Applications of Antenna Arrays to Mobile Communications, Part I: Performance Improvement, Feasibility, and System Considerations

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The demand for wireless mobile communications services is growing at an explosive rate, with the anticipation that communication to a mobile device anywhere on the globe at all times will be available in the near future.

An array of antennas mounted on vehicles, ships, aircraft, satellites, and base stations is expected to play an important role in fulfilling the increased demand of channel requirement for these services, as well as for the realization of the dream that a portable communications device the size of a wristwatch be available at an affordable cost for such services.

This paper is the first of a two-part study. It provides a comprehensive treatment, at a level appropriate to nonspecialists, of the use of an antenna array to enhance the efficiency of mobile communications systems. It presents an overview of mobile communications as well as details of how an array may be used in various mobile communications systems, including land-mobile, indoor-radio, and satellite-based systems. It discusses advantages of an array of antennas in a mobile communications system, highlights improvements that are possible by using multiple antennas compared to a single antenna in a system, and provides details on the feasibility of antenna arrays for mobile communications applications.

***Keywords*—** *Antenna arrays, blind signal estimation, channel assignment, diversity combining, handoff, mobile communications, multiple access, satellite communications, wireless communications.*

NOMENCLATURE

AMPS	Advanced mobile phone services.
BER	Bit error rate.
BPSK	Binary phase shift keying.
CDMA	Code division multiple access.
CMA	Constant modulus algorithm.
C/N	Carrier-to-noise ratio.
CT2	Second generation cordless telephone.
DBS	Direct broadcasting system.
DCS	Digital cellular system.
DECT	Digital European cordless telecommunication.
DFT	Discrete Fourier transform.
DOA	Direction of arrival.
EIRP	Effective isotropically radiated power.
ESA	European Space Agency.
ESTEC	European Space Research and Technology Center.
ETACS	European total access communication system.
FDD	Frequency division duplex.
FDMA	Frequency division multiple access.
FPLMTS	Future Public Land-Mobile Telecommunications Systems.
GEOS	Geostationary satellite.
GMSK	Gaussian minimum shift keying.
GPS	Global positioning system.
GSM	Global system for mobile communications.
G/T	Gain-to-noise temperature ratio.
HEOS	Highly elliptical orbit satellite.
IF	Intermediate frequency.
ISI	Intersymbol interference.
LEOS	Low earth orbit satellite.
LMS	Least mean square.
LS	Least square.
MEOS	Medium earth orbit satellite.
MMIC	Monolithic microwave integrated circuit.
NMT	Nordic Mobile Telephone.
PDC	Personal digital cellular.
PHS	Pocket handphone service.
PN	Pseudonoise.
PSK	Phase shift keying.
QPSK	Quadrature phase shift keying.
RF	Radio frequency.
RLS	Recursive least square.
RMS	Root mean square.
SCARP	Smart Communication Antenna Research Program.

Manuscript received August 15, 1996; revised April 10, 1997.

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Publisher Item Identifier S 0018-9219(97)05307-3.

SDMA	Space division multiple access.
SER	Symbol error rate.
SIR	Signal-to-interference ratio.
SMI	Sample matrix inversion.
SNR	Signal-to-noise ratio.
TACS	Total access communications system.
TDD	Time division duplex.
TDMA	Time division multiple access.
UHF	Ultrahigh frequency.
UMTS	Universal Mobile Telecommunications Systems.
VHF	Very high frequency.

I. INTRODUCTION

The field of wireless mobile communications is growing at an explosive rate, covering many technical areas. Its sphere of influence is beyond imagination. The worldwide activities in this growth industry are perhaps an indication of its importance. The demand for wireless communications is anticipated to expand steadily, and projections indicate that annual activities will exceed $100 billion by the year 2000 [1]–[4].

An application of antenna arrays has been suggested in recent years for mobile communications systems to overcome the problem of limited channel bandwidth, thereby satisfying an ever growing demand for a large number of mobiles on communications channels. It has been shown by many studies that when an array is appropriately used in a mobile communications system, it helps in improving the system performance by increasing channel capacity and spectrum efficiency, extending range coverage, tailoring beam shape, steering multiple beams to track many mobiles, and compensating aperture distortion electronically. It also reduces multipath fading, cochannel interferences, system complexity and cost, BER, and outage probability. It has been argued that adaptive antennas and the algorithms to control them are vital to a high-capacity communications system development [4].

An array of antennas may be used in a variety of ways to improve the performance of a communications system. Perhaps most important is its capability to cancel cochannel interferences. An array works on the premise that the desired signal and unwanted cochannel interferences arrive from different directions. The beam pattern of the array is adjusted to suit the requirements by combining signals from different antennas with appropriate weighting.

