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AN OVERVIEW OF SMART ANTENNA TECHNOLOGY FOR MOBILE COMMUNICATIONS SYSTEMS

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ABSTRACT

The technology of smart or adaptive antennas for mobile communications has received enormous interest worldwide in recent years. The purpose of this article is to give an overview of the technology and of the different ways in which it is foreseen to influence mobile communications systems. A broad definition of smart antennas is used in this article, namely base station antennas with a pattern that is not fixed, but adapts to the current radio conditions. The article starts with an explanation of the basic principles of smart antennas. Different levels of intelligence are introduced, ranging from simple switching between predefined beams to optimum beamforming. Also, an evolutionary path for the development of smart antennas is suggested. A discussion of the consequences for mobile systems is given. The principle reason for introducing smart antennas is the possibility for a large increase in capacity: an increase of three times for TDMA systems and five times for CDMA systems has been reported. Other advantages include increased range and the potential to introduce new services. Major drawbacks and cost factors include increased transceiver complexity and more complex radio resource management. The basic principles for implementation of smart antennas at the base stations are explained. First, the general principles for beamforming using array antennas are explored, then the special cases of different smart antenna implementations are discussed. Also, the fundamental difference between performing beamforming on uplink (base station receiving) and downlink (base station transmitting) is dealt with. Special attention is given to the critical factors and technological challenges, including achieving equal performance on uplink and downlink as well as real-time calibration of the receiver and transmitter chains. The article concludes with a short description of some of the trials and testbeds that have been implemented. In the autumn of 1998 Ericsson, in cooperation with Mannesmann Mobilfunk in Germany, became the first to allow commercial traffic through a base station employing smart antennas.

It is foreseen that in the future an enormous increase in traffic will be experienced for mobile and personal communications systems. This is due both to an increased number of users as well as new high bit rate data services being introduced. This trend is observed for second-generation systems and will most certainly continue for third-generation systems being introduced worldwide within a few years.[1] The increase in traffic will put a demand on both manufacturers and operators to provide enough *capacity* in the networks. Presently, one of the most promising techniques for increasing the capacity in cellular systems by the amount necessary is *smart* or *adaptive antennas*.

[1] *While the data calls in the GSM network are in the order of 4 percent of the total traffic, data calls contribute to more than 50 percent of the total traffic in the fixed network (1998). It is expected that in the future a similar trend will be visible for cellular networks.*

This article will describe the basic principles behind the technology as well as provide a discussion about the advantages and technical challenges. Although it is feasible to also use these techniques in, for example, satellite systems and high frequency wireless local area networks, the discussion here is limited to cellular systems in the frequency range 1-2 GHz. At these frequencies it is difficult to introduce smart antennas into the mobile stations due to the limited size of the terminal in terms of wavelengths.

CAPACITY ASPECTS

In a cellular system the radio communication is between the user and a *base station*, which provides radio coverage within a certain area, which is called a *cell*. Capacity in such a system can be defined as the total bit rate per unit bandwidth per unit area, or bit/s/Hz/m^2. Because the available frequency band is limited, the capacity is given by the *cell density*, the *fre -*

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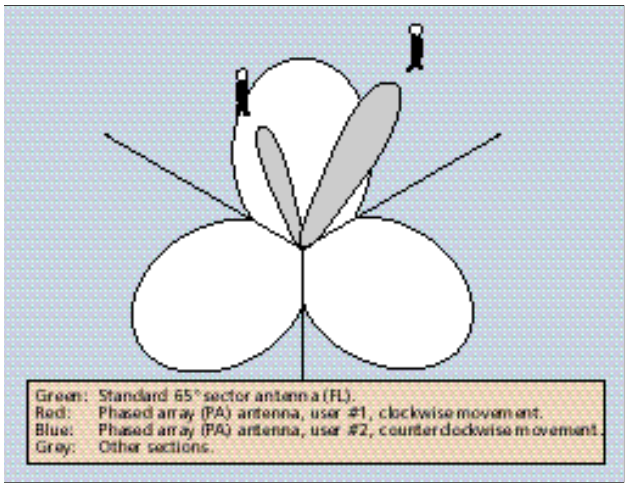


■ **FIGURE 1.** *Illustration of the difference between a traditional base station radiation pattern and a smart antenna base station.*

quency reuse distance and the number of users that can be served simultaneously by each base station. Techniques for increasing capacity in cellular systems have included using smaller cells, so-called *microcells*, and *frequency hopping*, a technique that disperses interference and averages the fading rate.

WHAT ARE SMART ANTENNAS?

Base station antennas have up till now been omnidirectional or sectored. This can be regarded as a "waste" of power as most of it will be radiated in other directions than toward the user. In addition, the power radiated in other directions will be experienced as interference by other users. The idea of smart antennas is to use base station antenna patterns that are not fixed, but adapt to the current radio conditions. This can be visualized as the antenna directing a beam toward the communication partner only. The difference between the fixed and the smart antenna concept is illustrated in Fig. 1. Smart antennas will lead to a much more efficient use of the power and spectrum, increasing the useful received power as well as reducing interference.

SHARING THE RADIO SPECTRUM

Traditionally, users communicating via the same base station have been separated by frequency, as in FDMA (frequency division multiple access); by time, as in TDMA (time division multiple access); or by code, as in CDMA (code division multiple access). Smart antennas add a new way of separating users, namely by space, through *SDMA (space division multiple access)*. As will be explained later, SDMA, which means that users in the same cell can use the same *physical communication channel*, is the final step in an evolutionary path toward increasingly more advanced utilization. The *physical communication channel* is defined as a combination of carrier frequency, time slot and spreading code.

WHY NOW?

In the last couple of years smart antennas for mobile communications have received enormous interest worldwide. So why is the interest appearing now, and not five or ten years ago? The answer probably lies with the fact that for most operators there has not been much reason to worry about capacity and spectrum efficiency. Also, as will be apparent later on, if the base station is to track a large number of users simultaneously, the computational cost will be large. Only recently are processors with sufficient power becoming available. In addition to increased capacity, smart antennas also introduce a number of other advantages to cellular networks, including *increased range*, *a higher level of security*, and the *possibility for new services*. This will be discussed in more detail later.

OUTLINE

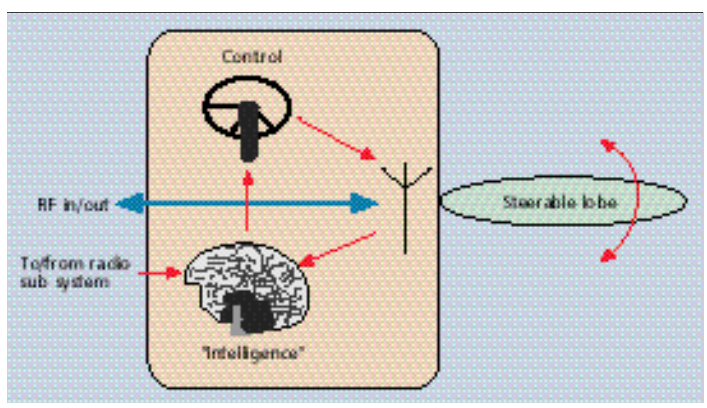
This article consists mainly of four parts. In the next section definitions of terms and descriptions of the basic principles are given. There is a discussion of the consequences of introducing the new technology into mobile communications networks. Later, implementation issues are discussed in more detail. We also describe some of the field trials and testbeds for smart antennas that have been carried out.

The general principles are valid for both TDMA systems (e.g., GSM) and CDMA systems (e.g., IS-95 and UMTS). In this article, most reported techniques and test results stem from TDMA-based testbeds, so the discussion is somewhat limited to this case. A comprehensive treatment of smart antennas applied to CDMA is, however, given by Liberti and Rappaport in [1].

BASIC PRINCIPLES

What do we mean by the term "smart antenna?" The theory behind smart antennas is not new. The technique has for many years been used in electronic warfare (EWF) as a countermeasure to electronic jamming. In military radar systems similar techniques were already used during World War II. There are in principle a number of ways in which an adaptively adjustable antenna beam can be generated, for instance by mechanically steered antennas. However, the technology almost exclusively suggested for land-based mobile and personal communications systems is *array antennas*. This technology will be explained in more detail later.

The main philosophy is that interferers rarely have the same geographical location as the user. By maximizing the antenna gain in the desired direction and simultaneously placing minimal radiation pattern in the directions of the interferers, the quality of the communication link can be significantly improved. In personal and mobile communications, the interferers are other users than the user being addressed.



■ **FIGURE 2.** *Principle of a smart antenna.*

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CONCEPTS

Several different definitions for smart antennas are used in the literature. One useful and consistent definition can be that the difference between a smart/adaptive antenna and a "dumb"/fixed antenna is the property of having an adaptive and fixed lobe-pattern, respectively. This is the definition to be used in this article. Figure 2 illustrates the concept of a smart antenna.

