all-unity off-diagonals. The column in the shift index matrix preceding this section is defined so that the first and last indices (indicated by x) are identical, with

only one non-“1” entry (indicated by γ) in the remainder of the column. This construction results in the last column in the $\mathbf{H}$ identified by this column in the shift matrix being of weight three.

The purpose of this strict general definition of the shift matrix (and hence of the $\mathbf{H}$ matrix) is that, for encoding schemes based on the general Richardson-Urbanke method (some specific implementations of which are explained as informative in the IEEE 802.16e amendment), a matrix that requires inversion results in the identity, making the inversion unnecessary.

Interleaving

The mandatory interleaver follows the IEEE 802.11a/g interleaver, with the identical base 16 (unlike WirelessMAN-OFDM, which uses base 12).

Because, as explained in the previous chapter, the interleaver's first step is intended to map adjacent coded bits to nonadjacent subcarriers, this does create an additional permutation on top of the logical to physical carrier mapping. In the late stages of the development of the IEEE 802.16e amendment, it was discovered (see [B12]) that the net effect of this combination of permutations could result in a performance loss as high as 5 dB. To resolve this problem, an optional interleaver was added. It has the same structure, but it uses as its base 16 times the number of slots per FEC block.

Modulation

As for the WirelessMAN-OFDM PHY, the modulation of the OFDMA PHY consists of square BPSK through 64-QAM constellations for all data. Exceptions exist for special channel feedback messages, which are encoded with various forms of circular constellations.

CONTROL MECHANISMS

Fast-feedback

The OFDMA defines two fast-feedback methods for the UL. These can be used to relate time-critical PHY parameters. Parameters for which this feedback is defined are SNR, specific MIMO coefficients for two antennas, and MIMO configuration parameters [space-time transmit diversity (STTD) vs spatial multiplexing, open- vs closed-loop spatial multiplexing, the permutation type, antenna selection, and precoding matrix selection]. Fast-feedback subchannels can be allocated by the use of a special MAC subheader or by the use of various DL MAP IEs.

The data to be transmitted within the fast-feedback channel are not encapsulated in an ordinary PDU message, but are instead in an orthogonal encoding of only a few bits of data using QPSK modulation. Each of the possible bit combinations is mapped to a sequence with one octal value per tile in the subchannel. This octal value represents a QPSK sequence for each of the eight data carriers per tile.

The specification allows for both full- and half-subchannel fast-feedback channels. The full subchannel can transfer 4 bits or 6 bits, depending on whether the fast-feedback is regular or enhanced. The half subchannel transfers 3 bits of data per slot. Although the IEEE 802.16 standard does not explicitly state so, the orthogonality of this setup allows for multiple SSs to transfer parameters during the same slot.

CDMA ranging and BW requests

To allow for initial ranging, maintenance ranging, handover ranging, and BW requests, the OFDMA PHY provides a collision-based method using PN sequences. The mandatory ranging allocation (called *ranging channel*) consists of six (and optionally eight) contiguous subchannels. Multiple channels may be allocated contiguously as well. The ranging and bandwidth channel are specified in the UL MAP.

Note that the specification of a minimum of six subchannels for initial ranging makes operation of this PHY with 128-FFT currently impossible, as, for 128-FFT, only four subchannels are defined in the uplink.

The initial ranging and handover ranging transmission may, on instruction from the BS, span either two or four OFDM symbols. When the two-symbol type is to be used, the transmission follows the depiction of Figure 12-7. This depicts the dual transmission of the same BPSK-modulated PN sequence, with the cyclic prefix (CP) and cyclic postfix replacement as indicated.

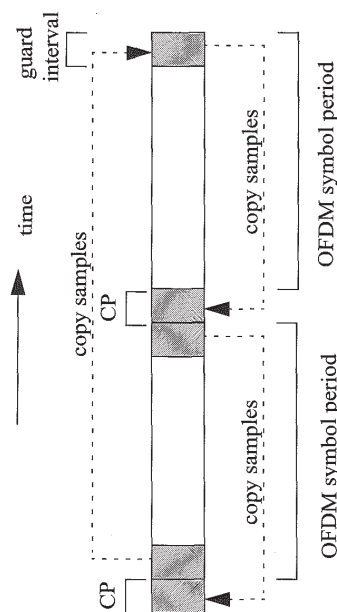


Figure 12-7: Single-slot initial ranging transmission for OFDMA

The transmission of the PN sequence in this fashion results in a phase-contiguous symbol and provides an addition gain on top of the spreading gain due to the repetition. To provide even more gain, the BS can instruct the use of the four-symbol alternative, in which the SS transmits two of the above symbols built from consecutive PN sequences out of the list of available sequences (in which the first PN sequence must be an even-numbered choice). Due to the spreading gain, this method can resolve multiple initial ranging transmissions simultaneously and is hence called *CDMA ranging*. In contrast to traditional CDMA, the PN sequences are modulated on the carriers in the frequency domain, rather than transmitted sequentially in the time domain.

For periodic (maintenance) ranging and BW requests, the same ranging channel is used, but the symbols are transmitted with the regular cyclic prefix instead of by the method shown in Figure 12-7. For these two methods, the transmission may be one or three OFDM symbols in duration (remember that a UL slot is three OFDM symbols in duration), but in the case of BW requests, three consecutive PN sequences must be used.

All PN sequences are created by a PRBS with generator polynomial $1 + x + x^4 + x^7 + x^{15}$ and an initial state that is partially fixed and partially consists of the IDcell so that different BSs can distinguish between the sequences. This PRBS results in 256 unique PN sequences, each 144 bits in length, a consecutive set of which is allocated to a BS through configuration. The BS can then divide its allocated sequences among the four functions (initial ranging, periodic ranging, BW requests, and handover ranging) by means of the UCD message.

Because the sequences for these methods are known, they can be used not only to identify the transmitting SS by the received sequence but also as a preamble, allowing extraction of (among other things) channel response for the used subchannels and timing and frequency offset information. Specifically, in response to an initial ranging sequence, the BS can immediately provide power, timing, and frequency offset corrections in its response.

PAPR reduction/safety zone

As discussed previously, a PAPR that exceeds the backoff of the amplifier results in nonlinear distortion at the transmitter that is unrecoverable at the receiver. Typically, this is tolerated by randomizing the data and backing the amplifier off until the error probabilities are tolerable. WirelessMAN-OFDMA also provides another method to minimize PAPR and allow for reduced backoff (and, therefore, higher average power or less expensive amplifiers). This method consists of allocating of subchannels, both in the DL and UL, in which the BS and SSs, respectively, can modulate arbitrary data to reduce the overall PAPR of their transmissions. These subchannels are filled with, in effect, random energy that can be freely ignored by the receiver. Naturally, this method comes with a cost: the transmitting party must first

pass the data to be transmitted through the IFFT, compute the PAPR, and determine additional data that, when transmitted in the PAPR reduction subchannel, will ensure a low overall PAPR.

Note that the specification does not preclude the use of other PAPR reduction mechanisms, such as windowing and time-domain peak cancellation (see, for example, [B55]) as long as the transmitter relative constellation error does not exceed the required values.

The BS may also provide safety zones. These are gaps in the UL and DL schedule. To be used, they must be explicitly indicated because the MAPs specify only the duration of an allocation, with the remaining positioning information being implicit from the sequence of allocation. Gaps can be specified in coordination with other BSs to reduce interference on the indicated subchannels for the other BS or BSs.

HARQ support

To support HARQ feedback, the BS may allocate one or multiple pairs of UL acknowledgment channels, each of which consists of the even- or odd-numbered tiles that make up half a subchannel. As with the fast-feedback channel, data are QPSK-modulated directly on the channel, without packetization. The data consist of only a NACK or ACK bit, each of which is expanded to a specific orthogonal sequence to fill the three tiles. The location in the acknowledgment channels in which an HARQ-enabled SS returns its positive or negative acknowledgment is determined by the number of preceding SSs in the DL MAP that are to return such a signal.

HARQ is defined to support chase combining (implying simple retransmission of the data) for all coding methods as well as incremental redundancy methods for both the CC and CTC codec. For CC, the incremental redundancy is achieved through retransmission of the data using a different puncturing sequence.

Chapter 13 Multiple antenna systems

Support for advanced antennas

For operations below 11 GHz, the IEEE 802.16 standard provides support for advanced multi-element antenna systems, including adaptive antenna systems (AAS), space-time coding (STC), and multiple-input, multiple-output (MIMO) systems. These techniques are not supported above 11 GHz as they exploit spatial diversity not substantially present above 11 GHz. This chapter provides an overview of the IEEE 802.16 MAC and PHY support for these multiple antenna systems. This chapter subsequently discusses AAS, open-loop transmit diversity methods (i.e., all methods not requiring feedback), and closed-loop transmit diversity methods (i.e., all methods requiring feedback). AAS is also a closed-loop method, but it is described separately in this chapter, due to the fact that its use has, unlike all other methods, systemwide consequences.

The descriptions in this chapter refer to specific numbers of antenna elements, but should not be construed as limiting the number of physical antennas a system may have. A system may use more than the specified number of physical antennas as long as the resultant signal waveform meets the standard's specification. It is, for example, possible for a compliant system to use cyclic delay diversity (CDD) with multiple transmit antennas, resulting in a signal comparable to a single antenna's signal passed through a multipath channel. On the receive side, the number of antennas beyond the minimum (for example, four in the case of 4x4 MIMO) is completely transparent to the air interface and hence permissible as well.

ADAPTIVE ANTENNA SYSTEMS (AAS)

AAS technology, popularly known as a smart antennas (see [B2], [B32], and [B37]), accommodates the spatially diverse location of energy sources by discriminating signals based on their angles of arrival (AoAs) and angles of departure (AoDs) at an antenna array. In very general terms, the

discrimination of signals, which is outside the scope of the IEEE 802.16 standard, is achieved by computing a complex weighted sum of the signals of all antenna elements, where the weights may be computed according to various metrics.

Through the AAS options, the IEEE 802.16 standard supports the use of smart antennas to perform beam forming. Beam forming can effectively create a narrower signal beam, resulting in increased gain and, therefore, higher range. This in turn increases capacity by increasing the range at which a particular PHY burst profile can be received. In addition, if a BS is capable of multiple simultaneous beams, capacity can be increased through spatial diversity. Theoretically, the spectral efficiency can be increased linearly with the number of antenna elements at the BS. This can lead to an in-cell frequency reuse proportional to the number of antennas.

AAS also allows for the suppression of noise sources, improving the SNR at the receiver; and discrimination on the AoD allows energy to be concentrated in the direction of the intended recipient, enabling larger cell ranges. In addition, nulls can be steered in particular directions, enhancing the interference resistance of the system. An example beam-forming network is shown in Figure 13-1. Obviously, beam forming toward mobile devices adds challenges.

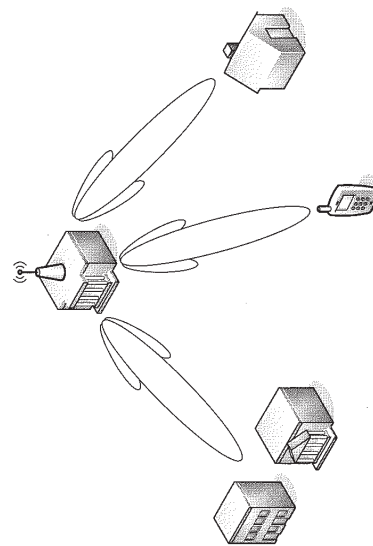


Figure 13-1: Example beam-forming network

Drawbacks of these approaches include the increased system complexity and the inability to broadcast messages, reducing the spectral efficiency due to repetition of broadcast MAC messages to the various recipients.

AAS support in IEEE Std 802.16

While the AAS option requires some AAS-specific capabilities in an SS, the actual beam forming is defined only at the BS side of the link. Therefore, AAS systems in the context of the IEEE 802.16 standard are discussed purely as a BS feature, with both DL and UL AAS components. This limits the complexity of the AAS requirements in the SS to such functions as understanding the AAS zones, implementing AAS-specific preambles and permutations, and using AAS-specific messaging such as private DL MAPs and UL MAPs. At the BS, the algorithms and hardware designs necessary for AAS support are implementation-specific and left to vendor differentiation.

An AAS-enabled SS is an SS capable of establishing and maintaining connectivity with a BS that is actively using an antenna array. This predominantly requires synchronization and MAC capabilities. It does not pose any requirements on the number of SS antenna elements. An SS may also employ an antenna array, and could do so transparently from the standard's perspective, but SS arrays are unlikely due to complexity and size constraints. If AAS is used to extend the range of the cell, both the SS and BS need to be prepared to take additional steps to allow the SS to enter the network. The frame start preamble is a repetitive, well-known pattern. The SS may take advantage of processing gain associated with that preamble to synchronize with the DL in time and frequency, even if it is receiving the DL too weakly to decode the DL MAP and DCD messages.

The AAS option supported by IEEE Std 802.16 is defined so that a single BS can support both AAS-enabled and non-AAS SSs simultaneously. The key difference between pure PMP and AAS is that some AAS SSs may be outside the coverage area of some beams of an AAS BS. The basic framing needs to be modified to accommodate this; a single broadcast cannot be used to communicate information to all AAS SSs. For an IEEE 802.16 system, this results in a challenge, as IEEE Std 802.16 relies on broadcast data (UCD, DCD, DL MAP, UL MAP) to communicate the transmission schedules and to

schedule contention slots. These messages must either be repeated to each individual SS or repeated to SS clusters in the same general direction, although the MAPs need contain only the schedule elements relevant for the targeted SS(s).

As AAS is optional, the BS must always support non-AAS SSs and, therefore, support broadcast transmissions. The coexistence of AAS and non-AAS SSs is achieved by partitioning the IEEE 802.16 frame in time into AAS and non-AAS zones, where the AAS zone is dedicated to AAS-capable SSs. In the AAS zone, AAS-capable SSs receive or transmit, knowing that the BS is directing a beam in their direction. This partitioning can be adjusted dynamically by the BS, as with dynamically asymmetric TDD. The IEEE 802.16 MAC and PHY also support additional functions necessary to support and manage AAS SSs, such as the ability to dynamically choose the best “beams” for each AAS SS and to support ranging of AAS-capable SSs. Since the AAS zone of the frame is explicitly indicated in the broadcast MAP by the BS, non-AAS SSs would not be confused by AAS-specific messages sent in the AAS zone.

We noted above that AAS in the IEEE 802.16 context has both a DL and UL component and provides range extension. However, the structure of the UL MAP allows for scheduling simultaneous or time-overlapping transmissions on the UL, as each scheduled transmission has both a start time and duration. Therefore, a BS may exploit this property to achieve spatial division multiple access (SDMA) transmissions in the UL. This approach can be used to substantially increase the UL capacity, with or without an increase in the range. Strictly speaking, these simultaneous transmissions can be achieved with non-AAS SSs, as it does not require the use of AAS zones or any other AAS-specific messages. On the DL, however, this is not possible, as each allocation implicitly ends with the start of the next allocation.

DL and UL framing

Figure 13–2 shows the TDD framing with AAS support, with both non-AAS and AAS zones. In the OFDM case, the AAS DL zone starts with an AAS-specific preamble; and, in the UL, all SSs require a separate preamble. Also,

again in the OFDM case, the allocation start time in the UL MAP transmitted in an AAS zone is always relative to the start of that AAS zone.

It should be noted that the UL MAPs transmitted in the mandatory broadcast and in the AAS zone may overlap. Whenever such overlap occurs, the most recently received UL MAP with overlapping IE takes precedence.

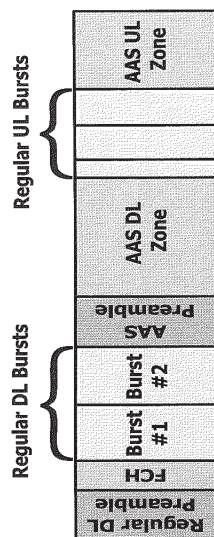


Figure 13–2: TDD framing for AAS Systems

The partitioning concept is very similar for FDD systems. Figure 13–3 shows the FDD framing of AAS systems.

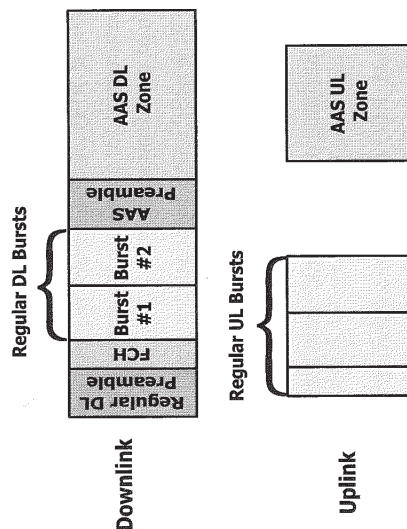


Figure 13–3: FDD framing for AAS systems

MAC service and control functions

The IEEE 802.16 MAC supports the following functions for AAS-capable SSSs:

- The ability to transmit private management messages (such as UL MAP, DL MAP, UCD, and DCD) that may be sent directly to the AAS SS Basic CID, instead of to the Broadcast CID as in generic PMP. It is still possible for an AAS SS to receive broadcast information in certain deployments. During the initial ranging process, the AAS SS communicates to the BS its ability to receive broadcasts.
- Dynamic allocation of specific regions within the frame for initial ranging and BW requests for AAS SSSs. The initial AAS ranging is achieved using a separate CID in order to avoid conflicts with the regular Initial Ranging CID used by non-AAS SSSs.
- A set of AAS MAC management messages, such as those required for obtaining feedback from an AAS SS for channel estimation and for selecting the most optimal beam for an AAS SS.