The scheme needs to differentiate the desired signal from the cochannel interferences and normally requires either the knowledge of a reference signal, a training signal, or the direction of the desired signal source to achieve its desired objectives. There exists a range of schemes to estimate the direction of sources with conflicting demands of accuracy and processing power. Similarly, there are many methods and algorithms to update the array weights, each with its speed of convergence and required processing time. Algorithms also exist that exploit properties of signals to eliminate the need of training signals in some circumstances.

There has been a wide range of research covering development of antennas suitable for mobile communications systems, and many experimental results have been reported to show the system requirements and feasibility. It is anticipated that a future mobile communications system would consist of a hand-held terminal the size of a wristwatch capable of steering beams toward a satellite. The system would also consist of many radiating elements fabricated by microstrip technology, each with its own phase-shifting network, power amplifier, and so on along with other required processors manufactured by the microwave monolithic integrated circuits technology. And all this is expected to be available at an affordable price.

In recent years, the material applicable to array processing for mobile communications has been reported in many IEEE publications, as well as in many non-IEEE publications covering many specialized areas. The aim of this two-part paper is to provide a comprehensive overview of the subject at a level appropriate to readers of this PROCEEDINGS by bringing all the relevant material together, along with a large reference list to probe further.

The two papers in this study give a brief overview of the mobile communications system consisting of satellites, vehicles, hand-held portables, base stations on the ground, and their associated terminology. The advantages of arrays at the base as well as at the mobile along with the system requirements are discussed. It is shown how the use of an array could improve the system performance. A detailed treatment of different algorithms to estimate array weights and the directions of sources is provided. Performance evaluation of different schemes to show the improvement in symbol and BER are considered. Relevant details of antenna array design and fabrication are provided along with the results of feasibility studies reported by many authors. In short, these papers provide a complete picture of the field at a level where nonexperts may be able to appreciate it.

These papers have a general coverage. In the process of simplifying concepts, the rigor might have been sacrificed at times. The large and very comprehensive reference lists are by no means complete, and no effort has been made to include all papers on the subject. However, all possible efforts have been made to give credit where due; omissions where they exist are unintentional and are due to the author's being unaware of a source's existence.

In Section II, a brief overview of mobile communications is presented by discussing its working principle, various multiple-access schemes, propagation characteristics, concepts of channel assignment, channel reuse, and handover. This section also contains discussions on satellite mobile communications as well as on progress and trends in the field. Antenna array terminology required to understand the paper is presented in Section III, whereas Section IV contains detailed treatment of how an array may be used in various mobile communications systems, including land-mobile, indoor-radio, and satellite-based systems. Discussion on transmitting arrays and the use of arrays for blind estimation of cochannel signals is also found in this section.

Section V discusses the advantages of an array of antennas in a mobile communications system and improvements that are possible by using multiple rather than single antennas in a system. It provides references to studies where such improvements are realized and also discusses the existence of angular spreading in the mobile communications environment and its impact on system performance. Issues related to complexities, cost, and network implications of the use of an array in a system are also highlighted in this section. Section VI contains details on the design of antenna arrays suitable for mobile communications and on some of the experiments that have been carried out to see the feasibility of antenna arrays for mobile communications applications.

A detailed treatment of various beam-forming schemes, adaptive algorithms to adjust the required weighting on antennas, DOA estimation methods, and sensitivity of an array system to parameter perturbations will be provided in the second part of this paper.

II. Overview of Mobile Communications

In this section, a brief overview of mobile communications is presented to understand its principle of working, introduce the terminology required to understand the rest of the paper, and provide references to issues under current investigation. A very good treatment of the subject discussing technologies utilized in existing and currently planned services, the performance of these services, and trends in wireless system development can be found in [5].

Throughout this paper, the generic term “mobile” or “mobile phone” is used to denote a communications device on the move, including a hand-held portable and a mobile vehicle on land (also known as land mobile), a ship, or an aircraft. To begin, let us see how a typical mobile communications system involving land mobiles and base stations works [6]–[9].

A. Base Station

The area served by a mobile phone system is divided in small areas known as *cells*. Each cell contains a base station, which is connected to a switching center, communicates to mobile phones on the site by radio links, and connects these mobiles to the public switching telephone network. A typical setup is shown in Fig. 1. Two types of radio channels are used: control channels to carry control signals and traffic channels to carry messages.

In mobile communications literature, the transmission from a base station to a mobile is given many names, such as downstream, forward link, and downlink. The corresponding terms for the transmission from a mobile to a base are upstream, reverse link, and uplink.

1) Call Initiation from a Mobile: When a mobile phone is switched on, it scans the control channels and is tuned to the channel with the strongest signal, usually arriving from the nearest base station. The phone user identifies itself and establishes authorization to use the network. The base station then sends this message to the switching center connected to the telephone network, which controls many base stations. It assigns a radio traffic channel to the phone under consideration, as the control channels are used by all phones in that area and cannot be used for data traffic. Once the traffic channel is assigned, this information is relayed to the phone via the base and the phone tunes itself to this channel. The switching center then completes the rest of the call.