Normally, the term "antenna" comprises only the mechanical construction transforming free electromagnetic (EM) waves into radio frequency (RF) signals traveling on a shielded cable and vice versa. We may call it *the radiating element*. In the context of smart antennas, the term "antenna" has an extended meaning. It consists of a number of radiating elements, a combining/dividing network and a control unit. The control unit can be called the smart antenna's intelligence, normally realized using a digital signal processor (DSP). The processor controls feeder parameters of the antenna, based on several inputs, in order to optimize the communications link. Different optimization criteria can be used, as will be explained in the next section. This shows that smart antennas are more than just the "antenna," but rather a complete transceiver concept.

LEVELS OF INTELLIGENCE

Based on the definition above, one can define "levels of intelligence." One set of definitions often used are described below and illustrated in Fig. 3.

- *Switched lobe (SL)*: This is also called switched beam. It is the simplest technique, and comprises only a basic switching function between separate directive antennas or predefined beams of an array. The setting that gives the best performance, usually in terms of received power, is chosen. Because of the higher directivity compared to a conventional antenna, some gain is achieved. Such an antenna will be easier to implement in existing cell structures than the more sophisticated adaptive arrays, but it gives a limited improvement.
- *Dynamically phased array (PA)*: By including a *direction of arrival* (DoA) algorithm for the signal received from the user, continuous tracking can be achieved and it can be viewed as a generalization of the switched lobe concept. In this case also, the received power is maximized.
- *Adaptive array (AA)*: In this case, a DoA algorithm for determining the direction toward interference sources (e.g., other users) is added. The radiation pattern can then be adjusted to null out the interferers. In addition, by using special algorithms and space diversity techniques, the radiation pattern can be adapted to receive multipath signals which can be combined. These techniques will maximize the *signal to interference ratio* (SIR) (or signal to interference and noise ratio (SINR)).

Conventional mobile systems usually employ some sort of antenna diversity (e.g., space or polarization diversity). Adaptive antennas can be regarded as an extended diversity scheme, having more than two diversity branches. In this context, phased arrays will have a greater gain potential than switched lobe antennas because all elements can be used for diversity combining [2, 3].

All these concepts are analyzed in more detail later.

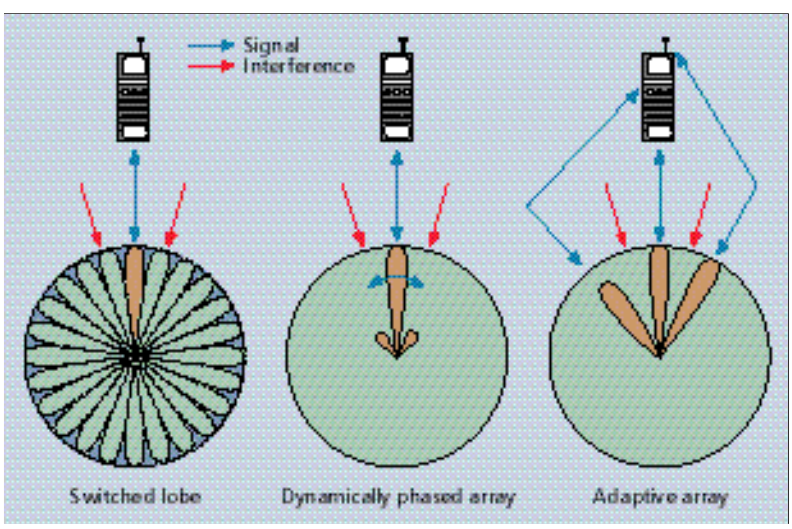
EVOLUTIONARY PATH

All the levels of intelligence described in the previous section are technologically realizable today. However, in the domain of personal and mobile communications, an evolution can be foreseen in the utilization of smart antennas toward gradually more advanced solutions. The evolution can be divided into three phases [4]:

- Smart antennas are used on *uplink* only (uplink means that the user is transmitting and the base station is receiving). By using a smart antenna to increase the gain at the base station, both the sensitivity and range are increased. This concept is called *high sensitivity receiver* (HSR) and is in principle not different from the diversity techniques implemented in today's mobile communications systems.
- In the second phase, directed antenna beams are used on the *downlink direction* (base station transmitting and user receiving) in addition to HSR. In this way, the antenna gain is increased both on uplink and downlink, which implies a spatial filtering in both directions. Frequencies can be more closely reused, thus the system capacity increases. The method is called *spatial filtering for interference reduction* (SFIR). It is possible to introduce this in second-generation systems.
- The last stage in the development will be full *space division multiple access* (SDMA). This implies that more than one user can be allocated to the same physical communications channel simultaneously in the same cell, only separated by angle. In a TDMA system, two users will be allocated to the same time slot and carrier frequency at the same time and in the same cell.

In phase 2, the capacity is increased due to closer frequency reuse allowing more carriers per base station. In phase 3, an additional increase in capacity is achieved by allowing more users per carrier. Introducing SDMA in second-generation TDMA systems will be difficult and maybe undesirable [5], but it may become a natural component in third-generation systems.

The "levels of intelligence" in the previous section describe the level of technological development, while the steps described here can be regarded as part of a system evolution.



■ **FIGURE 3.** *Different smart antenna concepts.*

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CONSEQUENCES

The introduction of smart antennas will have a large impact on the performance of cellular networks. It will also affect many aspects of both the planning and deployment of mobile systems. This chapter will discuss the potential benefits and cost factors, and will also briefly describe the implications on radio planning.

IMPROVEMENTS AND BENEFITS

Capacity Increase — The principle reason for the growing interest in smart antennas is the capacity increase. In densely populated areas mobile systems are normally interference-limited, meaning that interference from other users is the main source of noise in the system. This means that the signal to interference ratio, SIR, is much larger than the signal to thermal noise-ratio, SNR. Smart antennas will on average, by simultaneously increasing the useful received signal level and lowering the interference level, increase the SIR. Especially, the adaptive array will give a significant improvement. Experimental results report up to 10 dB increases in average SIR in urban areas [6].

In TDMA systems, the implication of the increased SIR is the possibility for reduced frequency reuse distance. An example is shown in Fig. 4, where the traditional seven-cell cluster has been reduced to a three-cell cluster. This will lead to a capacity increase of 7/3 as all the cells can be allocated this amount more carriers.

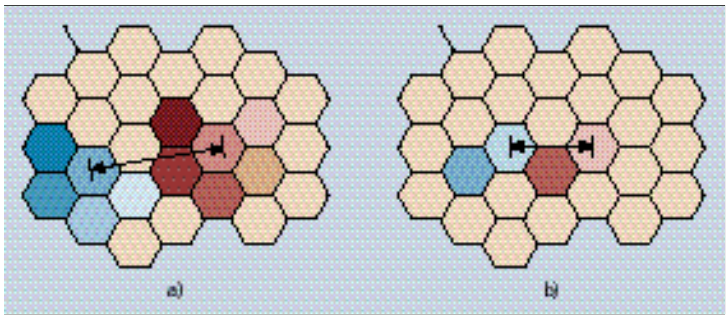
Simulations performed on a FH-GSM network with 1/3 reuse distance utilizing SFIR reports that a capacity increase of 300 percent can be expected [5].

CDMA systems, such as IS-95 or UMTS, are more inherently interference-limited than TDMA systems. The main source of noise in the system is the interference from other users due to the spreading codes being non-ideally orthogonal. This means that the expected capacity gain is even larger for CDMA than for TDMA. A fivefold capacity gain has been reported for CDMA in [7].

Range Increase — In rural and sparsely populated areas radio coverage rather than capacity will give the premises for base station deployment. Because smart antennas will be more directive than traditional sector or omnidirectional antennas, a range increase potential is available. This means that base stations can be placed further apart, potentially leading to a more cost-efficient deployment. The antenna gain compared to a single element antenna can be increased by an amount equal to the number of array elements, e.g., an eight-element array can provide a gain of eight (9 dB).

New Services — When using smart antennas the network will have access to spatial information about the users. This information can be used to estimate the positions of the users much more accurately than in existing networks. Positioning can be used in services such as emergency calls and location-specific billing. The FCC (Federal Communications Commission) in the United States has decided that by October 2001 user location information with an accuracy of 125 meters RMS error must be provided [8].

Security — It is more difficult to tap a connection when smart antennas are used. To successfully tap a connection the intruder must be positioned in the same direction as the user as seen from the base station.