AAS MAC management messages

The following AAS MAC management messages are defined:

- The AAS-FBCK-REQ (AAS feedback request) message is used to request channel measurement for a specific frequency. This may be used to adjust the direction of the adaptive array.
- The AAS-FBCK-RSP (AAS feedback response) message is sent in response to AAS-FBCK-REQ and contains the channel measurements.
- The AAS_Beam_Select (AAS beam select) message is used by an AAS-capable SS to indicate the preferred beam. The BS may use this information in deciding on the optimal beam for communication with this SS.
- The AAS_BEAM_REQ (AAS beam request) message is used to request channel measurement for a specific beam in order to adjust the adaptive array at the BS.

- The AAS_BEAM_RSP (AAS beam response) message is sent by an SS in response to an AAS_BEAM_REQ.

Channel state information

The adaptive array operation depends on the estimation of the channel state in both directions. The BS can estimate the UL channel state directly. In TDD systems, the BS may use this UL channel information to estimate the DL channel. However, for FDD systems this method is not accurate due to the different frequencies used for UL and DL. Therefore, for the FDD case, an AAS-FBCK-REQ message is used by the BS to instruct the SS to measure and send channel state estimation using an AAS-FBCK-RSP message. The BS may automatically allocate UL slots for transmitting AAS-FBCK-RSP messages after the measurement period.

AAS DL synchronization and initial ranging

Since a new SS trying to join the system may lie outside all beams, special measures are required to support DL synchronization of AAS SSSs. Some SSSs with high processing gain may be able to decode the broadcast DL frame boundaries for timing and frequency synchronization. The BS may also periodically perform active scanning by aiming at different directions or may use some PHY-specific diversity methods to support DL synchronization of such SSSs.

An AAS-enabled SS that is outside broadcast range and wants to perform initial ranging has no information on the BS. It must, therefore, wait until it receives the AAS network entry preamble, which provides substantial processing gain, and respond immediately. The cell range in which SSSs can join the BS is, therefore, limited by the directional gain of the AAS, which is related to the number of antenna elements, by the broadcast link budget, and by the processing gain of the AAS network entry preamble.

As with DL synchronization, some AAS stations may be able to decode MAP and channel descriptor information from the broadcast frame. If an SS is able to reliably decode this information, the initial ranging process can be performed as in the non-AAS case. Adjustments to the adaptive arrays can be made by the BS during this process. In order to support SSs that cannot decode the broadcast portion of the frame, a BS may use PHY-specific predefined AAS contention regions for the various general directions in order to allow AAS SSs to alert the BS of their presence. This approach has substantially higher overhead.

The SS always attempts initial ranging by trying to decode the broadcast DL MAPs and DCD. If it is unable to decode that broadcast, it tries the AAS slots. These AAS alert slots are similar to the regular contention slots for initial ranging. However, an AAS SS uses all contention slots, as opposed to just one slot used by a regular SS, so that the BS has sufficient time and processing gain to aim the beam at the SS's direction. If the BS is able to receive the alert message with sufficient processing gain, it may focus a beam on the SS and transmit the MAPs and channel descriptors. If the SS receives the DL parameters, it continues with the rest of the network entry process. If no DL MAP and DCD are received, the AAS SS performs an exponential backoff identical to the non-AAS case to select the next frame to send the alert.

AAS BW requests

An SS that wants to request bandwidth may lie outside a beam. When an SS performs ranging, its ability to receive broadcast allocations is communicated in the RNG-REQ message. The BS can instruct the SS to use broadcast allocations for BW requests, just like non-AAS SSs. If the SS is not capable of receiving broadcast or if the BS does not want the SS to use broadcast allocation, the BS is responsible for polling in the general direction of the SS to allow BW requests. The BS may modify the BW request method dynamically by instructing the SS in a RNG-RSP.

AAS support in OFDM PHY

Similar to DL subchannelization, AAS is supported in a zone logically separated from the remainder of the frame. Within the AAS zone, the BS can create what can be conceptualized as parallel instances of the PHY and lower MAC, each active on one or more beams in both SDM(A) and TDM(A) fashion. Each instance has its own preambles, FCH (termed *AAS-FCH*), and MAPs, with periodic use of a dedicated UCD and DCD. The IEEE 802.16e addition of private MAPs is particularly useful for this feature. Within each AAS-FCH, the BS transmits an AAS-DLFP that is different from the regular DLFP in that some of the functionality of the MAPs, such as provisioning UL allocations and contention-based opportunities, is embedded in it.

Two MAC management messages are specified to support the AAS PHY. The first allows the exchange of channel feedback information, which consists of CINR, RSSI, and the complex channel coefficient for a regularly spaced (on either side of the DC carrier) set of carriers with intervals of 4, 8, 16, or 32 carriers, depending on the request. The measurements are to be performed on a specific indicated burst. The second message is a similar exchange of channel information except that measurement information is requested and provided on one or more beams.

For initial ranging, two separate messages are provided, one to be used with full channel AAS initial ranging opportunities and one to be used with subchannelized AAS initial ranging opportunities. Both messages violate the IEEE 802.16 MAC architecture in that they have no MAC header. It is unclear whether this omission is by design or by error; but, because they are the only responses allowed in the respective allocation, it is not a fatal violation.

The full channel initial ranging message allows the SS to provide the BS with measured amplitude values of up to four beams, providing the BS with an initial indication of which beam may best be used for the SS in question. The subchannelized initial ranging message, which may be used only if full channel initial ranging repeatedly failed, must be filled with the measured phase offset of three beams relative to a first beam (i.e., four beams total), providing the BS a measure of directionality for the SS and the average RSSI over those beams. In both messages, the SS sets a randomly selected network entry code, which the BS will use in its response to identify the SS.

AAS support in OFDMA PHY

AAS is supported by the OFDMA PHY for FFT sizes larger than 128 by means of the creation of an AAS diversity MAP zone (DMZ). The AAS DMZ can be allocated only on a specific set of subchannels of the DL: the highest two numbered subchannels in the segment $(N - 1 \text{ and } N)$ for FUSC and PUSC; and the fourth and $(N - 4)^{\text{th}}$ subchannel for AMC. The reason for this difference is that FUSC and PUSC provide frequency diversity through their permutations (logical subchannel to physical subcarrier mapping), whereas AMC does not.

The AAS DMZ contains pairs of the AAS DL preamble followed by the AAS-DLFP, each sent on a (directional) beam. The AAS-DLFP contains some configuration information (the beam used and type and presence of preambles) as well as a pointer to an initial ranging opportunity and a pointer to a DL allocation. The latter pointer may point to the broadcast DL MAP or to a private DL MAP or may constitute a private DL MAP in the form of a single allocation depending on the CID and DIUC in the pointer.

In addition to provisioning AAS as a zone within the general frame, the OFDMA PHY allows the use of so-called *superframes*. A superframe is a period of up to 1 s that must meet the following requirements:

- It must start with at least 20 regular frames, each containing UCD, DCD, UL MAP, and DL MAP, and ranging channel.
- It contains AAS-only periods no longer than 200 ms followed by at least one regular frame containing UCD, DCD, and DL MAP.

The motivation for this construct is that it allows the BS to spend up to 95.2% of its time in AAS-only mode, which is advantageous from a capacity and range perspective, without violating the timeout limitations on synchronization, which are defined as the ability to receive the DL MAP and the DCD. Because those timeouts have a maximum limit of 600 ms, the superframe construct provides at least three synchronization opportunities in that period and provides at least 20 regular frames to reacquire synchronization and network entry for non-AAS devices.

In terms of MAC support, the OFDMA PHY makes use of the same channel feedback message as discussed in regard to the OFDM PHY.

OPEN-LOOP TRANSMIT DIVERSITY

An “open-loop” transmit diversity method exploits the diversity provided by multiple antennas, but requires no knowledge at the transmitter of the channel. These methods require no MAC support.

The OFDM PHY specifies STC as its sole open-loop transmit diversity scheme. The OFDMA PHY, on the other hand, specifies three such methods. Although the IEEE 802.16 standard describes all these methods broadly as STC, a distinction is made in the proceeding between actual STC, *frequency-hopped diversity coding* (FHDC), and *spatial multiplexing* (SM), which is more popularly known as *open-loop MIMO*. The basic transforms for these methods are summarized in Figure 13-4.

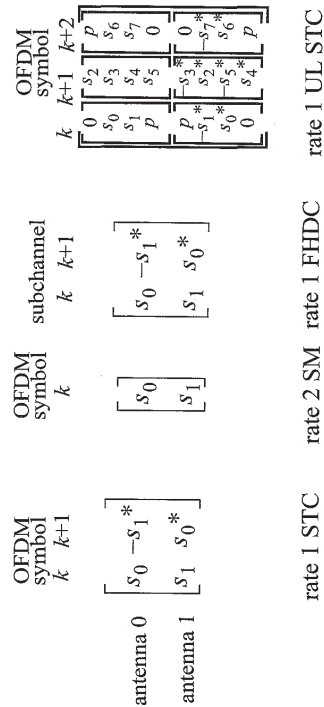


Figure 13-4: Open-loop transmit diversity schemes

Each of the methods shown in Figure 13-4 requires two antenna elements at the transmitter or, if the BS is sectorized, two elements per sector.

STC uses the optimal space-time block code presented by Alamouti [B1], which achieves channel capacity (see [B44]). This STC is also known by the abbreviations *STTD* (space-time transmit diversity) or *STBC* (space-time block coding) and is, for example, also defined as part of the wideband CDMA (W-CDMA) standard [B17] (although in transposed form, which does not change its properties). This method requires that the channel be constant during the two-symbol interval over which the code is defined.

STC support in OFDM PHY

In the OFDM PHY, STC specifications are provided only for the DL.

The method is applied as follows: Data for two subsequent OFDM symbols s_0 and s_1 are collected after the modulation stage, where the pilot modulations are copied from the first symbol to the second. During the first OFDM symbol of the STC block, s_0 is transmitted from the first antenna and s_1 from the second antenna. During the second OFDM symbol of the STC block, the first antenna transmits $-s_1^*$ and the second antenna s_0^* .

The SS will hence receive $r_0 = h_0 \cdot s_0 + h_1 \cdot s_1$ during the first OFDM symbol, where h_0 and h_1 are the channel responses from antenna 0 and 1 to the SS antenna, respectively, and $r_1 = -h_0 \cdot s_1^* + h_1 \cdot s_0^*$.

The reception of this post modulation transform can be denoted as follows:

$$\begin{bmatrix} r_0 \\ r_1 \end{bmatrix} = \begin{bmatrix} s_0 & s_1 \\ -s_1^* & s_0^* \end{bmatrix} \begin{bmatrix} h_0 \\ h_1 \end{bmatrix}$$

Because the preamble for this PDU is transmitted on alternate subcarriers from the two antennas (even subcarriers for antenna 0 and odd subcarriers for antenna 1), the SS has knowledge of the channel responses $\hat{h}_0$ and $\hat{h}_1$ through simple frequency interpolation.

The receiver then applies the following transform to achieve the estimates $\{\hat{s}_0, \hat{s}_1\}$ using the channel estimates:

$$\begin{bmatrix} \hat{s}_0 \\ \hat{s}_1 \end{bmatrix} = \begin{bmatrix} \hat{h}_0^* & \hat{h}_1 \\ \hat{h}_1^* & -\hat{h}_0 \end{bmatrix} \begin{bmatrix} r_0 \\ r_1 \end{bmatrix} = \begin{bmatrix} \hat{h}_0^* \cdot h_0 + \hat{h}_1 \cdot h_1 & \hat{h}_0^* \cdot h_1 - \hat{h}_1 \cdot h_0 \\ \hat{h}_1^* \cdot h_0 - \hat{h}_0 \cdot h_1 & \hat{h}_1^* \cdot h_1 + \hat{h}_0 \cdot h_0 \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix}$$

The above equation shows the diversity combining on the diagonal terms and shows that the off-diagonal interference terms go to zero if the channel estimates are accurate. Note that this transform is also used for the modulated pilots.

The STC codec gain can be used to increase modulation/coding efficiency within the broadcast range. Also, to extend the cell range beyond the

broadcast range, a separate STC zone is allocated, in which the BS sends an STC-encoded preamble and FCH as well as the MAPs and DCD/UCD, as needed. The inclusion of broadcast messages in the STC zone is necessary since a station outside broadcast range will be unable to decode the FCH and MAPs outside the STC zone.

STC, FHDC, and MIMO support in OFDMA PHY

The OFDMA PHY provides the same method of STC as the OFDM PHY for deployments in which the BS has two antennas (or four, where the second pair transmit the same signal as the first pair but with a respective phase rotation received through the fast-feedback mechanism so that directional gain is achieved). The method is defined only for FUSC and PUSC.

Using FUSC, the permutation during an STC zone changes only once per two OFDM symbols; an FUSC slot using STC can, therefore, be said to last two OFDM symbols. Within those two symbols, data are modulated from both antennas, as described for the OFDM PHY. For the pilots, different sequences apply to odd and even OFDM symbols, but the pilots are placed on the same subcarriers in both symbols. This method can be represented by the transfer matrix shown on the left in Figure 13-4. Because it encodes two data symbols over two OFDM symbols, this method is classified as a rate one encoding method.

Another method allowed by the OFDMA PHY is spatial multiplexing, in which a separate data symbol is transmitted from each antenna without repetitions in the subsequent OFDM symbol. Spatial multiplexing provides increased capacity, but provides no diversity gain and requires a more complex receiver including multiple receiver chains.

Another variant allowed is FHDC, which is conceptually the same as STC, but with encoding over two subchannels instead of over two OFDM symbols.

Unlike in the case of the OFDM PHY, STC and SM are also defined for the UL, specifically for PUSC. Recall that a tile for UL PUSC is defined as four contiguous carriers over a span of three OFDM symbols, with the corners reserved for pilots. Using STC and SM on the UL, this tile definition is slightly modified so that the pilots on the diagonal are not transmitted on

antenna 0 and the pilots on the cross-diagonal are not transmitted on antenna 1. The STC encoding is subsequently applied per two subcarriers within the same OFDM symbol, as shown in Figure 13-4, where each vector indicates the encoding of the four subcarriers within the tile for a specific OFDM symbol per antenna.

PUSC also allows what is termed *virtual MIMO*, in which antenna 0 and antenna 1 belong not to the same SS but to completely different SSs. This allows SSs to transmit simultaneously with near certainty of the channels being uncorrelated and without requiring any additional complexity.

Lastly, a provision is established for STC and SM where the transmitter has four antennas, the matrices for which are shown in Figure 13-5.

	OFDM symbol		OFDM symbol		OFDM symbol	
	k	$k+1$	$k+2$	$k+3$	k	k
antenna 0	s_0	$-s_1^*$	0	0	s_0	$-s_1^* s_4 - s_6^*$
antenna 1	s_1	s_0^*	0	0	s_1	$s_0^* s_5 - s_7^*$
antenna 2	0	0	s_2	$-s_3^*$	s_2	$-s_3^* s_6 s_4^*$
antenna 3	0	0	s_3	s_2^*	s_3	$s_2^* s_7 s_5^*$
	rate 1 FHDC				rate 2 FHDC	
					rate 4 FHDC	
					$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}$	

Figure 13-5: Four-antenna STC and SM

CLOSED-LOOP TRANSMIT DIVERSITY

In addition to the open-loop schemes, the IEEE 802.16e amendment adds closed-loop transmit diversity methods for the OFDMA PHY. These methods rely on channel state information sent back by the SS on command from the BS. For this purpose, the BS uses the UL_Sounding_Command_IE, which provides a large array of possibilities for how the SS should parse the measurements it made.

Precoding

One of the closed-loop methods is so-called *precoding*, which is similar in application and motivation to STC but exploits knowledge of the channel. The coding in this case maps the orthogonal MIMO streams to the physical antennas.

There are principally two methods of conveying, from the SS to the BS, which precoding matrix to use. Using the first method, the SS simply returns quantized versions of the channel metrics. In the second method, both sides of the link have access to a set of so-called *codebooks*, each containing an indexed set of coding matrices. For each channel rank, which never exceeds the number of transmit antennas and dictates the number of spatial streams the channel can support, a different codebook is specified in the standard. The receiving station computes a precoding matrix to optimize throughput for the current channel rank, finds the nearest matrix in the codebook of the current channel rank, and sends the index of the selected matrix as well as the channel rank back to the transmitting station.

For each rank, the codebooks are designed so that the chordal distance between the code matrices is maximal. They are specified with 3-bit indexes (8 code matrices per codebook) and 6-bit indexes (128 code matrices per codebook). The choice allows the implementer a trade-off between complexity and performance. The receiver's decision about which index to select is implementation-dependent and may make use of various distance metrics between the computed optimal matrix and the available matrices in the codebook.