■ **FIGURE 4.** *Illustration of reduced frequency reuse distance: a) Traditional 7-cell cluster; b) cluster enabled by interference reduction like e.g. smart antennas.*

Reduced Multipath Propagation — By using a narrow antenna beam at the base station the multipath propagation can be somewhat reduced. The actual reduction depends on the scenario, and is not always significant. Although channel equalizers and RAKE receivers most often will handle and even exploit the multipath components, on very high-speed connections this may not be the case. Potentially, the reduction of multipath propagation can be used to ease the requirement on future modem design.

COST FACTORS

Although the benefits of using smart antennas are many, there are also drawbacks and cost factors. The gain should always be evaluated against the cost.

Transceiver Complexity — It is obvious that a smart antenna transceiver is much more complex than a traditional base station transceiver. The antenna will need separate transceiver chains for each of the array antenna elements and accurate real-time calibration of each of them. In addition, the antenna beamforming is a computationally intensive process, especially if *adaptive arrays* are to be used (see earlier section). This means that the smart antenna base station must include very powerful numeric processors and control systems. There will be a growing need for the development of efficient algorithms for real-time optimizing and signal tracking. Smart antenna base stations will no doubt be much more expensive than conventional base stations.

Resource Management — Smart antennas are mainly a radio technology, but they will also put new demands on network functions such as resource and mobility management. When a new connection is to be set up or the existing connection is to be handed over to a new base station, no angular information is available to the new base station and some means to "find" the mobile station is necessary. This can be handled by letting the base station continuously sweep through the cell with a "search" beam looking for candidates for a new connection or a handover. Another possibility is to use an external system for positioning, e.g., GPS. As far as handover is concerned, a third possibility is available: directional information from the existing cell can be used by the network to provide an "educated guess" about which cell to hand the connection over to.

As was explained earlier, SDMA involves different users using the same physical communication channel in the same cell, separated only by angle. When angular collisions between these users occur, one of them must quickly switch to another channel so that the connection is not broken. This means that in systems providing full SDMA, there will be much more *intracell handovers* than in conventional TDMA or CDMA

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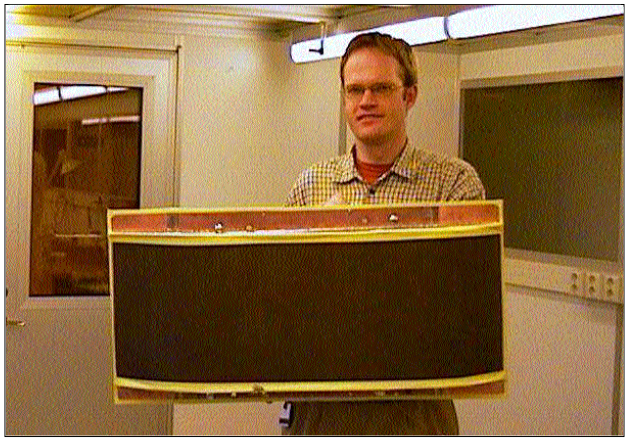


■ **FIGURE 5.** *Picture of an 8-element array antenna at 1.8 GHz. (Antenna property of Telia Research AB, Sweden).*

systems, and more monitoring by the network is necessary. The animation in Fig. 1 shows what is meant by an angular collision.

Physical Size — For the smart antenna to obtain a reasonable gain, an array antenna with several elements is necessary. Typically arrays consisting of six to 10 horizontally separated elements have been suggested for outdoor mobile environments [9–11]. The necessary element spacing is 0.4–0.5 wavelengths. This means that an eight-element antenna would be approximately 1.2 meters wide at 900 MHz and 60 cm at 2 GHz. With a growing public demand for less visible base stations, this size, although not excessive, could provide a problem. Figure 5 shows a picture of an eight-element antenna array at 1.8 GHz.

RADIO PLANNING

For the smart antennas to have the desired gain the base stations must be able to separate the users in the angular domain. This means that some of the current strategies for radio planning need to be modified. In existing networks base stations are often positioned along highways and railway lines. From a smart antenna point of view it is much more efficient to position the base station away from the road or railway. In this way the spatial dimension is better exploited. This strategy is illustrated in Fig. 6.

Another difficult point is small urban cells with base stations positioned below rooftop level. In these cases the signal from both the desired users and from the interferers will tend to arrive along the street canyons, making it difficult to separate them in the angular domain. Figure 7 shows an example of an average *power azimuth spectrum* (PAS)[2] measured in urban area microcells in Oslo [12] and shows that the signal tends to arrive from two perpendicular directions given by the street grid.

Radio channel models and radio planning tools need renewed attention upon the introduction of smart antennas. Statistical radio channel models are used in performance testing and design of radio systems. However, existing models do not describe the channel in the angular domain and can therefore not be used in the evaluation of systems employing smart antennas. Work is currently ongoing to provide statistical radio channel models describing the directional domain.

Similarly, existing commercial radio planning tools are normally only concerned with estimating the signal level and possibly the time dispersion on the link. However, in the future it will be beneficial for the tools to predict the angular dispersion as well. Some analytical radio prediction methods, such as *ray tracing*, have the possibility for estimation of angular information inherent.

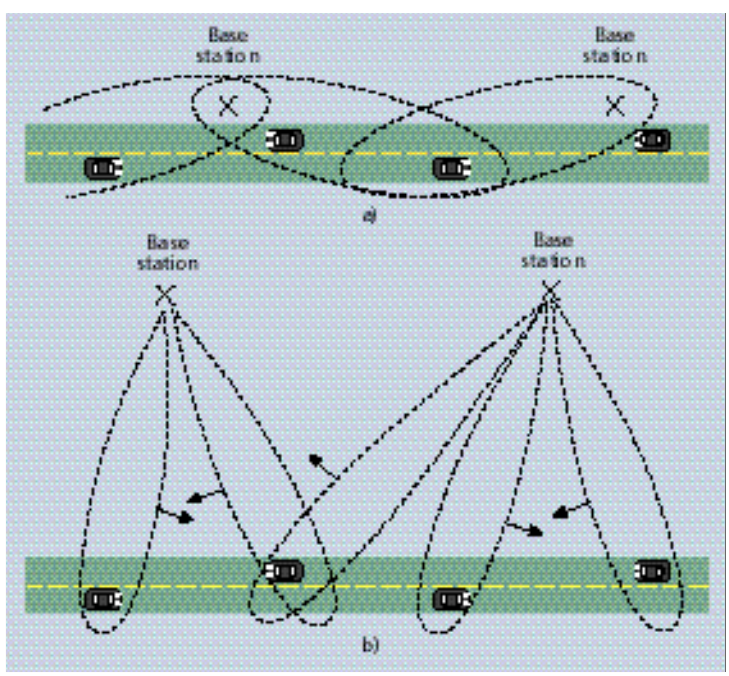
IMPLEMENTATION

This section explains some of the underlying technology employed in order to implement smart antennas. The treatment given here is not comprehensive, but should give an impression of the basic ideas. The technology is based on array antennas where the radiation pattern is altered by adjusting the amplitude and relative phase on the different array elements. Next we explain the fundamental principles of array beamforming. Then we explain how this is exploited in smart antennas. Even though the reception and transmission parts most often are integrated, and much of the same hardware normally will be used, they will be explained separately. This is because conceptually the uplink and downlink are quite different in terms of smart antennas.

ARRAY ANTENNAS

Electronically steerable antenna patterns are most often generated using array antennas. These are antennas consisting of a number of antenna elements on which the signal is divided or combined in both phase and amplitude. Generally, any combination of elements can form an array. However, usually equal elements in a regular geometry are used.