With the introduction of high-speed mobility as a consideration during the development of IEEE Std 802.16e, it was observed that, despite the use of the fast-feedback channel as discussed in Chapter 12, the protocol delays could in some cases exceed the coherence time of the channel. This would make the instantaneous channel metrics outdated by the time they were applied. To resolve this issue, a method was introduced to feed back not only the instantaneous channel metrics but also (long-term) first- and second-order statistics of the channel. The first-order statistic used is the LOS component of the Ricean fading channel approximation. The second-order statistics consist

of the channel's spatial correlation information. These statistics may be used to improve the estimate of the channel condition at the time of transmission.

Antenna selection

Using antenna selection, the receiving SS can use the fast-feedback channel to identify the group of antennas it prefers the transmitting BS to use for full-rate transmissions. The spatial multiplexing is performed by the selection of a single vector (similar to the rate 4 FDHC shown in Figure 13-5) where one or more elements are nulled (the vector being of a length equal to the number of transmit antennas, wherein the number of non-nulled elements is equal to the number of spatial streams desired). Antennas for which the element reads null are not used during the transmission. This method is defined only for systems with three or four transmit antennas.

Antenna grouping

The antenna grouping method uses the methods described in the open-loop section of this chapter. These methods are less than full-rate. Instead of disabling antennas as with antenna selection, the antenna grouping method groups antennas into STC pairs. This may be most trivially visualized as row permutations of the space-time coding matrix. For example, for four transmit antennas, these are row permutations of the rate 1 and rate 2 FHDC shown in Figure 13-5. The receiving SS uses the fast-feedback channel to indicate the index of the preferred permutation to use. This method is also defined only for systems with three or four transmit antennas.

Chapter 14 Performance analysis

MAC and PHY performance and throughput

INTRODUCTION

This chapter reviews several published simulations that assess the performance of WirelessMAN systems. Such simulations are complex and depend on a vast number of parameters, assumptions, and algorithms that are typically not fully detailed in the publications. However, due to the great interest among both industry and academia in the WirelessMAN technology, the research base is growing as the community has more time to study and evaluate the IEEE 802.16 standard. As more research becomes available, confidence in the results will begin to grow.

Due to the complexity of the simulations and the time required to run them, most studies chose to treat certain aspects of the system in a general way, while modeling other aspects in great detail. While simulation results may indicate potential performance, they cannot do so definitively.

WIRELESSMAN-OFDM, FIXED OPERATION

Capacity analysis

A 2005 paper by Ghosh, et al., [B18] reports the performance of the WirelessMAN-OFDM system with different frequency reuse patterns and cell sectorization. Figure 14-1, reproduced from that paper, illustrates the aggregate MAC-level throughput with a 3 km cell radius and a 50 W BS transmitter. The traffic model is not detailed, but the marginal differences between the PHY and MAC throughput presented suggest a full-buffer model. The calculations use three and six sectors per cell, with reuse factors 1 and 3. The reuse factor in this case is defined from cell to cell; for example, with six sectors per cell and a reuse factor of 3, a set of six channels, chosen from among three available sets of six channels, is used at each cell. According to

the paper, the results show the “average throughput over an entire cell per 5 MHz carrier.” However, it appears that, in calculating the average, the throughput has been divided by the number of channels per cell, not the total number in all cells. This is suggested by the paper’s conclusion that “if at all possible, 1/1 reuse (frequencies reused every cell) should be employed since the gain from going to 1/3 reuse (frequencies reused every third cell) does not come close to compensating for the associated tripling of consumed bandwidth.” To calculate the throughput per channel used in the system, it appears that the bars labeled “1/3 reuse” in Figure 14–1 should be divided by a factor 3.

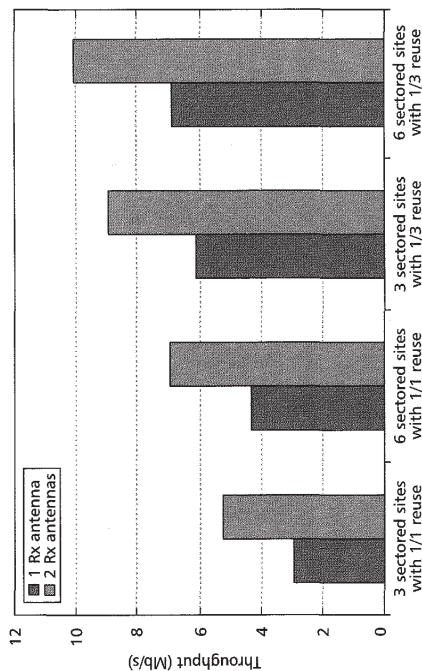


Figure 14–1: WirelessMAN-OFDM throughput per 5 MHz channel

The figure also shows the effect of adding a second receiver in the SS, with half a wavelength (7 cm) separation.

The performance of the system can also be improved by the use of STC. The paper shows that, in the three-sector case (with 1/1 reuse) and one receive antenna, adding STC with a second transmit antenna provides performance similar to the six-sector single-in, single-out (SISO) case, but with only half the channels.

Figure 14–2 shows the outage relative to 1.5 Mbit/s; that is, the fraction of cell area with maximum data rate less than this value. This figure indicates that narrower sectorization cuts down drastically on bad channel conditions and interference. Also the use of receive diversity improves the outage substantially.

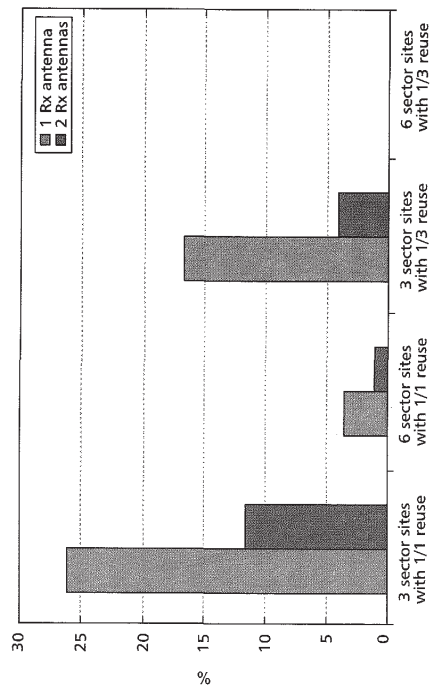


Figure 14–2: WirelessMAN-OFDM outage relative to 1.5 Mbit/s

MAC performance

MAC performance is assessed under more realistic traffic conditions (although less realistic environmental conditions) in a 2006 paper by Cicconetti, et al., [B10]. It considers an interference-free FDD WirelessMAN-OFDM system with 7 MHz bandwidth and 10 ms frame duration. The UL allocation start time is chosen to be 10 ms, meaning that all UL allocations point at a minimum to the next frame. This introduces a minimum delay of 10 ms, but it provisions terminals with very low processing power. The analysis is performed on a single cell (i.e., no interference) and assumes no transmission errors apart from contention-based collisions. The authors assumed that the SSs employ the following modulation methods and coding rates, which are evenly partitioned among SSs: QPSK 3/4, 16-QAM 3/4, and 64-QAM 3/4.

Two scenarios are studied in the paper. In the residential scenario, the authors consider offering broadband Internet access. The Internet traffic is modeled as a Web traffic source (see [B39]). Packet sizes are drawn from a Pareto distribution with cutoff (shape factor = 1.1, mode = 4.5 kB, cutoff threshold = 2 MB), while packet interarrival times are distributed exponentially (average = 5 s), which yields an average load of 25 kB/s. The resulting throughput delay curves are shown in Figure 14-3. In addition to the residential scenario, the paper covers a small- and medium-enterprise scenario. For details, please consult the paper.

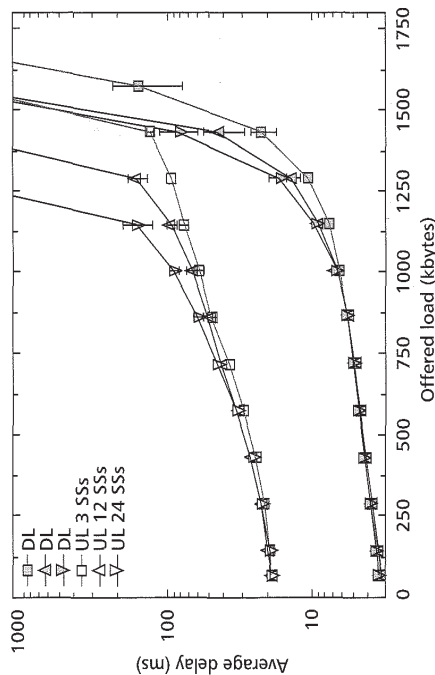


Figure 14-3: Average throughput delay vs offered load

The following sections deal with previously unpublished results generated by the authors of the previously discussed paper using the same simulator. The assumption for these results are, however, slightly different. In this set of results, a frame duration of 5 ms was used. The allocation start time was set to be equal to the length of the frame. The channel bandwidth is 7 + 7 MHz.

The system is loaded with a number of applications spanning all four defined service types (UGS, rtPS, nrtPS, BE) and resulting in eight connections in each direction:

- DL
 - MPEG video: 128 kbit/s
 - IP traffic: 200 kbit/s [10% gaming, 9% mail, 9% FTP, 4.5% Telnet, and 67.5% Hypertext Transfer Protocol (HTTP)]
 - Videoconference: 80 kbit/s
 - VoIP: 16 kbit/s
- UL
 - MPEG video: 128 kbit/s
 - IP traffic: 50 kbit/s (same mix as DL)
 - Videoconference: 80 kbit/s
 - VoIP: 16 kbit/s

The UL allocation start time is chosen to be 5 ms, meaning that all UL allocations point at a minimum to the next frame. This introduces a minimum delay of 5 ms, but it provisions terminals with very low processing power. The analysis is performed on a single cell (i.e., no interference) and assumes no transmission errors apart from contention-based collisions (except in the ARQ analysis, where a fixed 10^{-6} BER is assumed on each link).

Full-duplex with single burst profile

The SSs in this example are all full-duplex, and all use the same 64-QAM-5/6 burst profile, which implies a 28.23 Mbit/s raw PHY data rate. The DLFP and MAPs are transmitted at their required rates.

The most interesting delay curve is that for the IP traffic. Because this traffic is BE, it provides a good indicator of behavior as a function of load. This is because an increase in load increases the demand for the other services and hence reduces the capacity left over for BE traffic. In Figure 14-4 and Figure 14-5, an example of this performance is shown for the DL and UL, respectively.

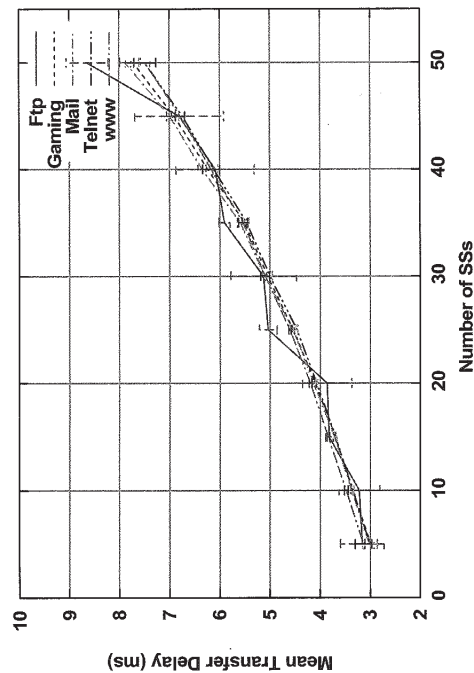


Figure 14-4: DL, IP traffic mean transfer delay

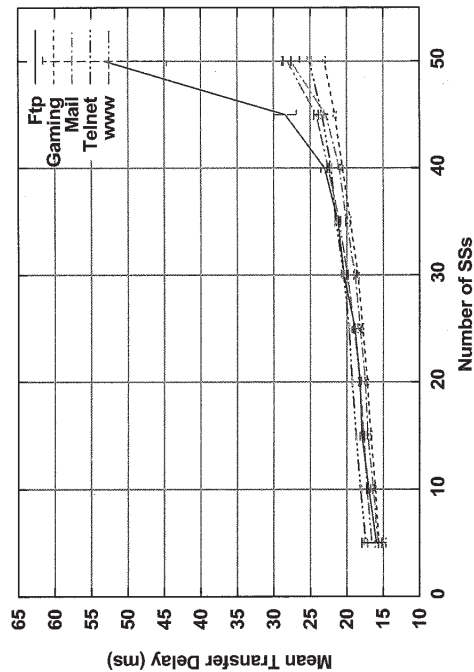


Figure 14-5: UL, IP traffic mean transfer delay

Besides the data transfer, the UL must carry contention-based request transmit opportunities. The absolute number of these, as well as the utilization (S) and load (G) of request transmit opportunity ($UIUC = 2$), is shown in Figure 14-6 and Figure 14-7, respectively. Notice that only the mandatory full contention method is used.

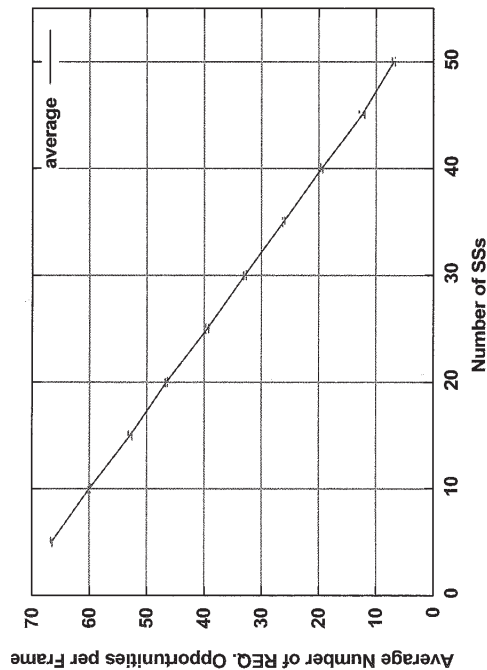


Figure 14-6: UL, Average transmit opportunities per frame

Lastly, the MAC overhead within a frame is of interest. This overhead, which consists of the FCH and MAPs, is shown in Figure 14-8. It can be seen that the overhead increases to 4.7% (7 OFDM symbols per frame) when supporting 400 connections (50 SSs) in both directions.

The loads of the DL and UL are roughly linear with the number of SSs. For 50 SSs, the load on the DL is roughly 75%, whereas the load on the UL approaches 90%, driving the UL faster into saturation than the DL, despite carrying only two thirds the net throughput.

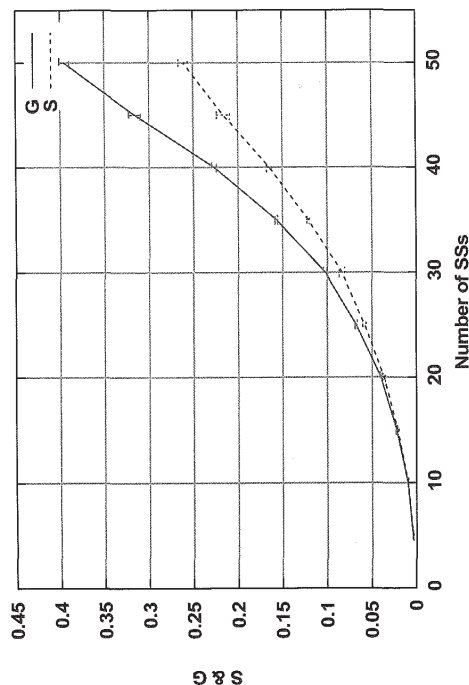


Figure 14-7: UL load and utilization of transmit opportunities

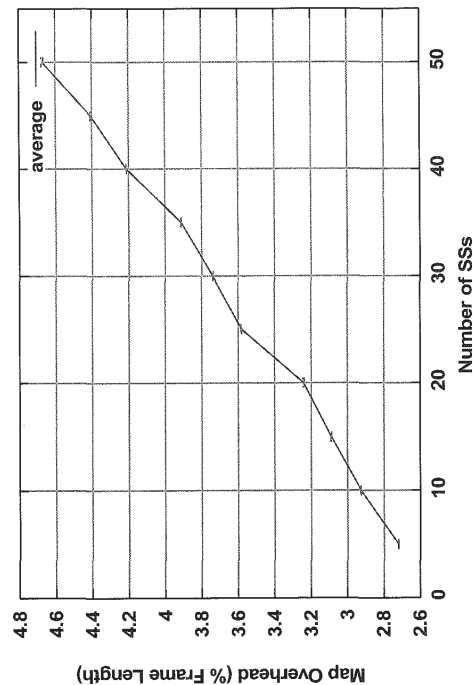


Figure 14-8: FCH + MAP overhead

Mixed full-duplex/half-duplex with burst profiles case

In this scenario, the DIUC and UIUC span the QPSK-1/2 to 64-QAM-5/6 range. Performance is evaluated for SSs having the same DIUC and UIUC, respectively. Half the SSs are full-duplex, and half are half-duplex. As the average PHY rate is substantially lower (on average around 10.8 Mbit/s) than in the previous case, simulations are limited to 30 SSs. Because the overhead is not depended on the used IUC and whether an SS is full-duplex or half-duplex, the overhead shown in Figure 14-8 remains valid for these cases.

Figure 14-9 and Figure 14-10 show the difference between full-duplex and half-duplex SSs with regard to the transfer delay for the VoIP application. It shows that the transfer delay for half-duplex SSs is around 20% higher than that of full-duplex devices, which is predictable as the uplink cannot be used by these devices while actively listening to the DL and during SSRTG and SSTTG.