Arrays can be one-, two- and three-dimensional, depending



■ **FIGURE 6.** *Illustration of base station positioning along roads and railways: a) Traditional deployment; b) Possible smart antenna deployment.*

[2] *An average power azimuth spectrum shows an area average of the power received from the azimuth antenna view angles.*

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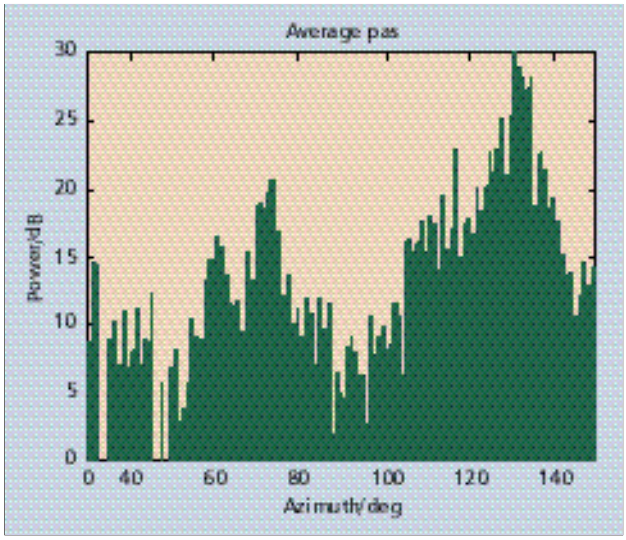


■ **FIGURE 7.** *Example of average power azimuth spectrum (PAS), recorded in Oslo.*

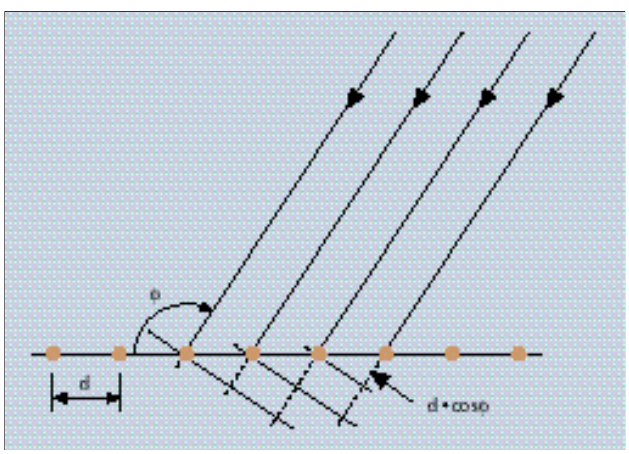
on the dimension of the space one wants to access. Figure 13 shows some examples of array geometries. Using regular geometries simplifies both analysis and synthesis of the array. In this section, the linear array principle will be worked through as an example. The mathematics can be extended to more dimensions and other geometries, but the principle is the same.

The total radiation pattern is given by the *element type*, the *relative positions* and the excitation (amplitude and phase). Using an array antenna, it is possible to obtain a very good control of the radiation pattern, e.g., the shape of the main lobe and the side lobe level (SLL). The radiation pattern is uniquely given by the aforementioned parameters.

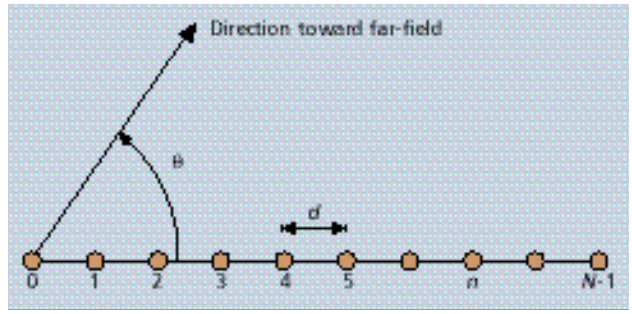
Linear Equidistant Arrays — The "simplest" geometry is the *one-dimensional linear equidistant array*. All the array elements are placed along a line with equal distance between them, as shown in Fig. 8. The figure also shows which parameters are available.

The far-field expression of the electrical field from a single array element is given by Eq. 1:

$$\vec{E}_n(r,\theta,\varphi) = I_n \frac{e^{-jkr}}{r} \vec{e}(\theta,\varphi) \qquad (1)$$



■ **FIGURE 9.** *Using the phase angle of each element to steer the lobe.*



■ **FIGURE 8.** *Geometry of the equidistant linear array.*

where I_n is the complex element current and $\vec{e}(\theta, \phi)$ is the element antenna pattern, usually called the *element factor*, and r, θ and φ are the spherical coordinates of the observation point.

The total field from an array consisting of N elements is the superposition of the element contributions as expressed in Eq. 2:

$$\vec{E}(r,\theta,\varphi) = \sum_{n=0}^{N-1} I_n \frac{e^{-jkr}}{r} e^{jkr'_n \cos\psi_n} \vec{e}(\theta,\varphi) \qquad (2)$$

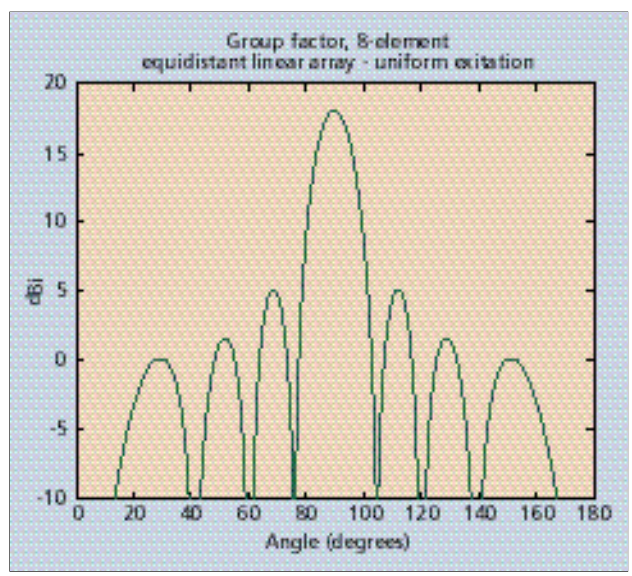
where

$$r'_n \cos\psi_n = z'_n \cos\theta = nd\cos\theta \qquad (3)$$

is the difference in distance for element n compared to element 0 toward the observation point in the direction θ due to the spatial separation in the array. The element spacing is d. (r'_n is the distance between the coordinate systems origin and element n, ψ_n is the corresponding angle, and z'_n, the distance along the array axis.) In the case of an array with equal elements, the far-field expression becomes

$$\vec{E}(r,\theta,\varphi) = \frac{e^{-jkr}}{r} \vec{e}(\theta,\varphi) \sum_{n=0}^{N-1} I_n e^{jknd\cos\theta}. \qquad (4)$$

The sum expression in Eq. 4 is the array factor which is independent of both the element type and the distance from the antenna. It is only dependent on the *array geometry* and the *element excitation*. Thus, the total far field is given by the product of the element factor and the array factor. The array



■ **FIGURE 10.** *The resulting array factor with uniform exicitation (α = 0).*

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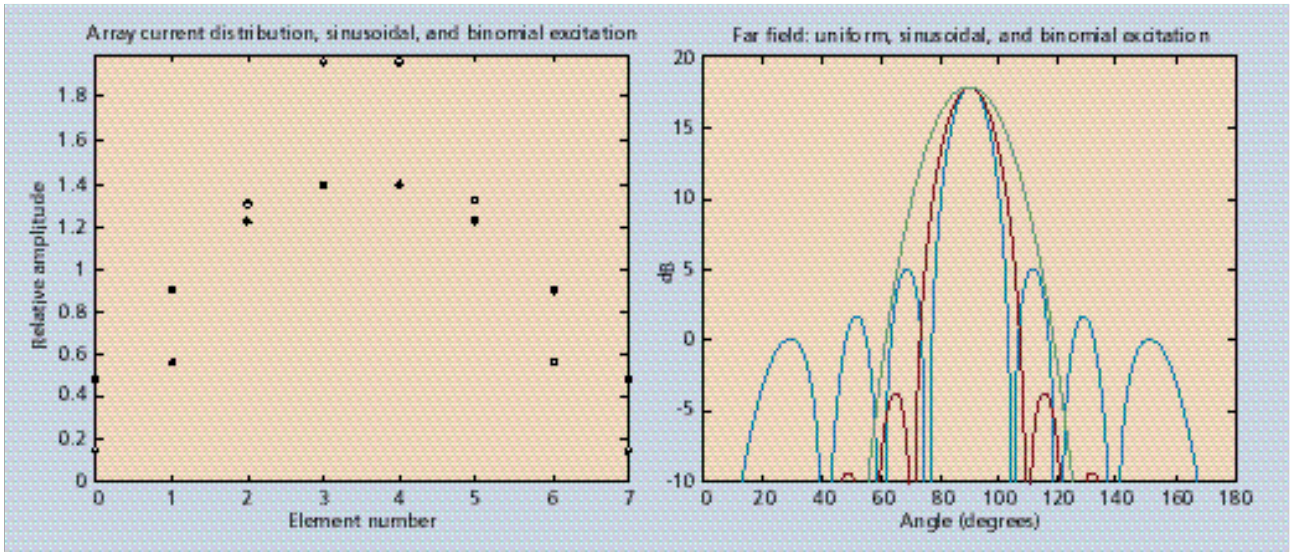


■ **FIGURE 11.** *Examples of non-uniform excitation and resulting far-field.*

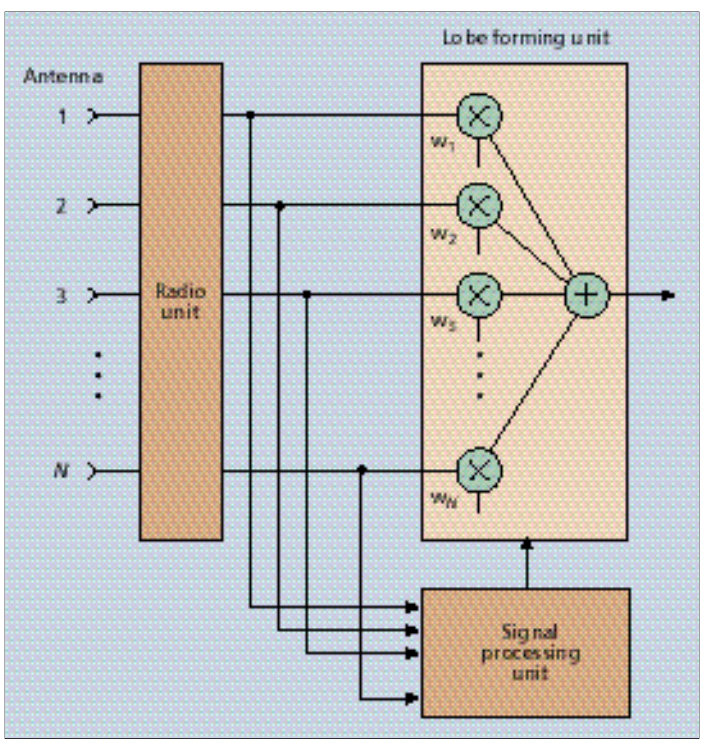
factor can be understood as the radiation pattern from an array antenna consisting of isotropic elements.

As the radiation pattern is uniquely given by the excitation parameters, a careful choice can give us the required effect. Consider, for example, that it is desired to steer the main lobe of the antenna in a certain direction, ϕ. Thus, we want the far-field signals from all the elements of the array to be added *in phase* in the wanted direction. Figure 9 shows what this means. If element number 0 is given the reference phase angle *0*, then the phase angle of element number 1 must be shifted (in this case negatively) with a value of $kd\cos\phi$, where $k = 2\pi/\lambda$ is the wave constant. We can call this angle α. Thus element number 2 must be shifted 2α, element 3 must be shifted 3α, and so on. In order to obtain maximum gain in the direction of ϕ, the amplitudes of all the elements must be equal. This example is called *uniform excitation* ($|I_0| = |I_1| = \ldots = |I_n| = \ldots = |I_{N-1}|$). Figure 10 shows the resulting array factor in this case.

A drawback of the linear array is the front-back ambiguity. A mirror of the antenna pattern will appear around the antenna axis, i.e., in the direction $-\phi$ ($\cos\phi = \cos(-\phi)$). Most often we want only to have one main lobe, and this is usually obtained by using directive elements. It is also worth noting that for skew angles, the gain decreases and the main lobe width increases, because the element separation appears smaller in the maximum direction of the main lobe (apparent distance: $d\sin\phi$). In practice, the linear array is only useful in a sector of at most 120°.

Using uniform excitation gives the highest gain but also the highest sidelobe level (SLL) of –3.2 dB. From the expression for the array factor one sees that the far-field is given as the Fourier-transform of the current distribution along the array. Thus, main lobe width and width of the current distribution are inverse. Using a non-uniform excitation with an amplitude roll-off toward the end of the array results in both a wider main lobe and a lower SLL. Figure 11 shows some examples.

Practical Considerations — Above we have anticipated that the element patterns are all identical and "perfect." In implementing an array antenna, this is not the case. The different elements of the antenna will have slightly different patterns due to production tolerances and so on. Additionally, when mounting several elements close together (typically less than $\lambda/2$) they influence each other. This mutual coupling gives changes both to the element patterns and the impedance match. This means that the array performance will be somewhat degraded.



■ **FIGURE 12.** *Reception part of a smart antenna.*

RECEIVER

Figure 12 shows schematically the elements of the reception part of a smart antenna. The antenna array contains *N* elements. The *N* signals are being combined into one signal, which is the input to the rest of the receiver (channel decoding, etc.).

As the figure shows, the smart antenna reception

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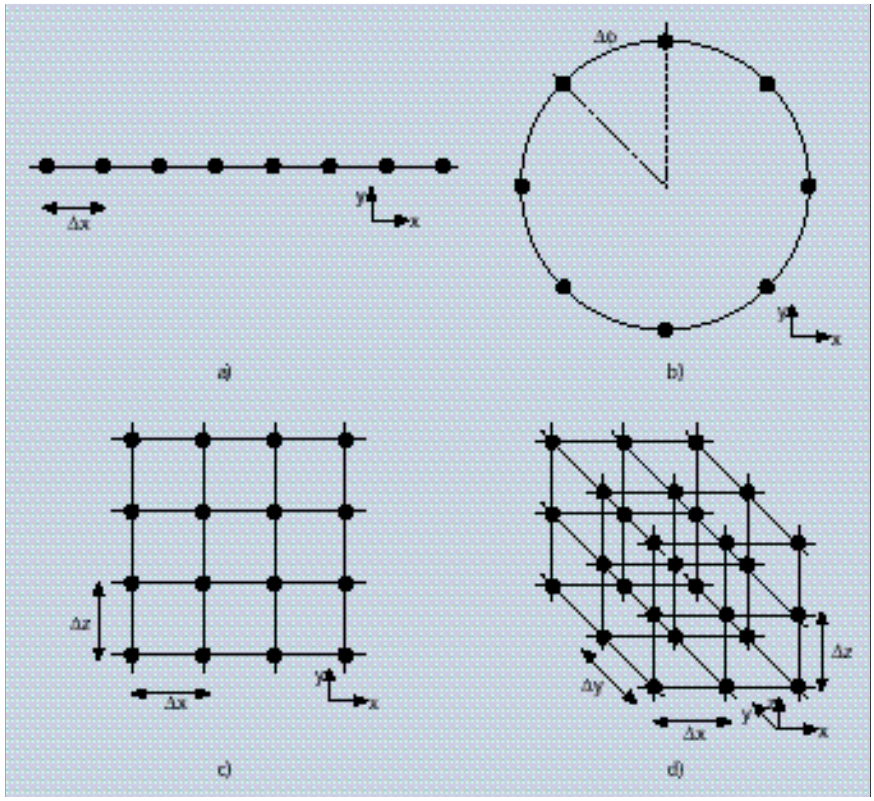
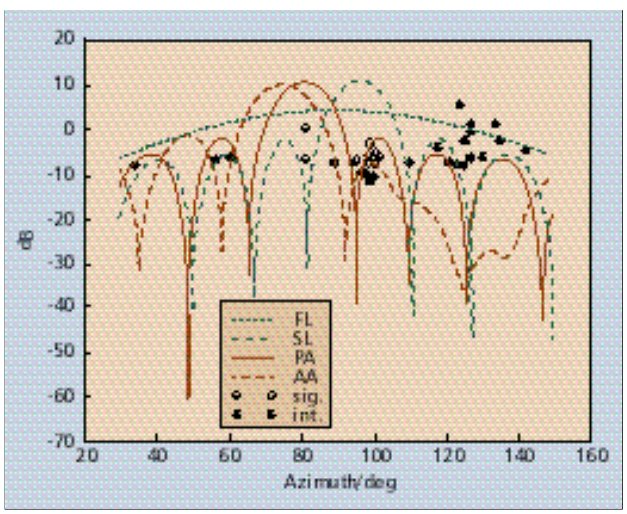
part consists of four units. In addition to the antenna itself it contains a radio unit, a lobe forming unit, and a signal processing unit [13].

The array will often have a relatively low number of elements in order to avoid unnecessarily high complexity in the signal processing. Figure 13 shows four examples of different array geometries. The first two structures are used for beamforming in the horizontal plane (azimuth) only. This will normally be sufficient for outdoor environments, at least in large cells. The first example (a) shows a one-dimensional linear array with uniform element spacing of Δx. This structure can perform beamforming in azimuth angle within an angular sector. This is the most common structure due to its low complexity. The second example (b) shows a birds eye view of a circular array with angular element spacing of $\Delta\Phi = 2\pi/N$. This structure can perform beamforming in all azimuth angles. The last two structures are used for performing two-dimensional beamforming, in both azimuth and elevation angles. This may be desirable for indoor or dense urban environments. Figure 13c is the front view of a two-dimensional linear array with horizontal element spacing of Δx and vertical element spacing of Δz. This structure can perform beamforming within a solid angle. Beamforming in the entire space, within all solid angles, requires some sort of cubic or spherical structure. Figure 13d shows an example of a cubic structure with element separations of Δx, Δy and Δz.



■ **FIGURE 13.** *Different array geometries for smart antennas: a) uniform linear array; b) circular array; c) 2 dimensional grid array; d) 3 dimensioanl grid array.*

The radio unit consists of down-conversion chains and (complex) analog-to-digital conversion (A/D). There must be N down-conversion chains, one for each of the array elements.