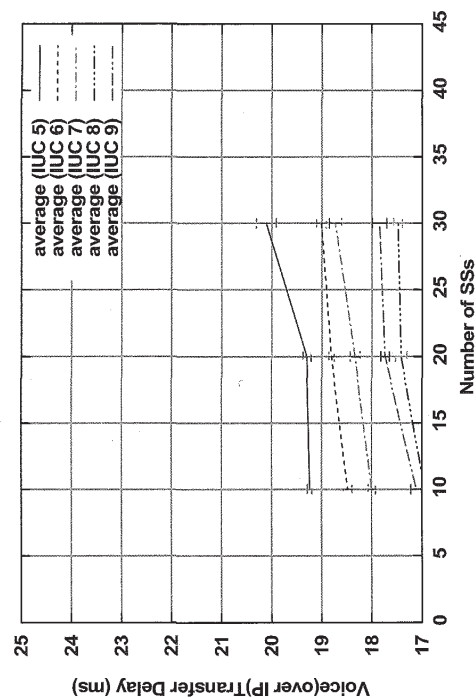


Figure 14-9: UL, full-duplex SSs, VoIP mean transfer delay

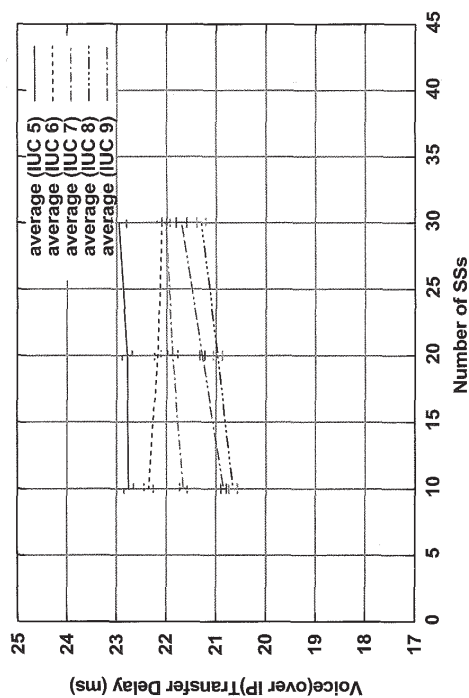


Figure 14-10: UL, half-duplex SSs, VoIP mean transfer delay

Figure 14-11 and Figure 14-12 show the transfer delay difference between DL and UL for the same best effort HTTP service. Figure 14-11 shows that, on the DL, the traffic is on average allocated either to the immediately following frame or to the next frame after that. On the UL, shown in Figure 14-12, an SS may first have to use a contention slot to request bandwidth or, if it has other data scheduled for transmission, can use piggy-backing. The allocation for the burst will then appear in the DL MAP no sooner than the next frame with an allocation for the frame following that. Because of this, the average transfer delay for any service will typically exceed 10 ms. Lastly, in Figure 14-13, the same scenario is shown with ARQ enabled, assuming a 10^{-6} BER on each link. It can be seen that the transfer delay roughly doubles, which is to be expected from retransmissions and the increase in system load. For 30 SSs, the UL can be seen to go rapidly into saturation.

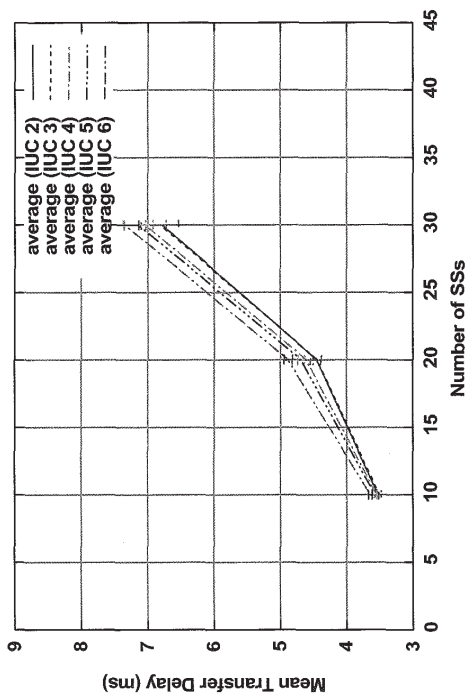


Figure 14-11: DL, half-duplex SSs, HTTP mean transfer delay

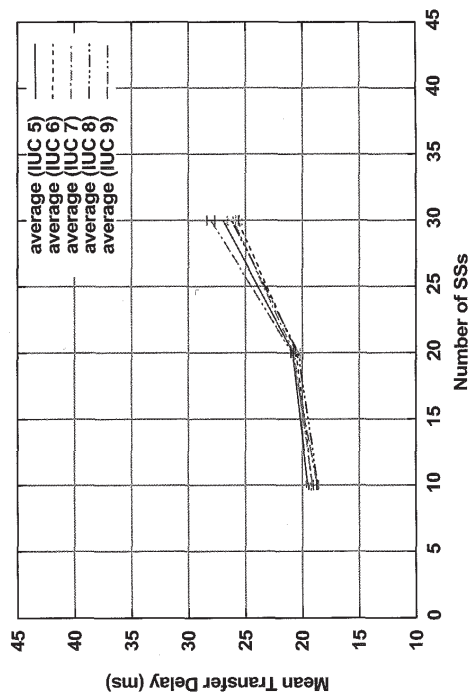


Figure 14-12: UL, half-duplex SSs, HTTP mean transfer delay

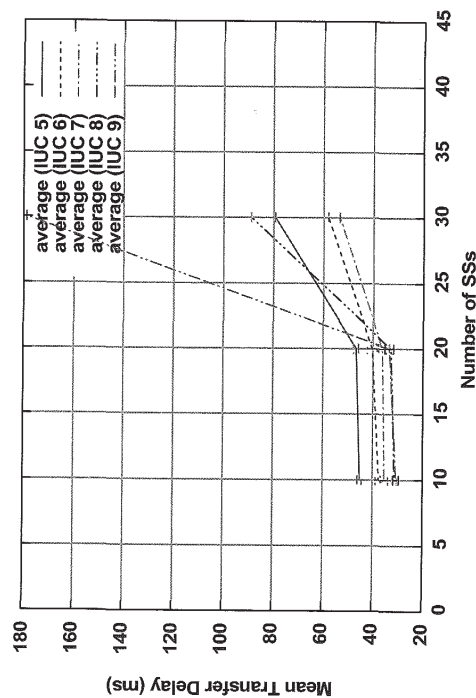


Figure 14-13: UL, half-duplex SSs, HTTP mean transfer delay w/ARQ

WIRELESSMAN-OFDM, MOBILE OPERATION

Basic PHY performance

In this section, we present unpublished calculations regarding the WirelessMAN-OFDM performance with limited mobility. Figure 14-14 shows the coded block error rate (CBLER) for WirelessMAN-OFDM using the ITU Vehicular A (VehA) 3 km/h channel model [B30]. These results include all of the synchronization loss, which comes to 1 dB to 2 dB.

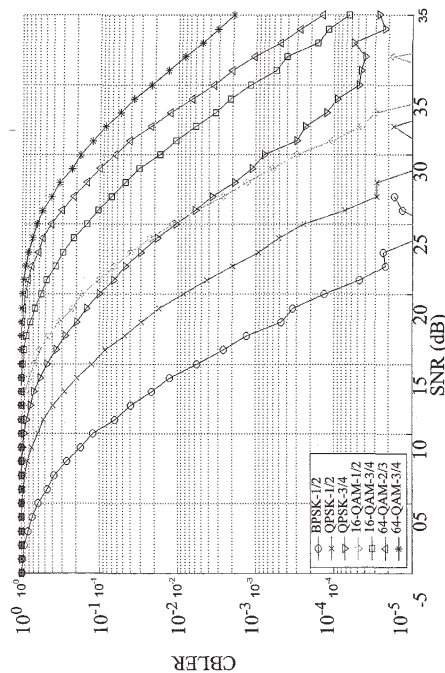


Figure 14-14: OFDM CBLERs—ITU VehA 3 km/h

Figure 14-15 shows the CBLER as a function of OFDM symbol index and SNR using the ITU VehA 30 km/h channel model with QPSK modulation and 1/2 rate coding. The symbol index is the count of data OFDM symbols following the preamble within the same burst, and the CBLER is computed individually over each OFDM symbol (as the outer RS code is a per-OFDM-symbol block code). Due to the rapidly varying channel condition, the channel estimate computed from the preamble will be increasingly less accurately matched to the instantaneous channel condition for the OFDM symbol as the OFDM symbol index in the burst increases. For BPSK 1/2, the degradation will be slower, while for higher order modulations, it will be more severe. This figure shows that, even at this modest speed, the degradation is severe due to the changing channel conditions. For this reason, the nonsubchannelized bursts in mobile operation must be relatively short. To address the problem, midambles, for subchannelized operation, have been added through IEEE Std 802.16e. The degradation can also partially be mitigated by updating the channel estimates by means of data-driven decision feedback, which is not included in Figure 14-15.

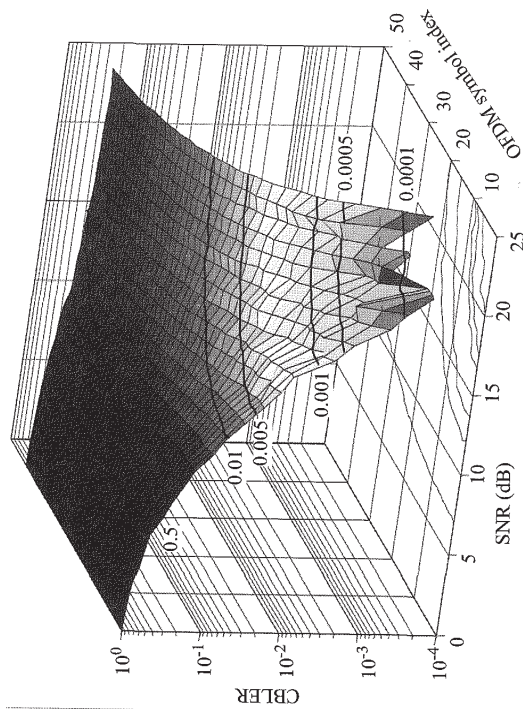


Figure 14-15: OFDM CBLERs—ITU VehA 30 km/h

Capacity analysis

In a 2005 paper, Ball, et al., [B5] report a study of a mobile network using WirelessMAN-OFDM in a 3.5 MHz channel at 3.5 GHz with cell radius of 300 m. The 2 W BS uses three sectors with 17.5 dBi antennas. The analysis considers a full-buffer FTP model with up to 300 randomly distributed nomadic clients per sector. The analysis is performed with reuse factors of both 1 and 3.

Figure 14-16 depicts the channel utilization of each sector utilization as a function of the offered load, showing a limit of around 3 Mbit/s for a reuse factor of 1 and at 4.25 Mbit/s for a reuse factor of 3. This corroborates the findings of Ghosh, et al., [B18] that the spectral efficiency is higher with a reuse factor of 1. Figure 14-17 shows, as a function of the offered load (which is varied identically in each cell), the fraction of SSs served with each modulation/coding rate in this simulation. For reuse factor 1, the modulation/coding rate efficiency is substantially lower due to the increased

interference (lower C/I); roughly 80% of the SSs are using modulation/coding no more efficient than QPSK-3/4.

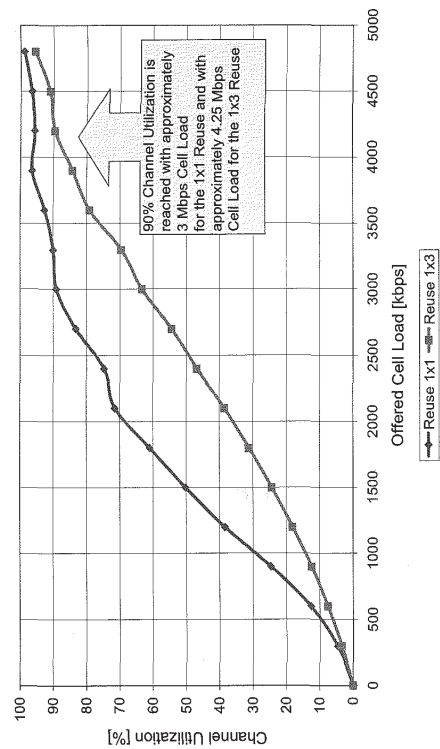


Figure 14-16: Channel utilization as function of offered load

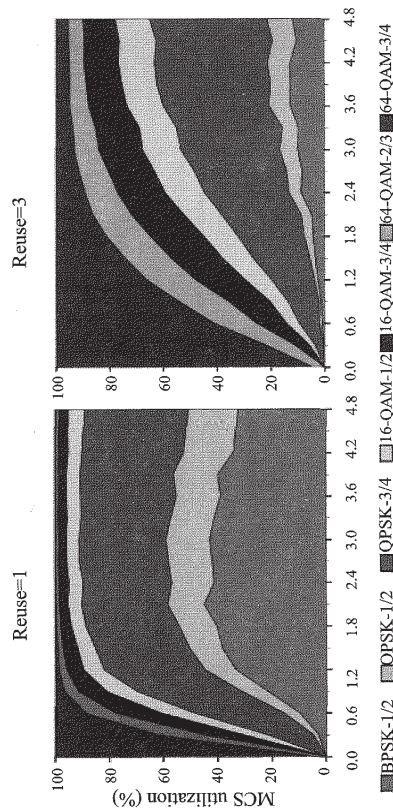


Figure 14-17: Modulation/coding utilization as function of offered load

The Ball paper further analyzes (see Figure 14–18) the occurrence of call blocking (i.e., rejection by admission control due to insufficient C/I). In the reuse factor 1 scenario, a cell load of 1 Mbit/s results in 10% call blocking, whereas the reuse factor 3 scenario experiences no substantial call blocking up to the channel utilization limit shown in Figure 14–16. The spectral efficiency is hence $1 \text{ Mbit/s} / 3.5 \text{ MHz} = 0.29 \text{ (bit/s)/Hz}$ per sector for the reuse factor 1 case and $4.25 \text{ Mbit/s} / (3 * 3.5 \text{ MHz}) = 0.40 \text{ (bit/s)/Hz}$ per sector for reuse factor 3. The reuse factor 3 scenario hence provides higher spectral efficiency when both channel utilization and call blocking limitations are observed. It should be noted that the analysis considers none of the optional WirelessMAN-OFDM features to improve C/I performance, such as STC, diversity techniques, advanced coding, and subchannelization. Applying these options would likely provide a substantial performance improvement, particularly for the reuse factor 1 scenario.

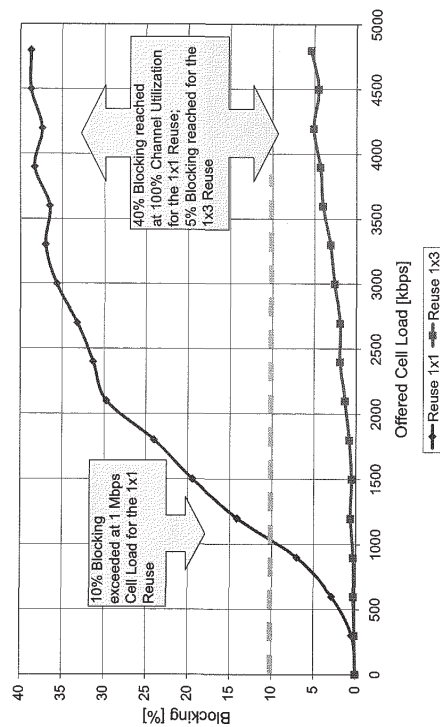


Figure 14–18: Call blocking (C/I < 1 dB) as function of offered load

WIRELESSMAN-OFDMA, MOBILE OPERATION

Overhead and capacity

In a 2005 paper, Lee, et al., [B35] report on studies of a system considered for “WiBro” services. The system studied is “somewhat similar” to a draft of IEEE Std 802.16e at some stage prior to approval. According to the paper, the differences include “the structure and performance of preamble” and “subcarrier permutation in FCH/DL MAP.” The results may shed some light on WirelessMAN-OFDMA performance. Recall that WirelessMAN-OFDMA is defined in IEEE Std 802.16-2004 [B20] using a 2048-FFT. The system under study uses a 1024-FFT, which is an option for WirelessMAN-OFDMA in IEEE Std 802.16e.

The system studied uses a channel of 8.447 MHz and a 10 MHz sampling bandwidth. The system is TDD, with a 2/1 DL/UL ratio. The overhead, including all PHY overhead as well as control subchannels for channel quality information (channel feedback), acknowledgment, and initial ranging, was found to be between 22% and 31%.

This paper also analyzes performance as a function of cell radius. It assumes a fixed modulation/coding and maximizes the number of subchannels to satisfy the CINR required to achieve a 1% PER. Figure 14–19, redrawn from the published data, illustrates the results. Combining the results by selecting the maximum capacity at a given range, the solid line in Figure 14–19 shows the DL sector capacity if the only modulation/coding options available for the link adaptation algorithm to choose were the three indicated in this figure. Introducing the remaining modulation/coding combinations would have the effect of largely removing the jaggedness of the curves.

Figure 14–20 is the parallel to Figure 14–19 for the UL.

Figure 14–19 and Figure 14–20 suggest that, in order to guarantee a single user 512 kbit/s DL and 256 kbit/s UL, the cell radius must be limited to 2.3 km.

Using the same approach with an outdoor-to-indoor channel model, Figure 14–21 and Figure 14–22 show the 512 kbit/s DL / 256 kbit/s UL cell radius to be limited to approximately 0.7 km.

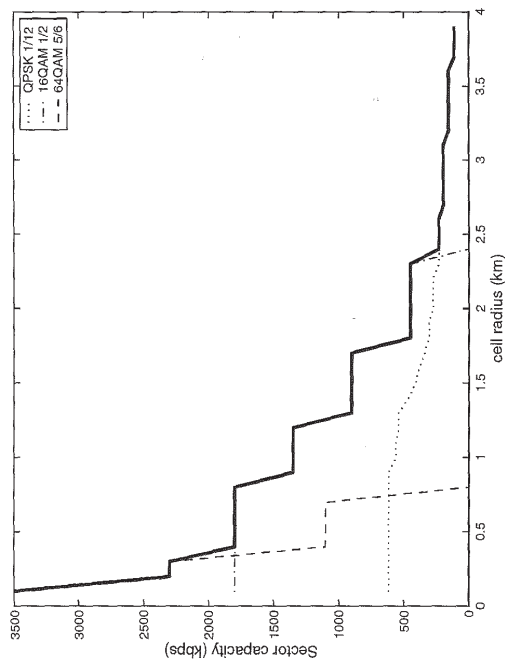


Figure 14-19: DL sector capacity per cell radius—ITU VehA (60 km/h)

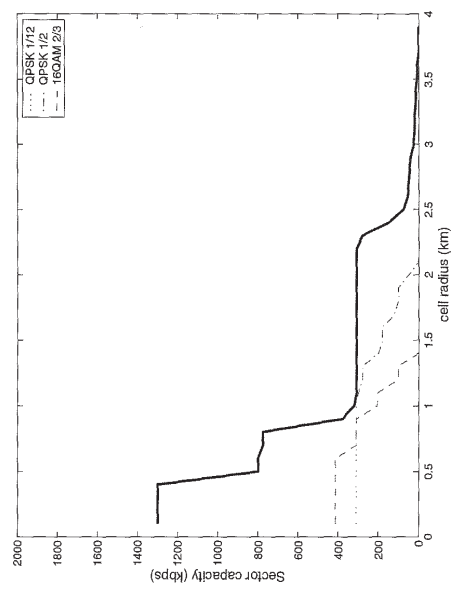


Figure 14-20: UL sector capacity per cell radius—ITU VehA (60 km/h)

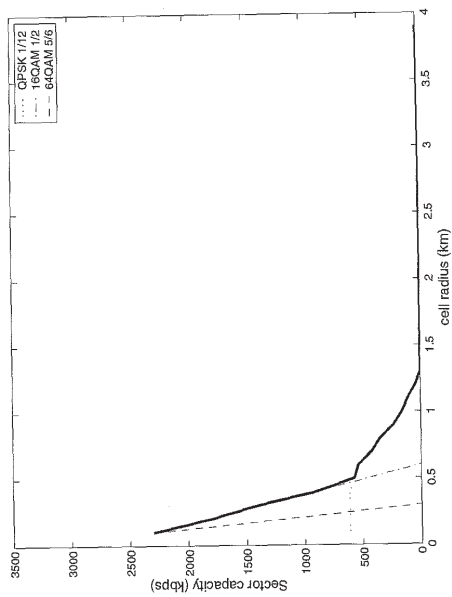


Figure 14-21: DL sector capacity per cell radius (ITU outdoor-indoor)

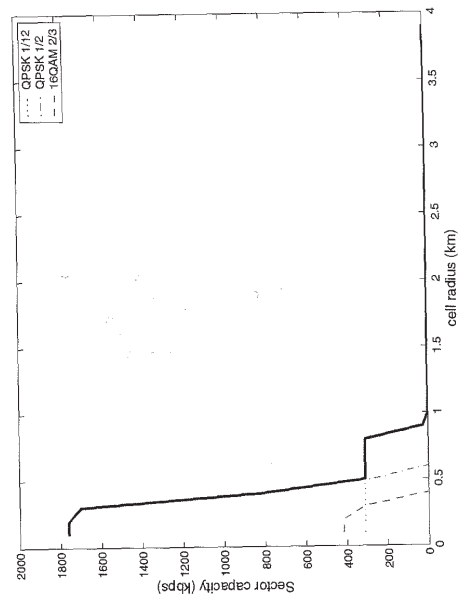


Figure 14-22: UL sector capacity per cell radius (ITU outdoor-indoor)

A 2005 paper by Kwon, et al., [B34] presents an alternative study of the system capacity. The modeled system is TDD using a 1024-FFT, 9 MHz bandwidth, 5 ms frame duration, and a 2/1 DL/UL frame split. The network is loaded with a number of applications spanning all four service types (UGS, rtPS, nrtPS, and BE) defined in IEEE Std 802.16-2004 as well as the extended rtPS (ertPS) introduced in IEEE Std 802.16e for real-time flows generating variable packet sizes on a periodic basis, such as VoIP with silence suppression. The traffic load per user is as follows:

- DL

Video: 32 kbit/s, 10 frames/s

IP traffic: ~90 kbit/s FTP and ~15 kbit/s HTTP traffic (according to 1xEV-DV traffic models; see [B8])

VoIP: 9.6 kbit/s with 0.403 activity factor

- UL

VoIP: 9.6 kbit/s with 0.403 activity factor

IP traffic: As needed to support UL FTP, HTTP, and video traffic

The analysis is performed in a hexagonal cellular environment considering interference from first and second tier cells with identical traffic distributions. Figure 14-23 shows the delay in transmitting VoIP data using rtPS, UGS, and ertPS. On the DL, the number of VoIP calls is limited to 92 when the delay limit is 60 ms. This figure shows that the introduction of ertPS in IEEE Std 802.16e is justified for voice with silence suppression since the call limit is similar to the DL limit using ertPS, but is significantly lower using rtPS and UGS.

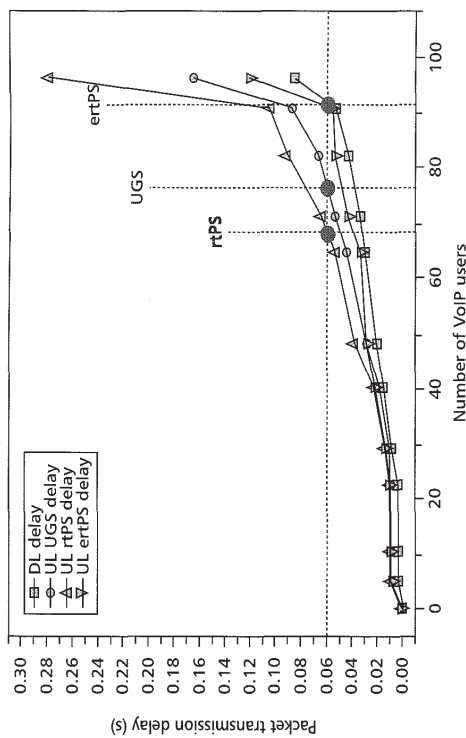
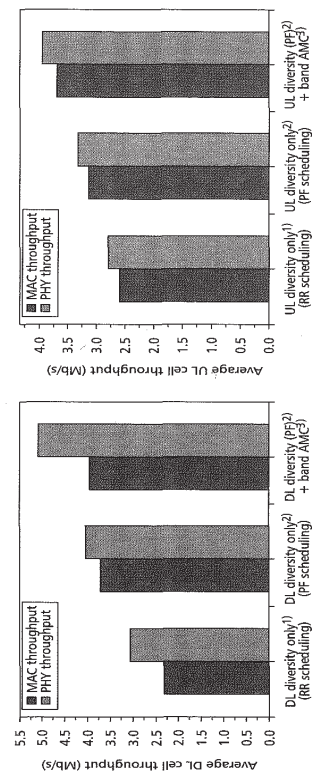


Figure 14-23: Delay for VoIP using rtPS, UGS, and ertPS

Figure 14-24 shows the average cell throughput both for UL and DL using various scheduling mechanisms, permutations, and feedback.



RR scheduling: Round robin scheduling
PF scheduling: Proportional fair scheduling

- 1) Using average channel quality information
- 2) Using instantaneous channel quality information in the time domain
- 3) Using instantaneous channel quality information in the frequency domain as well as the time domain

Figure 14-24: Average cell throughput for various schemes

WirelessMAN-OFDMA vs high-speed DL packet access (HSDPA)

A 2005 paper by Shin, et al., [B48] compares the capacity of a WiBro-compatible version of WirelessMAN-OFDMA (based on a preapproved draft of IEEE Std 802.16e) with that of HSDPA. The study concludes that the OFDMA approach has “much better performance.” In particular, it finds that the spectral efficiency of WirelessMAN-OFDMA is close to double that of HSDPA for the ITU VehA channel model and also for the ITU Pedestrian A (PedA) channel at 10 km/h [B30]. For the ITU PedA channel model at 3 km/h, the spectral efficiency of WirelessMAN-OFDMA is found to be about one third greater than that of HSDPA. The authors ascribe the WirelessMAN-OFDMA advantage to two main factors:

- **TDD vs FDD:** Both systems work within a system bandwidth of 10 MHz. However, the OFDMA system under study uses TDD (with a fixed 2/1 DL/UL ratio) with signal bandwidth of 8.3 MHz. HSDPA uses FDD carried in two 5 MHz channels, but its effective signal bandwidth is just 3.84 MHz times two. The wider bandwidth of OFDMA is naturally not all positive, as it can result in a shrinkage of the coverage area due to the 3.4 dB higher thermal noise. In a noise-limited scenario, this coverage shrink is estimated at 19%, but the real situation may be interference-limited in both cases.
- **Multipath performance:** As discussed in Chapter 3 and Chapter 11, OFDM is very robust to multipath due to the use of the cyclic prefix and the cyclical nature of the FFT. Multipath channels that do not exceed the cyclic prefix duration will not significantly deteriorate the system performance (provided the sampling is adequate). CDMA, on the other hand, typically makes use of a rake receiver to extract the multipath energy. This results in deteriorated performance. The paper by Shin reports as much as 40% HSDPA capacity loss going from a single-path (multipath-free) channel to a three-path channel. Naturally, the move away from conventional rake receivers to more advanced receiver designs provides a means to reduce that capacity loss.

Basic WirelessMAN-OFDMA PHY performance

This section reports on unpublished studies of the basic WirelessMAN-OFDMA PHY performance. It assumes 10 MHz channelization at 2.5 GHz with a 1024-FFT, a 1/8 cyclic prefix, and practical levels of phase noise, mixer I/Q imbalance, and frequency offset. The reported $E_s N_0$ is equivalent to the SNR per subcarrier. For the repetition codes, postdetection combining of soft decisions is employed. All simulations shown use the mandatory CC.

Figure 14-25 and Figure 14-26 present the CBLER for the OFDMA modulation using the ITU VehA 3 km/h channel model. The first figure represents ideal synchronization and channel estimation, whereas the second represents a practical system of moderate complexity. The poor performance of QPSK-3/4 is a result of the mandatory interleaver problem discussed in Chapter 12.

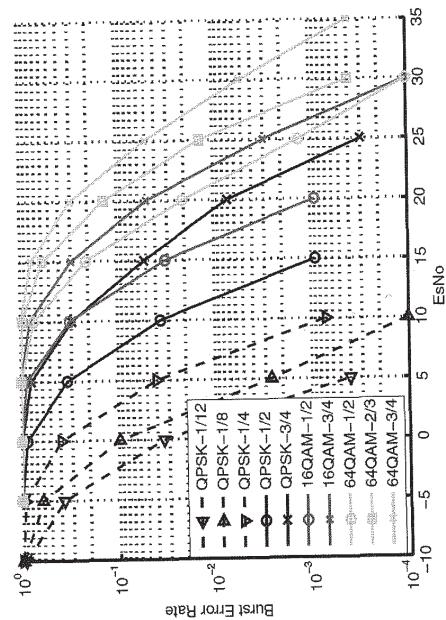


Figure 14-25: CBLER, UL PUSC, ITU VehA 3 km/h, CC, ideal

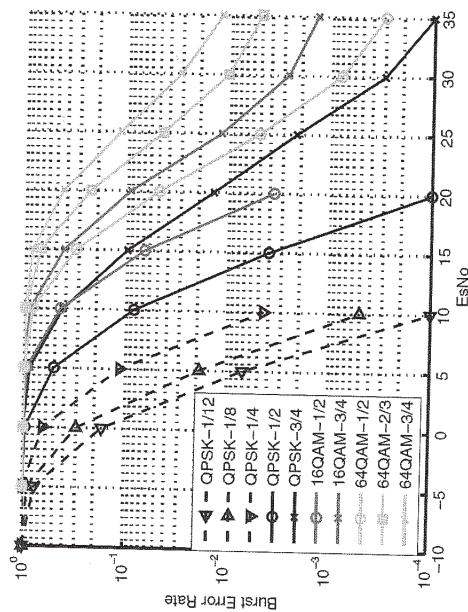


Figure 14-26: CBLER, UL PUSC, ITU VehA 3 km/h, CC, estimated

Figure 14-27 and Figure 14-28 provide similar data using the ITU VehA 120 km/h channel model. The ideal performance suffers only moderately as a result of the higher speeds, even for the higher modulation orders. However, the practical challenges of synchronization and channel estimation cause the performance at the higher modulation orders to degrade substantially, with error floors developing. For the lower order modulations, including the omitted repetition rates, the PHY is fairly robust to the rapidly changing channel.

Similar analysis for VehA 30 km/h channel shows no significant degradation compared to the VehA 3 km/h model, showing that the OFDMA PHY is substantially robust to practical speeds. On the other hand, the performance degrades substantially using the VehB 10 km/h model due the insufficient cyclic prefix duration compared to the impulse response in that model.

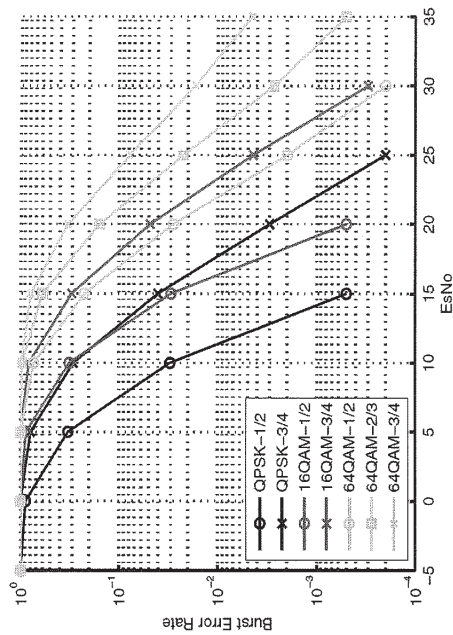


Figure 14-27: CBLER, UL PUSC, ITU VehA 120 Km/h, CC, ideal

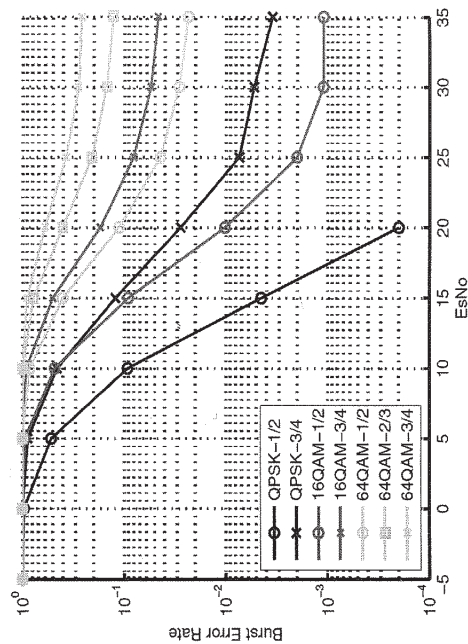


Figure 14-28: CBLER, UL PUSC, ITU VehA 120 km/h, CC, estimated

Figure 14-29 shows the ideal performance using the optional CTC codes, which is the optional code of choice within the WiMAX profiles. The improvement over the CC code varies from 1 dB to 1.5 dB although it need be noted that in this analysis only the longest code word is used. Use of shorter code words can result in a loss of up to two dB (compared to the longest code word).

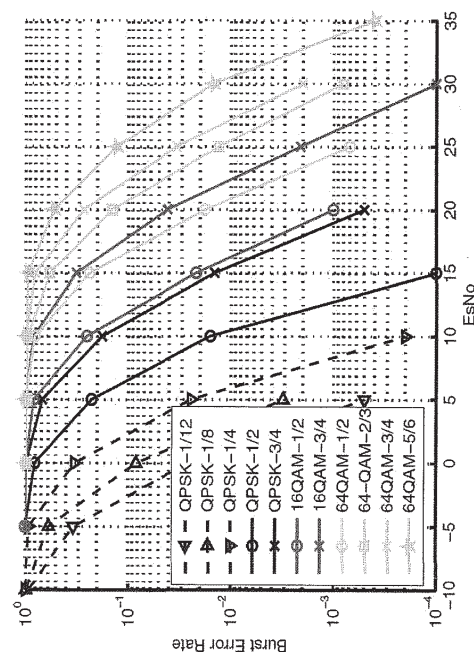


Figure 14-29: CBLER, UL PUSC, ITU VehA 3 km/h, CTC, ideal

Figure 14-30 shows the ideal performance of the DL modulations, including that of the DLFP. It is best to protect the DLFP since it constitutes a single point of failure within the frame.