■ **FIGURE 14.** *Resulting antenna patterns for SL, PA, and AA for measured signal and interference channels. The figure also shows a so-called "fixed lobe" (FL) conventional antenna pattern for comparison.*

The signal processing unit will, based on the received signal, calculate the complex weights $w_1 - w_N$ with which the received signal from each of the array elements is multiplied. These weights will decide the antenna pattern in the uplink direction as described in the previous section. The weights can be optimized from two main types of criteria: maximization of received signal from the desired user (e.g., switched lobe or phased array) or maximization of the SIR by suppressing the signal from interference sources (adaptive array). In theory, with M antenna elements one can "null out" $M-1$ interference sources, but due to multipath propagation this number will normally be lower.

The method for calculating the weights will differ depending on the type of optimization criterion. When *switched lobe* (SL) is used the receiver will test all the pre-defined weight vectors (corresponding to the lobe set) and choose the one giving the strongest received signal level. If the *phased array* approach (PA) is used, which consists of directing a maximum gain beam toward the strongest signal component, the *direction-of-arrival* (DoA) is first estimated and then the weights are calculated as described in the previous section with uniform amplitude and phase in accordance with the desired steering angle. A number of well documented methods exist for estimating the DoA, for instance, MUSIC, ESPRIT, or SAGE [4, 14].

If maximization of SIR is to be done (AA), the optimum weight vector (of dimension N) $\mathbf{W}_{opt}$ is given by the dominant generalized eigenvector of the matrix pair $[\mathbf{R_k}, \mathbf{Q_k}]$ where $\mathbf{R_k}$ is the $N \cdot N$ correlation matrix of the total received signal and $\mathbf{Q_k}$ is the $N \cdot N$ correlation matrix of the total interference. This is called *optimum combining* [15]. Figure 14 shows an example of the resulting antenna patterns for PA, SL, and AA in a case where both the signal and interference are measured in a real channel. Note how the AA directs nulls toward the

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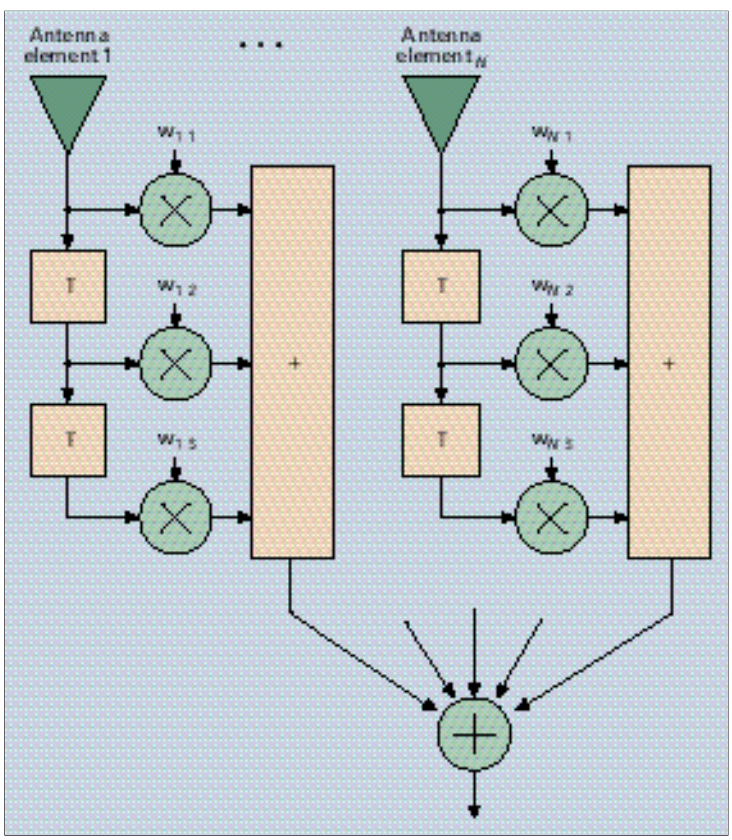
strongest interference sources. Other techniques are also possible, for example, well documented diversity algorithms such maximum-ratio in multiple dimensions [16].

For the base station to be able to estimate the radio channel, a reference or training sequence is normally necessary, i.e., a known bit sequence must be transmitted periodically. The methods that maximize the SIR do in principle require knowledge of the instantaneous channel response from both the desired user and all the interference sources, which means the training sequence must be unique for each user.

In the lobe forming unit the actual weighting of the received signal from each of the array elements is done. In the most advanced case this unit will be an integration of the channel equalizer/RAKE receiver and the smart antenna. In this case $N \cdot D$ weights will be required, where D is the number of symbol periods (depth) in the channel equalizer or number of fingers in the RAKE receiver. This is called a *spatio-temporal filter* [17, 18], because it removes the undesired signal components and keeps the desired ones both in time and space domains. Such a lobe forming unit is shown schematically in Fig. 15 [19]. In this example the number of weights is $N \cdot 3$, showing that the depth of the equalizer is 3. The time between the taps on each antenna element is T. In a RAKE receiver, the time delay between the taps is not uniform.

When the lobe forming is done digitally (after A/D) the lobe forming and signal processing units will normally be integrated in the same unit, namely the DSP. The separation in Fig. 12 is done to clarify the functionality. It is also possible to perform the lobe forming in hardware at *radio frequency* (RF) or *intermediate frequency* (IF) [20].

The three aforementioned methods (SL, PA, and AA) differ in complexity and computational burden. However, a detailed analysis of this is out of the scope of this article because many parameters and assumptions must be defined in order to quantify this difference. Generally, SL is less complex than PA, which in turn is less complex than AA. Conditions that influence this are, for example, the required accuracy and performance in terms of power or C/I-gain. It is also expected that the radio access method makes a difference, i.e., TDMA vs. CDMA.



■ **FIGURE 15.** *Illustration of the lobe forming unit in the case of a spatio-temporal filter with three time bins and N antenna elements.*

TRANSMITTER

The transmission part of the smart antenna will be schematically very similar to the reception part. An illustration is shown in Fig. 16. The signal is split into N branches, which are weighted by the complex weights $z_1 - z_N$ in the lobe forming unit. The weights, which decide the radiation pattern in the downlink direction, are calculated by the signal processing unit. The radio unit consists of D/A converters and the up converter chains. In practice, some components, such as the antennas themselves and the DSP, will of course be the same as on reception.

The principal difference between uplink and downlink is that since there are no smart antennas applied to the user terminals (mobile stations) no knowledge of the spatial channel response is available on downlink. In a time division duplex (TDD) system the mobile station and base station use the same carrier frequency only separated in time. In this case the weights calculated on uplink will be optimal on downlink if the channel does not change during the period from uplink to downlink transmission. However, this can not be assumed to be the case in general, at least not in systems where the users are expected to move at high speed. If frequency division duplex (FDD) is used, the uplink and downlink are separated in frequency. In this case the optimal weights will generally not be the same because of the channel response dependency on frequency.

Thus optimum beamforming (i.e., AA) on downlink is difficult, and the technique most frequently suggested is the geometrical approach of estimating the direction-of-arrival (DoA). The assumption is directional reciprocity, i.e., the direction from which the signal arrived on the uplink is the direction in which the signal should be transmitted to reach the user on downlink. This assumption has been strengthened by recent experimental results [21]. The strategy used by the base station is to estimate the DoA of the direction (or directions) from which the main part of the user signal is received. This direction is used on downlink by choosing the weights $z_1 - z_N$ so that the radiation pattern is a lobe (or lobes) directed toward the desired user. This is similar to PA. In addition, it is possible to position zeros in the direction toward other users so that the interference suffered by these users is minimized. Due to fading on the different signal paths, it has been suggested to choose the downlink direction based on averaging the uplink channel over a period of time [11]. This will, however, be sub-optimum compared to the uplink situation where knowledge about the instantaneous radio channel is available.

It should be stressed that in the discussion above it is assumed that the interferers observed by the base stations are mobile stations and that the interferers observed by the mobile stations are base stations. This means that when the base station on

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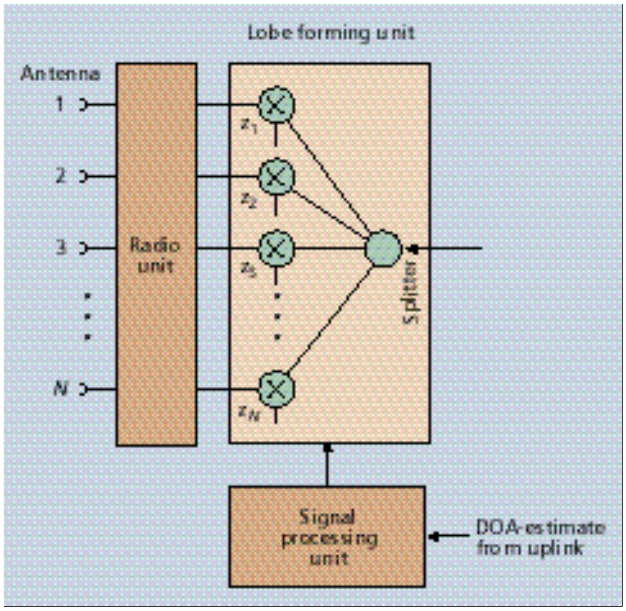


■ **FIGURE 16.** *Transmission part of a smart antenna.*

transmission positions zeros in the direction toward other mobile stations than the desired one, it will reduce the interference suffered by these mobiles. If, however, the interferers observed by mobiles are other mobiles, as may be the case, for instance, in UTRA TDD [22], there will be a much more fundamental limitation in the possibility for interference reduction at the mobile.

CRITICAL FACTORS AND CHALLENGES

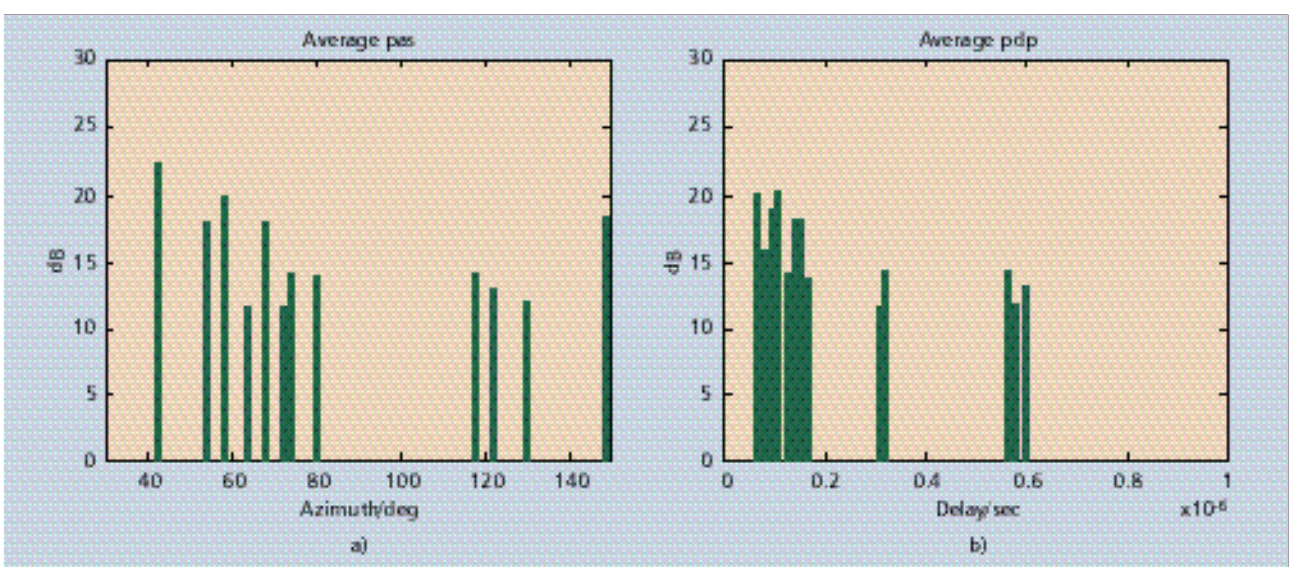
A number of technical challenges remain to be solved for smart antennas to reach their full potential. These are aspects on both modem implementation as well as the algorithms for beamforming.

As mentioned in the previous section, beamforming on the downlink is made more difficult by the lack of knowledge about the instantaneous channel response. The strategy of directing the lobe (or lobes) in the direction(s) of the user signal DoA is often used, but this makes the downlink performance very dependent on the radio channel and its rate of change. If the channel suffers from much angular spread, i.e., the signal arrives from many directions, directing a single lobe in the direction of maximum reception is far from optimum in terms of maximizing the power transfer to the user. Directing zeros toward other users to minimize the interference suffered by these is difficult for the same reason. When the channel is changing rapidly, which will be the case for fast moving mobiles and for very dense, complicated environments, the difficulties on downlink will be worsened. Figure 17 shows a recording of an angular radio channel from a suburban microcellular environment. The distance between each channel measurement was 2 cm corresponding to 10 ms between measurements at a speed of 2 m/s (walking speed).

Another critical factor is the linearity in reception and transmission chains. The transfer functions of all the up- and down-converter chains need to be perfectly known for the beamforming to be accurate. However, since there are active components involved the responses will change with time and temperature. This means that for the smart antenna to function properly frequent on-line calibration of the radio units needs to be performed [20].

The requirements on linearity in transceiver chains can possibly be relaxed by performing the A/D (and D/A) conversion as close to the array element as possible, that is sampling on RF or IF. This requires very fast and specialized hardware.

The complexity of the smart antenna is a great challenge because the most advanced smart antenna implementations involve simultaneously maximizing the useful signal and nulling out the interference sources. In addition, this beamforming needs to be done for each user communicating via the base station in question. Even with the powerful signal processing units available today it is a very challenging task to perform this in real time. Much work will need to be done on optimizing code and developing efficient algorithms for this to work properly. However, developments in computer technology over the past few years have undoubtedly made it possible to perform even more complex processing in real time. In the last three years processor speed has increased more than five times, and if this trend continues, there will be processors with 2-3 GHz clock frequency available when UMTS is to be introduced.



■ **FIGURE 17.** *Recording of an angular radio channel in a surburban microcellualr environment. The distance beetween measurmens is 2 cm.: a) Power azimuth spectrum (PAS); b) Power delay profile (PDP).*

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STATUS: TRIALS AND TESTBEDS

Smart antennas for mobile communications are not yet available commercially. But it is a well known fact that many manufacturers are working on solutions for both second-generation systems and third-generation systems. This section will give a short overview of some of the documented trials and testbeds, but should not be considered as a complete list.

ERICSSON/MANNESMANN TRIAL IN GIESSEN, GERMANY

Ericsson has performed a trial in cooperation with the German GSM1800 operator Mannesmann in the city of Giessen. Detailed results from the trial have not yet been published, but preliminary results are promising [9]. Three base stations were equipped with smart antennas. The base stations were placed at high positions, giving a large coverage. In the autumn of 1998 the Ericsson/Mannesmann trial became the first trial to demonstrate commercial traffic through base stations equipped with smart antennas.

Physically, the smart antennas were six-element stacked dipoles. Each element was dual polarized, with ±455 polarized elements. The combining on uplink was based on maximal ratio combining, while the downlink beam forming was based on switching between eight lobes.

TSUNAMI II TRIAL IN BRISTOL, UK

TSUNAMI II is a project in the European 4th framework program ACTS[3] dealing with the development of a smart antenna testbed and the implementation of a smart antenna base station. Some of the participants in this project have been the University of Aalborg (DK), Bosch Telekom (D), Orange (UK), and the University of Bristol (UK).

The project has finished and performed trials near Bristol (UK) in both urban and rural environments. Even though not all data analyses have been published yet, the trials confirm the capacity increase of a smart antenna. In the rural environment (macrocell) an extension of the range of up to 54 percent was reported, using the HSR principle. Interference reduction was better than 30 dB, which is much higher than expected. However, only one interferer was used, which in addition was placed more than 10 degrees away from the transmitter system [10, 23].

The antenna was eight-element dual polarized. Different strategies for combining were tested. It was shown that the adaptive array-based combining techniques, which included some sort of interference rejection, showed the best results [10].

OTHER

The U.S. company Arraycomm has developed smart antenna solutions for the GSM standard and for the Japanese Personal Handyphone System (PHS). In June 1997 a smart antenna wireless local loop (WLL) solution based on using PHS was commercially available [24]. Field trials have been performed in several countries, including the U.S., Brazil, and Malaysia. The Canadian company Nortel also claims to have been the first to implement a smart antenna for GSM [25].

Other manufacturers and research institutions are also developing testbeds and trials. Alcatel, in cooperation with the University of Vienna, is planning a testbed [11]. Much work has also been performed in the U.S., including at Telcordia [26] and Virginia Tech [27]. Other test results have been reported from Korea [28] and Japan [29].

[3] *Advanced Communication Technologies & Services.*

CONCLUSIONS

The main goal of this article has been to provide an overview of smart antenna technologies with respect to third-generation land mobile systems, i.e., IMT2000 and UMTS. It is obvious that smart antennas at the base stations will be an important technology to provide the necessary capacity and coverage. It also helps to realize new services, e.g., based on user location.