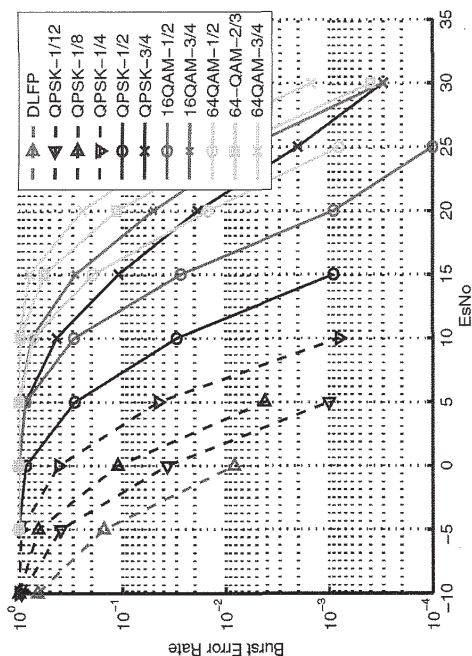


Figure 14-30: CBLER, DL PUSC, ITU VehA 3 km/h, CC, ideal

In Figure 14-31, the performance of the DL repetition coding as a function of channel impulse response (CIR) is shown. This result is important to determine which repetition code can be used at the cell edge. As may be observed from the figure, the use of QPSK-1/4 (QPSK-1/2, repetition rate 2) or QPSK-1/8 (QPSK-1/2, repetition rate 4) has sufficient CIR performance to make usage at the cell edge feasible. The large gap between the solid (ideal synchronization) and dashed (practical synchronization) curves is the result of the general difficulty of achieving good synchronization under low signal to noise-plus-interference ratio, regardless of the method used.

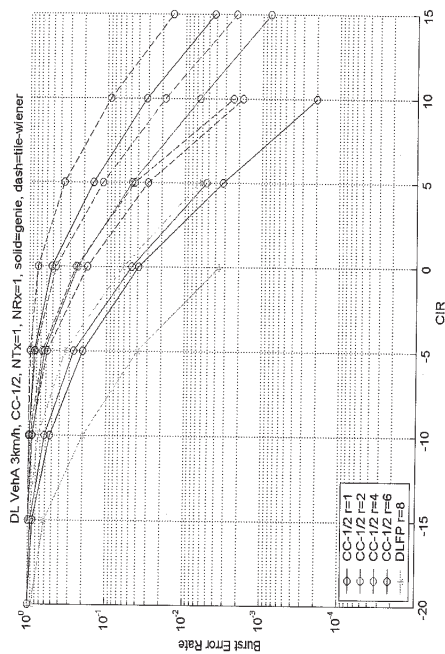


Figure 14-31: CBLER, DL PUSC, ITU VehA 3 km/h, CC, ideal

Finally, Table 14-1 shows the cell ranges that may be achieved with the DL modulations with a 20 W transmitter, 10 dB backoff, 15 dB antenna gain, and a 10 dB noise figure. For this case, the mobile is assumed to have two antennas on which it performs MRC. Achievable cell ranges are shown both with and without a 10 dB shadowing margin using the Cost 231 Hata channel model [B11].

Table 14-1: Cell-ranges DL PUSC

Modulation/ code rate	Max. PHY throughput (Mbit/s)	SNR @ 0.01 CBLER (dB)	Cell range (m)	Cell range with fade margin (m)
QPSK-1/12	1.19	-1.1	1586	825
QPSK-1/8	1.79	0.7	1410	733
QPSK-1/4	3.57	2.0	1259	674
QPSK-1/2	7.14	6.0	997	512
QPSK-3/4	10.71	9.2	809	421
16-QAM-1/2	14.28	10.3	753	392
16-QAM-3/4	21.42	14.9	557	290
64-QAM-1/2	21.42	15.5	536	279
64-QAM-2/3	28.56	19.0	426	222
64-QAM-3/4	32.13	21.2	369	192

MIMO capacity

This section discusses the capacity gain achieved by the use of MIMO. The capacity is analyzed at link level for a full-buffer FTP stream in an OFDMA network with 19 cells, each having three sectors, using 10 MHz bandwidth at 2.5 GHz. The channel models are a mix of stationary/pedestrian, pedestrian, mobile, and highly mobile models in analogue to the 1xEV-DV evaluation methodology (see [B8]). Some capacity results, in megabits per second, are shown in Table 14-2, where the notation $m \times n$ indicates m transmitter chains and n on the receiver. Note that the results are indicative only of the relative capacity gain, as a full-buffer FTP analysis provides an overly optimistic result for achievable capacity. The use of 2x1 STC on the DL, for which no simulation data were available for this specific scenario, would be expected to result in values between those of 1x1 SISO and 2x2 MIMO, but relatively closer to the 2x2 MIMO results.

Table 14-2: Relative performance benefit of MIMO and virtual MIMO^a

DL/UL ratio	DL				UL	
	Reuse	1x1	2x2 MIMO	2x4 MIMO	1x2 V-MIMO	2x2 MIMO
1/2	1	3.80	7.97	11.76	3.20	6.72
	3	1.52	3.98	7.06		
1/1	1	5.75	12.08	17.83	2.40	5.04
	3	2.30	6.04	10.70		
2/1	1	7.67	14.00	20.67	1.60	3.36
	3	3.07	7.00	12.40		

^a Data courtesy of Nortel Networks.

In Table 14-3, the spectral efficiency and capacity are shown for various antenna configurations in the same system, with DL/UL ratio of 2/1 and using the ITU PedA 3 km/h channel model.

Table 14-3: Performance using MIMO^a

	1x1	1x2	2x2	2x4	4x2	4x4
(bit/s)/Hz per sector	1.2	1.8	2.8	4.4	3.7	5.1
Aggregate sector throughput (Mbit/s)	7.6	11.6	17.8	27.7	23.6	32.6

^a Data courtesy of Nortel Networks.

Chapter 15 Conformance and interoperability

Conformance standards and testing

In this chapter, we discuss the IEEE 802.16 conformance standards and the WiMAX Forum® interoperability and certification procedures. The conformance standards are essentially comprehensive test plans to evaluate whether a particular vendor's implementation meets the requirements defined in IEEE Std 802.16. The WiMAX Forum is an industry alliance, analogous to the Wi-Fi Alliance for IEEE Std 802.11, that defines interoperability tests and certifies IEEE 802.16 BSs and SSs that pass these tests.

THE WiMAX FORUM

By the end of 2000, even before the original IEEE Std 802.16-2001 was approved, it became clear that the standard would include a plethora of options. For instance, the high-frequency WirelessMAN-SC mode has literally more than 4000 possible combinations of FEC and modulation alternatives, while in practice four or five would suffice. While most options have at least one corresponding proponent who can argue for its benefits under certain circumstances, implementing all of the options would clearly be an onerous and expensive task. Conversely, if equipment vendors independently chose which options to implement, full interoperability would be precluded, and IEEE Std 802.16 would be a standard in name only. Systems would be, for all intents and purposes, proprietary through the choice of options. In March of 2001, the outline of Clause 12 was added to the IEEE 802.16 draft standard.

It also became clear that full interoperability would require proper conformance testing, lest two vendors pick the same profile but interpret it differently. In IEEE 802, standards rarely include test specifications; in most cases, they stop with functional specifications. In the 2000 time frame, intense

debate surrounded IEEE Std 802.16 versus ETSI BRAN HiperACCESS as the standard of choice for PMP broadband wireless access above 10 GHz. ETSI BRAN HiperACCESS was a simpler but less efficient standard than IEEE 802.16 WirelessMAN-SC. ETSI BRAN HiperACCESS advocates criticized IEEE Std 802.16, citing the plethora of options and the impact on interoperability. They also cited the ETSI mandate for a full set of test documentation based on the ISO/IEC 9646 standards series (identical to the ITU x.290 series) specifying test documentation. In response, several companies involved in IEEE Std 802.16 were determined to eliminate this as a source of discredit to IEEE Std 802.16 so the two standards could be compared on a head-to-head technical basis.

These companies decided to take the concept a step further and initiate a certification body and process modeled as a hybrid of Wi-Fi and GSM type approval. In April 2001, representatives of Nokia, Ensemble Communications, Harris Corporation, and Crosspan (a division of Raytheon) met in Antibes, France, alongside an ETSI BRAN HiperACCESS meeting in neighboring Sophia Antipolis; and the WiMAX Forum was born. Unlike the WiMAX Forum of today, the original group was concerned with single-carrier systems above 11 GHz. This was due to the facts that this aspect of IEEE Std 802.16 was much further developed than the lower frequency specifications and that it was ETSI BRAN HiperACCESS to which they were reacting.

By the way, "WiMAX" is derived from the expression *worldwide interoperability for microwave access*. Jay Klein, who chaired the WirelessMAN-SC PHY Task Group, has been credited with creating the name.

The initial task of the early WiMAX Forum was to develop system profiles for WirelessMAN-SC operation. These were submitted during the development of IEEE Std 802.16c, which specified detailed system profiles in Clause 12. Following draft development and balloting, these profiles, with minor changes, were approved; and IEEE Std 802.16c was approved in December 2002. The WirelessMAN-SC profiles are shown in Table 15-1.

Table 15-1: WirelessMAN-SC system profiles

Identifier	Description
profM1	Basic ATM MAC profile
profM2	Basic packet MAC profile
profP1	25 MHz channel PHY profile
profP1f	25 MHz channel PHY profile—FDD
profP1t	25 MHz channel PHY profile—TDD
profP2	28 MHz channel PHY profile
profP2f	28 MHz channel PHY profile—FDD
profP2t	28 MHz channel PHY profile—TDD

Once this task was accomplished, the next step was to deal with the issue of test specifications. With the aid of other companies such as Nera, Intracom, Hewlett-Packard, and Hughes Network Systems, the founders of the WiMAX Forum started to create the test specification necessary to be on par with the ETSI test specifications. Four documents were identified:

1. Protocol implementation conformance statement (PICS) proforma:
A document that serves two purposes. First, it lists the features that are mandatory, optional, conditionally mandatory, forbidden, etc., for each of the system profiles. Second, it serves as a form that vendors fill out to specify which features they implement and for what sets or ranges of allowed values.
2. Test suite structure and test purposes (TSS&TP): A test plan for covering the features outlined in the PICS proforma.
3. Abstract test suite (ATS): Equipment-independent test procedures for implementing the tests identified in the TSS&TP.
4. Radio conformance test (RCT) specification: Tests for the radio portion of the system that could not be specified as protocol tests.

CONFORMANCE TEST STANDARDS FOR WIRELESSMAN-SC

The WiMAX Forum played a key role in the development of PICS proforma, TSS&TP, and RCT documents in IEEE Std 802.16. In each case, a new IEEE 802.16 project was proposed and initiated for each test specification, each to lead to an independent published standard. Once the project was underway, an open call for contributions was issued; in each case, a single proposal, developed within the WiMAX Forum, was received.

These proposals were unchallenged primarily because of the involvement of the same participants in both the WiMAX Forum and the IEEE 802.16 Working Group. Nonetheless, the documents proceeded through the official IEEE 802 process of working group review, working group letter ballot, and sponsor ballot, with comments addressed along the way. The result was three official IEEE standards: IEEE Std 802.16/Conformance01-2003 [B21], IEEE Std 802.16/Conformance02-2003 [B22], and IEEE Std 802.16/Conformance03-2004 [B23], each in accordance with ISO/IEC 9646.

By the time the RCT document was initiated, relations between companies participating only in ETSI BRAN HiperACCESS and those interested in both ETSI BRAN HiperACCESS and IEEE Std 802.16 had improved, and the ETSI BRAN HiperACCESS RCT was used as the foundation of the WirelessMAN-SC RCT document. Unfortunately, before the ATS document could be initiated, the bottom fell out of the market for high-frequency broadband wireless access equipment. Consequently, the WirelessMAN-SC ATS standards project was never initiated.

THE WiMAX FORUM'S MOVE TO LOWER FREQUENCIES

In April 2002, as the specifications for systems below 11 GHz were solidifying, entities interested in operation below 11 GHz began to join the WiMAX Forum. The first was the OFDM Forum in April, followed by Wi-LAN and Fujitsu in November 2002. Then, in January of 2003, the WiMAX Forum jumped to twelve "charter member" companies and, fueled by the efforts of Intel Corp., started expanding rapidly. The WiMAX Forum, with well over 300 member companies, is now certifying fixed-access WirelessMAN-OFDM systems through independent laboratory conformance

testing and overseeing interoperability "plug-fests." The WiMAX Forum is devoting great energy to the development of system profiles and test specifications for mobile systems based on the enhancements in IEEE Std 802.16e.

LOWER FREQUENCY PROFILES AND TEST SPECIFICATIONS

The WirelessMAN-OFDM, WirelessMAN-OFDMA, and WirelessMAN-SC PHY specifications were the first foray of IEEE Std 802.16 into the lower frequencies (less than 11 GHz). These were first defined in IEEE Std 802.16a. In late 2002, as IEEE Std 802.16a was nearing completion, the IEEE 802.16 Working Group opened the amendment project IEEE P802.16d, which was intended to develop profiles in support of the low-frequency modes. Eventually, IEEE P802.16d was dropped as a project to amend IEEE Std 802.16, replaced by a broader revision project that eventually led to IEEE Std 802.16-2004 [B20]. That revised standard does include the low-frequency profiles.

IEEE Std 802.16-2004 specifies profiles for all three PHY mode alternatives. However, for this fixed-access case, WirelessMAN-OFDM was of the greatest interest for two reasons:

1. The parallel ETSI BRAN HiperMAN standard initially supported a mode compatible with WirelessMAN-OFDM only.
2. The WiMAX Forum contributed only to the development of the WirelessMAN-OFDM and developed fixed-access interoperability tests only for that mode.

The low-frequency profiles are considerably more complex set than those for WirelessMAN-SC. In the case of WirelessMAN-OFDM, a system profile consists of four components: a MAC profile, a PHY profile, a duplexing selection, and a power class. The IEEE 802.16 standard defines two MAC profiles (PMP and mesh), six PHY profiles (1.75, 3.5, 7, 3, 5.5, and 10 MHz channel bandwidth, with the last one specified in the license-exempt case only), two duplexing alternatives (TDD and FDD), and five power classes.

In the case of WirelessMAN-OFDMA, only one MAC profile (PMP-based) is specified, along with nine PHY profiles (1.25, 3.5, 7, 8.75, 14, 17.5, 28,

10, and 20 MHz channel bandwidth, with the last two specified in the license-exempt case only), two duplexing alternatives (TDD and FDD), and four power classes.

The ATM CS is not included in either the WirelessMAN-OFDM or the WirelessMAN-OFDMA profiles. In both cases, RF profiles are mentioned, but not specified except in the license-exempt case.

The IEEE P802.16/Conformance04 project, to specify PICS proforma for the low-frequency modes, was initiated in March 2004. Draft 6, which entered IEEE-SA sponsor ballot in January 2006, includes no specification for WirelessMAN-SCa, which had lost support by the time the project got underway. The draft does include a detailed PICS specification for WirelessMAN-OFDMA. It should be noted that this PICS proforma concerns only fixed systems, not any mobile systems. In the case of WirelessMAN-OFDM, the draft simply makes normative reference to ETSI 102 385-1 V1.2.1, entitled "Broadband Radio Access Networks (BRAN); HiperMAN; Conformance testing for the Data Link Control Layer (DLC); Part 1: Protocol Implementation Conformance Statement (PICS) proforma." Since ETSI BRAN HiperMAN has long supported a PHY compatible with WirelessMAN-OFDM and since ETSI is recognized for its expertise in conformance test specifications, it is natural to defer to the ETSI standard on this issue. It is worth noting, however, that ETSI defers to IEEE standards as well. In fact, the ETSI test specifications have, in many cases, pointed not to ETSI air interface standards but to IEEE Std 802.16 for their references.

WIMAX FORUM CONFORMANCE TESTING FOR FIXED ACCESS

The only publicized industry activities related to the testing of conformance to IEEE Std 802.16 have been developed in the WiMAX Forum. In January 2006, the WiMAX Forum announced that four products (two BSs, one BS "solution," and one SS "solution") had been certified for 3.5 GHz operation following testing at its laboratory in Malaga, Spain. It also announced plans to test an additional 26 products. Protocol conformance, radio conformance, and basic interoperability were certified. Some additional capabilities, including QoS and security, were not tested. Certification testing of these features is

expected later in 2006. Testing of systems operating in the 5.8 GHz bands is also in development.

WIMAX FORUM AND MOBILE BROADBAND WIRELESS ACCESS

With the progress of the amendment project IEEE P802.16e, the WiMAX Forum developed an interest in this work also. The WiMAX Forum eventually came to the conclusion that it would strongly support the evolution of the IEEE 802.16 standard from fixed to mobile applications and would commit itself to the development of test specifications for mobile systems defined in IEEE Std 802.16e. Most of the WiMAX Forum effort on mobility has been directed at the WirelessMAN-OFDMA mode. Work to create the test specifications is well underway. This work is being undertaken jointly between ETSI and the WiMAX Forum based on agreement between the two. An activity related to the mobile enhancement of WirelessMAN-OFDM is also underway, but this has seen considerably less support among the member companies of the WiMAX Forum.

Chapter 16 Related standards

Other wireless standards with similar applications

This chapter opens by comparing the IEEE 802.16 (WirelessMAN) standard to the IEEE 802.11 (WLAN) standard. It next overviews progress in two IEEE 802 working groups, IEEE 802.20 and IEEE 802.22, that are engaged in developing standards, but have not at this time completed any. The chapter reviews some history and the status of related projects in ETSI's BRAN activity, briefly adding reports on the relation between the IEEE 802.16 Working Group and two other regional standardization activities: the Korean Telecommunication Technology Association (TTA) and the China Communications Standards Association (CCSA). We close the chapter with a review of the important relationships between IEEE Std 802.16 and the ITU, particularly those leading to the international recommendation of IEEE Std 802.16 through the ITU.

IEEE STD 802.11

The IEEE 802.11 standard defines MAC, PHY, and management protocols for WLANs. A LAN typically has a range on the order of 100 m and serves a space the size of a home, an office building, or a small campus. The distinction between LANs and MANs is especially important in the wireless case because the choices for MAC and PHY protocols and parameters essentially dictate the type of network that can be built. WLANs and wireless MANs have widely different requirements, and a MAC or PHY designed for one type of network may be unsuitable for the other.

Since its initial ratification in 1997, IEEE Std 802.11, and its later amendments, have become the foundation for a large and growing market. WLANs based on IEEE Std 802.11 are an essential network technology. With their standardization and subsequent widespread adoption in homes and enterprises, IEEE 802.11 devices—known as *Wi-Fi* to the general public, due

to the certification mark of the Wi-Fi Alliance—have become commodities in recent years. The following subsections summarize the IEEE 802.11 MAC and PHY and discuss the similarities and differences between IEEE Std 802.11 and IEEE Std 802.16.

IEEE 802.11 MAC

Medium access control layer (MAC)

The IEEE 802.11 MAC is based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol, in which IEEE 802.11 devices primarily follow a “listen before talk” rule, with random backoff to avoid collisions. The fundamental premise of CSMA is that all devices sharing the channel can hear each other. Most IEEE 802.11 devices have omnidirectional antennas and, in the local area of primary application, can hear each other. Some mechanisms [e.g., the request to send and clear to send (RTS/CTS) mechanism] do exist, albeit at a higher overhead, to partially address the “hidden node” case in which some nodes are within range of the AP (analogous to an IEEE 802.16 BS), but not within range of each other.

The IEEE 802.11 CSMA/CA protocol is similar to the CSMA/CD protocol of Ethernet. In the wireless case, carrier sensing is possible, except in the hidden node situation. However, collision detection (the “CD” of Ethernet) is not. An Ethernet node continues to sense the medium during transmission and is thereby able to detect collisions. IEEE 802.11 devices are half-duplex and, therefore, cannot listen while transmitting. In fact, given the fact that IEEE Std 802.11 uses the same frequency for UL and DL, it would be a significant challenge to design an IEEE 802.11 device that could accurately sense the medium for collisions during transmission.

In lieu of collision detection, IEEE 802.11’s collision avoidance process uses a physical carrier sense and a virtual carrier sense mechanism are used to avoid potential collisions. The physical carrier sense mechanism listens for the presence of any other transmissions on the channel before attempting a transmission of its own. The virtual carrier sense mechanism utilizes the explicit indication from another transmitter that essentially reserves the channel for a specific amount of time.

Since CSMA/CA is a fully distributed scheme with no central coordinator, collisions are still possible. The absence of collision detection makes it essential to use an acknowledgment scheme to ensure successful reception. IEEE Std 802.11 uses immediate MAC acknowledgments to confirm that an IEEE 802.11 frame has reached its destination. This is essentially a stop-and-wait ARQ scheme with synchronous acknowledgment, where the transmitter waits for the acknowledgment before attempting the next transmission or repeating the previous one. In the IEEE 802.11 MAC, the immediate acknowledgment is mandatory for all unicast frames⁷. Note that, in IEEE Std 802.11, the word *frame* is used in both the MAC sense (as a single MAC PDU, carrying data, management, or control content) and in the PHY sense (as a unit of PHY transmission) because each PHY frame carries one MAC frame. In contrast, IEEE Std 802.16 uses *frame* only as a PHY transmission unit; an IEEE 802.16 frame may carry one or more MAC PDUs or partial MAC PDUs. Although IEEE Std 802.11 supports fragmentation, it is optional and seldom implemented by IEEE 802.11 devices. The optional fragmentation is not dynamic and uses a fixed, configurable fragment size.

The duplexing method used in IEEE Std 802.11 is TDD, which is half-duplex by definition. However, in IEEE Std 802.11, no centralized coordinator allocates time slots; instead, transmission decisions are taken independently at each transmitter. The IEEE 802.11 AP, which is analogous to the IEEE 802.16 BS, has no special rules for accessing the media. The AP has to contend for the media just like any other IEEE 802.11 client communicating with it.

MAC overhead

The IEEE 802.11 MAC requires a minimum of 24 bytes of MAC header information per frame. Note that an IEEE 802.11 MAC frame can carry only one higher layer SDU; i.e., multiple higher layer SDUs such as IP packets cannot be packed into a single MAC frame. For example, each 40 byte TCP acknowledgment would require at least 42 bytes of MAC overhead (24 bytes of MAC header + 4 bytes of CRC + 14 bytes of acknowledgment) in addition to the per-frame PHY overhead. The PHY rates must be considered in this

⁷ IEEE Std 802.11e™-2005 includes an option to omit immediate acknowledgments in favor of delayed acknowledgments.

MAC discussion because the IEEE 802.11 acknowledgment is typically sent at one of the more robust PHY rates. A large frame sent at a lower rate can occupy the channel for a significant amount of time.

The transmission rate to be used is also chosen independently by the transmitters. The standard does not specify an algorithm to choose the transmission rate, and vendors implement their own rate-selection algorithm. However, an IEEE 802.11 AP can restrict the number of transmission rates that can be used in the network.

The IEEE 802.11 MAC supports two alternative channel access modes, the distributed coordination function (DCF) and the optional point coordination function (PCF). The DCF is the fully distributed scheme discussed in the previous paragraphs. PCF offers some centralized polling, although it is not scalable and the polling does not take the frame size or transmission rate into account. For these reasons, PCF is not widely supported and is rarely used.

MAC summary

The CSMA/CA protocol with DCF works reasonably well in a WLAN environment. However, it is not without problems in some situations. The following is a partial list of concerns in CSMA/CA WLAN:

- **Nondeterminism:** CSMA/CA is nondeterministic, and the stop-and-wait ARQ can make successful reception significantly unpredictable if frames need to be resent often. The situation can become drastically worse as the network load increases. Deterministic behavior is required for many QoS-sensitive applications.
- **Hidden nodes:** Two CSMA devices that cannot hear each other may simultaneously initiate transmission. A collision will result. Retransmission will take time and waste future transmission opportunities. This problem is somewhat addressed by the RTS/CTS-based reservation protocol, but its effectiveness declines with a large number of hidden nodes.
- **Near-far problem:** The near-far problem refers to a scenario in which devices closer to an IEEE 802.11 AP can overpower devices farther away, thus unfairly affecting the performance of those devices.

- **Slowest node:** Since transmission decisions are taken independently, one or more nodes choosing to transmit at the lowest rate will, by using a less efficient communication scheme, occupy a disproportionate fraction of airtime. This adversely affects other devices that can communicate at a higher rate.
- **Capture effect:** The capture effect is a fundamental problem in any CSMA protocol, including wired networks such as Ethernet. Since the CSMA devices make independent decisions on transmissions and backoff, the device that successfully completes a transmission resets its contention window and starts afresh for the next contention. This provides an unfair advantage to the device with a successful transmission when multiple devices are contending for access.
- **Overhead:** In general, the IEEE 802.11 MAC has high overhead, especially for smaller frames such as voice or TCP acknowledgments.

IEEE 802.11 PHY

IEEE Std 802.11 has standardized several PHY modes, including the following:

- Frequency-hopping spread spectrum (FHSS), up to 2 Mbit/s
- Direct sequence spread spectrum, up to 11 Mbit/s, in IEEE Std 802.11b™
- OFDM, up to 54 Mbit/s, in IEEE Std 802.11a™ and IEEE Std 802.11g™

The quoted data rates are raw PHY rates. For instance, the maximum IEEE 802.11a PHY rate is 54 Mbit/s, but the highest actual UDP throughput with maximum packet size is only about 30 Mbit/s due to the MAC and PHY overheads.

The OFDM PHY of IEEE Std 802.11a and IEEE Std 802.11g is based on a 64-FFT. The channel size is approximately 20 MHz. The maximum delay spread is about 800 ns, which is sufficient for a LAN with reasonable multipath.

IEEE 802.11 extensions

The IEEE 802.11 Working Group has recently developed and is currently developing many amendment projects, including the following:

- **IEEE Std 802.11e:** IEEE Std 802.11e-2005 defines MAC extensions to CSMA/CA in order to improve QoS. Some MAC efficiency improvements are also included. The QoS extensions improve both DCF and PCF by defining a new hybrid coordination function (HCF), which includes enhanced distributed channel access (EDCA) and the HCF coordinated channel access (HCCA) functions. Both EDCA and HCCA schemes are backward compatible with IEEE 802.11 DCF and frame formats. HCCA offers some centralized scheduled functions. Some of the efficiency improvements include the option of not having immediate acknowledgments and allowing block (i.e., delayed) acknowledgments. IEEE Std 802.11e works for any of the underlying PHY modes.
- **IEEE P802.11n:** The primary objective of the amendment project IEEE P802.11n is to improve the throughput of IEEE Std 802.11 beyond 100 Mbit/s, using techniques such as SDMA and MIMO. Both PHY and MAC enhancements are under consideration. This project is expected to make use of most of the IEEE 802.11e features and to define additional efficiency mechanisms. The project is expected to achieve most of the throughput improvements by doubling the channel size. Completion of the standard is expected in 2007.

- **IEEE P802.11p:** The objective of the amendment project IEEE P802.11p is to support communication between vehicles, and from vehicles to the roadside, while operating at speeds up to 200 km/h for communication ranges up to 1000 m. This is specifically targeted for the 5 GHz bands and in all forms of surface transportation. Both MAC and PHY enhancements are being considered, including a smaller channel size of 10 MHz.
- **IEEE P802.11s:** The amendment project IEEE P802.11s is working on defining a mesh MAC extension to IEEE Std 802.11. The objective is to use the existing IEEE 802.11 addressing format (especially the four-address format) to fully define a multihop network with autoconfiguration capabilities.

Using IEEE Std 802.11 as a MAN

Although IEEE Std 802.11 and its extensions were designed to operate in a LAN environment, many IEEE 802.11 systems, sometimes with modifications, are being operated in long-range outdoor MAN environments. To extend the range, most of these systems make use of high-gain directional antennas to support clients communicating with a (standard or modified) IEEE 802.11 AP. This situation massively exacerbates the hidden node problem, forcing every terminal to be hidden from every other. MAC customization becomes particularly important. Many proprietary and nonstandard extensions to IEEE Std 802.11 have been applied, including the following:

- **IEEE 802.16-like MAC over IEEE 802.11 PHY:** Some IEEE 802.11 chipsets allow an implementor to use the IEEE 802.11 PHY, but bypass the IEEE 802.11 MAC. Some vendors have used such an approach to implement a TDMA scheme. However, the PHY overhead and some of the MAC overhead cannot be eliminated using this approach. Similarly, the limitations of the IEEE 802.11 PHYs, such as the limited ability to address the delay spread typical of long-range outdoor environments, cannot be eliminated either.
- **Modified IEEE 802.11 MAC:** Some of the proprietary modifications include modification of basic IEEE 802.11 timing or channel access parameters, the turning off of acknowledgments, and modification of the acknowledgment timeout. The IEEE 802.11 standard requires that the immediate acknowledgment be received within a specific time. This time is sufficient to deal with smaller propagation delays in a LAN. However, long-range communication such as a MAC requires longer propagation delays.
- **FDD:** Some systems use an FDD-like approach, with communications in opposite directions using different IEEE 802.11 channels.

Quantitative comparison of IEEE Std 802.11 and IEEE Std 802.16

In general, the IEEE 802.11 and IEEE 802.16 technologies are complementary, as one is targeted for LANs and the other for MANs. However, we need to summarize the differences between the two standards in

order to stress the differences in the target markets, which is reflected in the design choices made. Table 16-1 shows some of these differences.

Table 16-1: Comparison of IEEE Std 802.11 and IEEE Std 802.16

Feature	IEEE Std 802.11	IEEE Std 802.16
Medium access	CSMA/CA Some TDMA-like functions in IEEE Std 802.11e	TDM/TDMA OFDMA (optional)
Channel size	~22 MHz (IEEE Std 802.11b) 20 MHz (IEEE Std 802.11a and IEEE Std 802.11g) 10 MHz (IEEE Std 802.11j™)	1.25–28 MHz
Maximum PHY data rate	54 Mbit/s	72 Mbit/s (10 MHz channel)
Maximum (bit/s)/Hz	~2.7	~5
Delay spread tolerance	Up to 800 ns	Up to 10 μ s
Minimum MAC overhead	28 bytes (header + CRC)	6 bytes
QoS	Limited QoS support (up to eight priorities per system) in IEEE Std 802.11e	Per-connection QoS

Although IEEE Std 802.11e supports a form of QoS, with eight priorities (or classes), the addition of QoS to IEEE Std 802.11 is an afterthought. On the other hand, the IEEE 802.16 MAC is a QoS-centric MAC that has been designed with QoS as an integral part of the MAC functions. Moreover, the IEEE 802.16 MAC is much more efficient than IEEE Std 802.11 for outdoor applications, with packing, ARQ, dynamic fragmentation, and smaller header overhead. The problems associated with the IEEE 802.11 CSMA/CA protocol, such as hidden nodes, capture effect, and the near-far problem, are eliminated by the use of a centrally scheduled IEEE 802.16 MAC with TDM/TDMA (and optionally OFDMA).

Ultimately, IEEE Std 802.11 and IEEE Std 802.16 are two parts of a team that can form the basis of a flexible network with an extensive range of applicability.

IEEE 802.20 WORKING GROUP

The IEEE 802.20 Working Group, chartered to develop a standard for mobile broadband access supporting vehicular speeds, first met formally in March 2003. The goal is to support operation in licensed bands below 3.5 GHz allocated to the mobile service. The main performance targets given in the IEEE P802.20 PAR are shown in Table 16-2.

Table 16-2: IEEE 802.20 performance targets

Characteristic	Target value
Mobility	Vehicular mobility classes up to 250 km/h (as defined in ITU-R M.1034-1)
Sustained spectral efficiency	>1 (bit/s)/Hz per cell
Peak user data rate	> 1 Mbit/s in paired 1.25 MHz channel
Peak aggregate data rate per cell in the DL	>4 Mbit/s in 1.25 MHz channel
Peak aggregate data rate per cell in the UL	> 800 kbit/s 1.25 MHz channel
Airlink MAC round-trip time	< 10 ms
Duplex	FDD, TDD
Channel bandwidth	1.25 MHz, 5 MHz

At the moment, very little can be said about the technology itself, and whether it meets the targets, as the group has addressed mostly the technology selection process and system requirements rather than developing draft specifications. The working group first considered proposals for draft text in

November 2005, but the process is in its early stages. It is too soon to speculate on the content of the future standard.

IEEE 802.22 WORKING GROUP

The IEEE P802.22 PAR on wireless regional area networks (WRANs) was approved in September 2004. The PAR covers "Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications of fixed point-to-multipoint wireless regional area networks operating in the VHF/UHF TV broadcast bands between 54 MHz and 862 MHz." This range of operation is based on U.S. frequency allocations and implies 6 MHz channelization. For other scenarios, the broader frequency range of 41 MHz to 910 MHz may be considered a target, with 6 MHz, 7 MHz, or 8 MHz channelization. However, the PAR specially addresses U.S. rules promulgated by the FCC.

The aim of the project is to develop a fixed broadband access standard for use in licensed but unused broadcast television spectra. Such a network is envisioned to have a long range, yet prevent interference with incumbent licensed services within the same spectrum. A primary objective is to provide rural, low-population markets with performance levels similar to those of broadband access technologies servicing urban and suburban areas. The WRAN must support QoS, enabling simultaneous support for data, voice, and audio/video applications, and must be available 99.9% of the time.

The target markets to be addressed by such a system are residential, small office/home office (SOHO), small business, multitenant dwellings, and campuses. IEEE P802.22 is intended to provide these customers with capabilities similar to those provided by digital subscriber line (ADSL) and cable modems, but more economically in sparsely populated rural settings. The system is expected to have a typical range of 33 km, with a maximum range of 100 km. The minimum peak throughput at cell edge is required to be 1.5 Mbit/s per subscriber in the DL and 384 kbit/s per user in the UL. To achieve this, the PAR proposes a spectral efficiency goal of 5 (bit/s)/Hz.