From a technology point of view, smart antennas can be seen as an extension of the "conventional" resource allocation schemes used in radio communications. In addition to dividing the space into cells, it will now also be possible to employ space division inside each cell. Different degrees of utilization of the spatial dimension are possible, and different steps have been described here.

Smart antenna technology is a broad concept and implementations range from simple techniques that involve switching between lobes to advanced algorithms maximizing the received signal-to-interference ratio. Implementation of smart antennas is done using array antennas. The techniques for beamforming with array antennas are well known, and must be employed in both duplex directions for the improvements to be substantial. However, with rapid channel variations it is not a trivial task to provide optimum beamforming, especially for the downlink direction.

The use of smart antennas is not purely a radio transmission issue. It also influences network services such as handover and connection setup. Introducing the spatial domain in the resource management system makes this more complex.

Several smart antenna testbeds and field trials have been set up and run by manufacturers and research institutions. The first tests allowing commercial traffic over a base station employing smart antennas were performed by Ericsson and Mannesmann Mobilfunk in Germany in the autumn of 1998.

REFERENCES

[1] J. C. Liberti and T. S. Rappaport, *Smart Antennas for Wireless Communications: IS-95 and Third-Generation CDMA Applications*, Prentice Hall, NJ, USA. 1999, ISBN 0-13-719287-8.

[2] J. H. Winters and M. J. Gans, "The Range Increase of Adaptive Versus Phased Arrays in Mobile Radio Systems," *28th Isilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, Oct. 31–Nov. 2, 1994, pp. 109–15.

[3] J. H. Winters *et al.*, "The Impact of Antenna Diversity on the Capacity of Wireless Communications Systems," *IEEE Trans. Commun.*, vol. 42, no. 2/3/4, Feb./Mar./Apr. 1994, pp. 1740–51.

[4] T. Bull *et al.*, Technology in Smart Antennas for Universal Advanced Mobile Infrastructure (TSUNAMI R2108) Overview, *RACE Mobile Telecommunications Summit 1995*, Cascais, Portugal, Nov. 22–24, 1995, pp. 88–97.

[5] P. E. Mogensen and P. Leth-Espensen, "Performance of Beam Steering in a 1/3 Reuse FH-GSM Network," TSUNAMI II Final Wksp., Aalborg, Denmark, Sept. 1998.

[6] P. H. Lehne, O. Rostbakken, and M. Pettersen, "Estimating Smart Antenna Performance from Directional Radio Channel Measurements," *Proc. 50th IEEE Vehic. Tech. Conf. – VTC '99 – Fall*, Amsterdam, the Netherlands, Sept. 19–22, 1999, pp. 57–61.

[7] G. V. Tsoulos, M. A. Beach, and S. C. Swales, DS-CDMA Capacity Enhancement with Adaptive Antennas," *Electronic Letters*, vol. 13, no. 16, Aug. 1995, pp. 1319–20.

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Petitioners' Exhibit 1010
Page 000011

[8] B. Ludden *et al.*, "Mobile Subscriber Location using Handset-Assisted Positioning Techniques," *3rd European Personal mobile Communications Conference – EPMCC '99*, Paris, France, Mar. 9–11, 1999, pp. 67–72.
[9] R. Bormann *et al.*, "Functional Tests of Adaptive Antenna Base Stations for GSM," *3rd European Personal mobile Communications Conference – EPMCC '99*, Paris, France, Mar. 9–11, 1999, pp. 323–327.
[10] D. Greenaway *et al.*, Final Report – TSUNAMI (II), CEC deliverable AC020/ERA/A52/DS/P/155/b1, Aug. 1998.
[11] A. Kuchar, M. Taferner, and E. Bonek, "A Run-Time Optimized Adaptive Antenna Array Processor for GSM," *3rd European Personal mobile Communications Conference – EPMCC '99*, Paris, France, Mar. 9–11, 1999, pp. 307–312.
[12] M. Pettersen *et al.*, "Characterization of the Directional Wideband Radio Channel in Urban and Suburban Areas," *Proc. 50th IEEE Vehic. Tech. Conf. – VTC '99 – Fall*, Amsterdam, the Netherlands, Sept. 19–22, 1999, pp. 1454–59.
[13] M. Barrett and R. Arnott, "Adaptive Antennas for Mobile Communications," *Electronics and Communications Engineering Journal*, Aug. 1994, pp. 203–14.
[14] K. Pedersen, B. Fleury, and P. Mogensen, " High Resolution of Electromagnetic Waves in Time-Varying Radio Channels," *Proc. 8th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'97)*, Helsinki, Finland, Sept. 1–4, 1997, Piscataway, NJ, IEEE, 1997, pp. 650–54.
[15] J. H. Winters, "Optimum Combining in Digital Mobile Radio with Cochannel Interference," *IEEE JSAC*, vol. 4, 1984, pp. 528–539.
[16] A. M. D. Turkmani *et al.*, "An Experimental Evaluation of the Performance of Two-Branch Space and Polarization Diversity Schemes at 1800 MHz," *IEEE Trans. Vehic. Tech.*, vol. 44, 1995, pp. 318–26.
[17] T. Öberg *et al.*, "Adaptiva Antenner för Mobil Kommunikation," *Nordisk Radioseminarium 1996*, Lund, Sverige, Aug. 27–28, 1996, (In Swedish), pp. 44–47.
[18] Y. Ogawa *et al.*, "Spatial-Domain Path-Diversity Using an Adaptive Array for Mobile Communications," *Proc. ICUPC '95-4th IEEE Int'l. Conf. Universal Pers. Commun.*, Tokyo, Japan, Nov. 6–10, 1995, pp. 600–04.
[19] H. Steyskal, "Aspects of Digital Beamforming and Adaptive Arrays," *Proc. COST259/260 Joint Workshop – Spatial Channel Models and Adaptive Antennas*, Vienna, Austria, Apr. 20–21, 1999.
[20] P. Mogensen *et al.*, "A Hardware Testbed for Evaluation of Adaptive Antennas in GSM/UMTS," *7th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. – PIMRC '96*, Taipei, Taiwan, Oct. 15–18, 1996, pp. 540–44.
[21] P. E. Mogensen *et al.*, "Measurements, Channel Statistics and Performance of Adaptive Base Station Antennas," *Proc. COST259/260 Joint Wksp. Spatial Channel Models and Adaptive Antennas,* Vienna, Austria, Apr. 20–21, 1999.
[22] 3GPP TS 25.201: Physical Layer – General Description, V2.1.1. (1999-07) ETSI 3rd Generation Partnership Project.
[23] M. Beach and C. Simmonds, "T2 Field Trial Deployment & Overview of Results," TSUNAMI II Final Wksp., Aalborg, Denmark, Sept. 1998.
[24] ArrayComm Homepage, [online], 24.6.99, URL: http://www.arraycom.com/
[25] Nortel Homepage, [online], 28.6.99, URL: http://www.nortelcom.com/
[26] J. C. Liberti, "Spatial Channel Measurements and Modelling for Smart Antenna Systems," *Proc. COST259/260 Joint workshop – Spatial Channel Models and Adaptive Antennas*, Vienna, Austria, Apr. 20–21, 1999.
[27] T. Biedka *et al.*, "Implementation of a Prototype Smart Antenna for Low Tier PCS," *Proc. 49th IEEE Vehic. Tech. Conf. – VTC'99 – Spring*, Houston, TX, USA, May 16–20, 1999.
[28] M. G. Kyeong *et al.*, "Outdoor Communications Using Adaptive Arrays in CDMA Mobile Systems," *Proc. 49th IEEE Vehic. Tech. Conf. – VTC'99 – Spring*, Houston, TX, USA, May 16–20, 1999.
[29] S. Tanaka *et al.*, "Experiment on Coherent Adaptive Antenna Array Diversity for Wideband CDMA Mobile Radio," *Proc. 49th IEEE Vehic. Tech. Conf. – VTC'99 – Spring*, Houston, TX, USA, May 16–20, 1999.

BIOGRAPHIES

PER H. LEHNE (per-hjalmar.lehne@telenor.com) graduated from the Norwegian Institute of Technology (NTH) in 1988 from the Department of Telecommunications, Radio Technology. Since then, he has been employed at Telenor Research and Development as a research scientist working on several aspects of mobile and personal communications. From 1988 to 1991 he was involved in the standardization of the pan-European radio paging system ERMES within ETSI. Later, the emphasis was on radio propagation aspects for cellular mobile communications. He was involved in the RACE MBS project, on millimeter-wave propagation. He has been a member of COST 259 — "Wireless Flexible Personalized Communications" since 1997. Currently, the main focus of his work is on smart antennas and access network technology for UMTS.

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