Use of the VHF/UHF TV broadcast frequency range is possible in near-LOS and NLOS situations. In the rural settings targeted, operation may include

partial or complete blockage by foliage, contributing to multipath and attenuation of the signal. We may expect that macrodiversity, repeaters, and other techniques will be combined with the natural propagation characteristics of the frequency band to solve the issues of range, multipath, and blockage.

The problems faced by systems operating in this spectrum are compounded by the fact that they are operating in an license-exempt mode in spectrum that technically is licensed to other uses. These other uses are not limited to broadcast TV services that would be relatively easy to map and avoid. They also include FCC Part 74 devices, such as licensed wireless microphones, wireless intercoms, etc. Regulations require that license-exempt users detect these licensed users and avoid interfering with them by moving to a different frequency. This may, however, be very challenging because some of the licensed users are transient and low power in nature.

To better ensure the proper avoidance of incumbents, designers envision that subscriber devices (and repeaters) will be in a master-slave relationship with the BS, with the BS providing centralized power and spectrum management and centralized scheduling control. They also imagine distributed sensing of the RF environment by the subscriber devices for the purpose of detecting incumbents, with the sensing also controlled by the BS.

In terms of services supported, the clear intent of the IEEE P802.22 functional requirements document (see [B46]) is to support variable-length IP-based services with some level of QoS.

There is currently some interest in using a version of IEEE Std 802.16, modified to provide the intended detection and avoidance of incumbents, in order to meet the needs of the IEEE P802.22 PAR.

ETSI BRAN

Within the European Telecommunications Standards Institute (ETSI), the Broadband Radio Access Networks (BRAN) Technical Committee has been active since 1997. Its three primary activities include ETSI BRAN HiperLAN/2 (a WLAN standard that is, in effect, defunct) and two broadband wireless access standards: ETSI BRAN HiperACCESS and ETSI BRAN HiperMAN.

The IEEE 802.16 Working Group has had an active liaison relationship with ETSI BRAN since 1999; for example, the two groups have exchanged over 60 documents and reports. The initial collaboration strove for harmonization between the WirelessMAN-SC and ETSI BRAN HiperACCESS projects, in which ETSI was the first mover. Although this effort made some progress, it ultimately failed. Later, the attention turned to the lower frequency work, in which IEEE Std 802.16 went first. In this case, the harmonization results were remarkably successful. ETSI BRAN HiperMAN, as discussed below, is compatible with the WirelessMAN-OFDM and WirelessMAN-OFDMA modes in IEEE Std 802.16.

ETSI BRAN HiperACCESS

ETSI BRAN HiperACCESS defines PMP broadband wireless for use in the frequency bands between 11 GHz and 66 GHz. In this respect, it attempts to fill the same niche as IEEE 802.16 WirelessMAN-SC.

The ETSI BRAN HiperACCESS standard was developed by many of the same participants involved in creating WirelessMAN-SC. Some parties, however, participated in only one. The result was less harmonization than would ultimately have been desirable. Both standards assume LOS operation and specify a single-carrier PHY. Many other similarities exist also. However, the two also have significant differences and are not compatible.

ETSI BRAN HiperACCESS shares the following features with IEEE 802.16 WirelessMAN-SC:

- Single-carrier modulation, with QPSK, 16-QAM, and 64-QAM
- Similar FEC
- Same basic request/grant scheme
- Same CoSs and QoS concepts
- Same basic ranging, power control, and PHY maintenance
- Similar UL and DL MAP structure
- Similar frame structure, including support for TDD, FDD, and H-FDD
- Similar RCT specification

ETSI BRAN HiperACCESS differs from IEEE 802.16 WirelessMAN-SC in the following ways:

- Fixed-length packet ATM cell transport only
- No packing
- No fragmentation
- Far fewer options of FEC combinations (a few options are defined, tailored for the size of an ATM cell)
- No incremental BW requests
- No piggybacked BW requests

The result was a standard that is simpler to implement than WirelessMAN-SC, but considerably less efficient (even for ATM cells) and not forward looking to IP as the preferred network protocol.

ETSI BRAN HiperMAN

When ETSI BRAN initiated the HiperMAN activity to consider fixed broadband wireless access below 11 GHz, the amendment project IEEE P802.16a was well on its way to adding the new PHY specifications WirelessMAN-OFDM, WirelessMAN-OFDMA, and WirelessMAN-SCa, all operating under the IEEE 802.16 MAC, first defined in IEEE Std 802.16-2001. Thanks to active cooperation between the IEEE 802.16 Working Group and the ETSI BRAN HiperMAN activity, a unified solution was obtained. One key player in this success was Mariana Goldhamer, who served as the IEEE 802.16 Working Group's liaison official to ETSI BRAN while also chairing the ETSI BRAN HiperMAN activity and later serving as vice chair of the ETSI BRAN Technical Committee. Another key player was Nico van Waes, the technical editor of the IEEE 802.16a and ETSI BRAN HiperMAN drafts as well as the area coordinator (ETSI terminology for chair) of ETSI BRAN HiperMAN during that period.

Rather than adapting the MAC from ETSI BRAN HiperACCESS, the ETSI BRAN HiperMAN group came to the conclusion that it would instead adopt the IEEE 802.16 MAC. However, it sought a single PHY solution, rather than three of them. It came to choose WirelessMAN-OFDM, eventually supporting a standard that was a subset of WirelessMAN-OFDM. The ETSI project was

not passive in the collaboration; it contributed ideas and comments to IEEE Std 802.16 during the refinement of that standard. Notably, ETSI moved first to specify UL subchannelization; this was not added into WirelessMAN-OFDM until IEEE Std 802.16-2004 [B20].

More recently, in 2005, the scope of the ETSI BRAN HiperMAN project was extended to include nomadic wireless access. At this stage, ETSI BRAN HiperMAN moved to extend its support of IEEE Std 802.16 and incorporated not only WirelessMAN-OFDM but also WirelessMAN-OFDMA.

As discussed in Chapter 15, ETSI is very active in the development of conformance test specifications for IEEE Std 802.16, particularly through its agreement with the WiMAX Forum. ETSI conformance test documents have referenced IEEE Std 802.16 as their source standards. IEEE Std 802.16 has already moved to accept the notion of making normative reference to ETSI conformance test documentation.

OTHER REGIONAL STANDARDS ACTIVITIES

Beyond its active relationship with ETSI, the IEEE 802.16 Working Group has developed and maintained relationships with some other regional organizations that are interested in broadband wireless access standardization.

Korean Telecommunication Technology Association (TTA) and WiBro

The Korean TTA approached the IEEE 802.16 Working Group in January 2004 with information concerning its effort to develop a parallel standard in the PG05 project, later renamed PG302. Unlike the ETSI BRAN interest, which was on fixed access, the TTA focus was on mobile access. Also, in contrast to ETSI BRAN HiperMAN's interest in WirelessMAN-OFDM, it was clear that the TTA focus was on WirelessMAN-OFDMA. Early in the process, it appeared that the TTA was headed toward a standard similar to, but different from, the WirelessMAN-OFDMA that was eventually approved in IEEE Std 802.16e. However, a number of letters and reports were exchanged, and meetings were held to coordinate activity. Eventually, the two projects began to see significant alignment.

In July 2004, the Korean Ministry of Information and Communication announced that service in the 2.3 GHz spectrum, which had been set aside for portable Internet service, "must comply with IEEE 802.16-2004 and IEEE 802.16e/Draft3 or later versions." The Korean regulations also stipulate some additional specifications, including use of the WirelessMAN-OFDMA mode with a 1024-FFT. The Korean government named this service *WiBro*, for wireless broadband. It is important to understand that WiBro is a service, not a technology. The regulations required that the technology be WirelessMAN-OFDMA.

In retrospect, the IEEE 802.16 Working Group's decision to support multiple modes turns out to have been well justified. The working group, in trying to develop a single standard for worldwide use, had a major challenge because the world includes many diverse interests. In this case, the Europeans leaned toward an OFDM solution and the Koreans toward OFDMA. The multimode decision included in IEEE Std 802.16a formed a basis to satisfy both.

China Communications Standards Association (CCSA)

The CCSA has been pursuing broadband wireless access standards through Working Group 3 of its Technical Committee 5. CCSA has been communicating actively with the IEEE 802.16 Working Group since IEEE Std 802.16's Session #31, which was held in Shenzhen, China, in May 2004. Since then, the organizations have remained in contact through letters, reports, and liaison exchanges. In November 2005, CCSA reported a number of standards projects in fixed access related to IEEE Std 802.16, including test specifications. Work regarding mobile broadband wireless access was at an earlier stage.

INTERNATIONAL TELECOMMUNICATIONS UNION (ITU)

Historically, some of the IEEE 802 standards have been entered into the more formal arena of "international" standardization through IEEE 802's engagement with Joint Technical Committee 1 (JTC1), the committee on information technology standards administered by two private Geneva-based organizations, the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). Although the original

collaborations covered only wired networks, the partnership was extended to wireless networks also by the adoption of IEEE Std 802.11 as ISO/IEC 8802-1 in 1999.

In spite of the successful relationship between IEEE 802 and ISO/IEC JTC1, the IEEE 802.16 Working Group has never shown an interest in following that precedent. The working group has always recognized the value of engaging with the formal international process in Geneva. However, instead of ISO/IEC, IEEE Std 802.16 looks to partner with the ITU, particularly the ITU Radiocommunications Sector (ITU-R). This is partly because IEEE Std 802.16 is the only IEEE 802 standard expected to operate significantly in licensed spectra, the administration of which is significantly dependent on the ITU. It is also because the ITU has always been a focal point of the telecommunications industry. IEEE Std 802.16 is a convergent technology, drawing significantly from the data communications community, but targeting applications that have historically been supported by the telecommunications establishment. Many of the potential customers for IEEE 802.16 systems have a natural home in ITU. The IEEE 802.16 community naturally seeks to engage that community and encourage its participation.

From the beginning, IEEE Std 802.16 has looked to engage with ITU. The original IEEE 802.16 PAR, submitted in March 1999, in answering the question "Is this standard planned for adoption by another international organization?" responded "Yes," referencing ITU. Since then, IEEE 802.16 PARs have done so consistently.

Central to building the IEEE 802.16 Working Group's relationship with ITU-R was Dr. José Costa, who has served since Session #1 in 1999 as the working group's ITU-R liaison official. Dr. Costa originally helped to connect the working group with ITU-R's Joint Rapports Group 8A/9B, on Wireless Access Systems, where Dr. Costa served as one of two principle rapporteurs.

The relationship strengthened significantly in October 2003, when ITU-R named IEEE as a Sector Member, under the same membership classification as ISO. Shortly before, the ITU-R's Strategy and Policy Unit had published its seminal document *The Birth of Broadband* [B28], which made numerous references to the role of IEEE Std 802.16, particularly regarding the expansion of Internet access in rural and developing areas. ITU, perhaps as a

consequence, invited the IEEE 802.16 Working Group chair to speak at its major conference, ITU Telecom World, in Geneva during October 2003. During that meeting, the working group chair, with the assistance of ITU-R Counsellor Fabio Leite, met with staff and various study group officials, discussing opportunities to develop the relationship and, in particular, on drafting new ITU-R recommendations based on the IEEE 802.16 standard and its amendments, which were seen to be valuable because of ITU-R's "global approach and visibility." Following those discussions, the working group began to pursue contacts with several ITU study groups, including some in ITU's Telecommunications Bureau (related to network access and cable modem technology).

In November 2003, the IEEE 802.16 Working Group followed up these discussions with a letter to ITU-R indicating its support for the idea of developing ITU-R recommendations referring to IEEE Std 802.16. This work was slightly delayed by the termination of Joint Rapports Group 8A/9B. However, with the assistance of Dr. Costa (who had assumed the chairmanship of Working Party 8A), the work progressed. IEEE, using its ITU-R membership, contributed a series of documents to Working Party 9B, coordinated with ETSI, on the development of a recommendation on "radio interface standards for broadband wireless access (BWA) systems in the fixed service operating below 66 GHz," pointing to IEEE Std 802.16 and the compatible ETSI BRAN HiperMAN standard. After many discussions and coordination actions, Study Group 9 approved this recommendation in December 2005. The ITU-R recommendation awaits a formal written consultation of the member administration in mid-2006.

In March 2005, the IEEE contributed a parallel proposal to ITU-R Working Party 8A, proposing a preliminary draft new recommendation on "radio interface standards for broadband wireless access systems in the mobile service operating below 6 GHz." The proposal would point to IEEE Std 802.16, including the IEEE 802.16e mobility amendment. The proposal has not progressed rapidly in Working Party 8A, mainly because supporters of a number of alternative technologies have become vocal. It is far from certain where this will lead.

Appendix A IEEE 802.16 headers, subheaders, and management messages

The list of IEEE 802.16 MAC headers, subheaders, and MAC management messages is provided here for quick reference. Table A-1 shows the list of MAC headers, subheaders, and special payloads.

Table A-1: MAC headers, subheaders and special payloads

Description	Size in bytes
Generic MAC header	6
BW request header	6
Fragmentation subheader (FSH)	1
FSH (ARQ)	2
FSH (Extended)	2
Grant management subheader (GMSH)	2
Packing subheader (PSH)	2
PSH (ARQ)	3
PSH (Extended)	3
Mesh subheader (MSH)	2
Fast-feedback allocation subheader (FFSH)	1

Table A-2 lists the management messages and the type of connections that may be used to send them.

Table A-2: Management messages

Type	Name	Description	Connection
0	UCD	UL channel descriptor	Fragmentable Broadcast
1	DCD	DL channel descriptor	Fragmentable Broadcast
2	DL-MAP	Downlink access definition	Broadcast
3	UL-MAP	Uplink access definition	Broadcast
4	RNG-REQ	Ranging request	Initial Ranging or Basic
5	RNG-RSP	Ranging response	Initial Ranging or Basic
6	REG-REQ	Registration request	Primary Management
7	REG-RSP	Registration response	Primary Management
8		Reserved	
9	PKM-REQ	Privacy key management request	Primary Management
10	PKM-RSP	Privacy key management response	Primary Management
11	DSA-REQ	Dynamic service addition request	Primary Management
12	DSA-RSP	Dynamic service addition response	Primary Management
13	DSA-ACK	Dynamic service addition acknowledgment	Primary Management
14	DSC-REQ	Dynamic service change request	Primary Management

Table A-2: Management messages (Continued)

Type	Name	Description	Connection
15	DSC-RSP	Dynamic service change response	Primary Management
16	DSC-ACK	Dynamic service change acknowledgment	Primary Management
17	DSD-REQ	Dynamic service deletion request	Primary Management
18	DSD-RSP	Dynamic service deletion response	Primary Management
19		Reserved	
20		Reserved	
21	MCA-REQ	Multicast assignment request	Primary Management
22	MCA-RSP	Multicast assignment response	Primary Management
23	DBPC-REQ	DL burst profile change request	Basic
24	DBPC-RSP	DL burst profile change response	Basic
25	RES-CMD	Reset command	Basic
26	SBC-REQ	SS basic capability request	Basic
27	SBC-RSP	SS basic capability response	Basic
28	CLK-CMP	SS network clock comparison	Broadcast
29	DREG-CMD	De/Re-register Command	Basic
30	DSX-RVD	DSx received message	Primary Management

Table A-2: Management messages (Continued)

Type	Name	Description	Connection
31	TFTP-CPLT	Config file TFTP complete message	Primary Management
32	TFTP-RSP	Config file TFTP complete response	Primary Management
33	ARQ-Feedback	Stand-alone ARQ Feedback	Basic
34	ARQ-Discard	ARQ Discard	Basic
35	ARQ-Reset	ARQ Reset	Basic
36	REP-REQ	Channel measurement report request	Basic
37	REP-RSP	Channel measurement report response	Basic
38	FPC	Fast power control	Broadcast
39	MSH-NCFG	Mesh network configuration	Broadcast
40	MSH-NENT	Mesh network entry	Basic
41	MSH-DSCH	Mesh distributed schedule	Broadcast
42	MSH-CSCH	Mesh centralized schedule	Broadcast
43	MSH-CSCF	Mesh centralized schedule configuration	Broadcast
44	AAS-FBCK-REQ	AAS feedback request	Basic
45	AAS-FBCK-RSP	AAS feedback response	Basic
46	AAS_Beam_Select	AAS beam select	Basic
47	AAS_BEAM_REQ	AAS beam request	Basic
48	AAS_BEAM_RSP	AAS beam response	Basic
49	DREG-REQ SS	SS deregistration message	Basic
50-255		Reserved	

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NOTE—When phrases have been abbreviated in the text of this book, the abbreviations have generally been used when creating this index. See the Acronyms and Abbreviations list at the beginning of the book for the complete phrase for each abbreviation.

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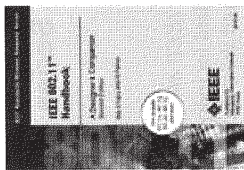
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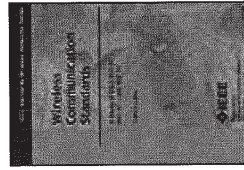
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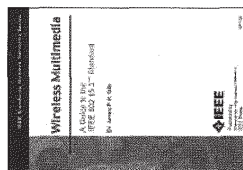


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