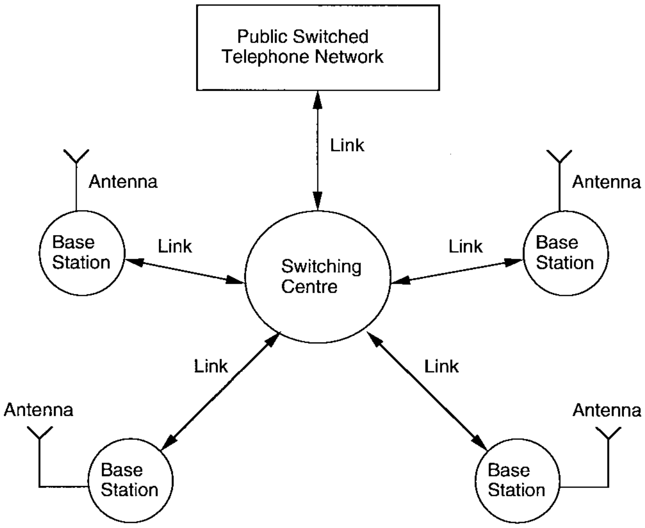


Fig. 1. A typical setup of a base mobile system.

2) Initiation of a Call to a Mobile: When someone calls a mobile phone, the switching center sends a paging message through several base stations. A phone tuned to a control channel detects its number and responds by sending a response signal to the nearby base, which then informs the switching center about the location of the phone. The switching center assigns a channel, and the call is completed.

3) Registration: A mobile is normally located by transmitting a paging message from various base stations. When a large number of base stations are involved in the paging process, it becomes impractical and costly. This problem is avoided by a registration procedure where a roaming phone registers with a base closer to itself. This information may be stored with the switching center of the area as well as the home switching center of the phone. The home base of the phone is the one where it is permanently registered. Once a call is received for this phone, its home switching center contacts the switching center where the phone is currently roaming. Paging in the vicinity of the previous known location helps to locate the phone. Once it responds, the call may be connected as discussed previously.

B. Multiple-Access Schemes

The range of frequencies available for mobile communications is utilized in a number of ways, referred to as multiple-access schemes. Three basic schemes are FDMA, TDMA, and CDMA.

The standard analog FDMA scheme allocates different carrier frequencies to different users. A TDMA scheme, useful for digital signals, allocates different time slots to different subscribers using the same carrier frequency and thus interleaves signals from various users in an organized manner. Traffic in the base-to-mobile direction is separated from that in the mobile-to-base direction by either using different carrier frequencies or alternating in time. The two schemes are referred to as FDD and TDD. The use of separate frequencies for transmission in both directions does not require as precise a synchronization of data flowing in the two directions as does the alternative transmission method. Details on various aspects of the TDMA scheme, including the capacity of a system using this scheme, may be found in [10] and [11].

A CDMA scheme, on the other hand, is a spread-spectrum method that uses a separate code for each user. These codes are large PN sequences that spread the spectrum over a larger bandwidth, simultaneously reducing the spectral density of the signal. Various CDMA signals occupy the same bandwidth and appear as random noise to each other. A general discussion on various characteristics of the CDMA scheme, its design considerations, and related issues is provided in [8] and [12]–[15].

In theory, the capacity provided by the three multiple-access schemes is the same and is not altered by dividing the spectrum into frequencies, time slots, or codes, as explained in the following example [12]. Assume that there are six carrier frequencies available for transmission covering the allocated spectrum. In a system using the FDMA scheme, six frequencies are assigned to six users, and six simultaneous calls may be made. TDMA generally requires a larger bandwidth than FDMA, so a system using this scheme creates two TDMA channels and divides each into three time slots, serving six users. A CDMA channel requires a larger bandwidth than the other two and serves six calls by using six codes, as illustrated in Fig. 2.

In practice, however, the performance of each system differs, leading to different system capacities [11], [13]. Furthermore, each scheme has its advantages and disadvantages, such as complexities of equipment design, robustness to system parameter variation, and so on. For example, TDMA processes signals from all users simultaneously, requiring complex time synchronization of the different user data. This is not the case for CDMA, which processes individual data independently at the receiver. It does, however, require code synchronization. It is argued in [15] that although there does not appear to be a single scheme that is the best for all situations, the CDMA scheme possesses characteristics that give it distinct advantages over other schemes. An interesting discussion on these and related issues encompassing the recent research on multiple access, along with a large reference list, is provided in [16]. Multiple access in digital networks is also discussed in [17].

The SDMA scheme, also referred to as space diversity, uses an array of antennas to provide control of space by providing virtual channels in an angle domain [18], [19]. Using this scheme, simultaneous calls in different cells can be established at the same carrier frequency.

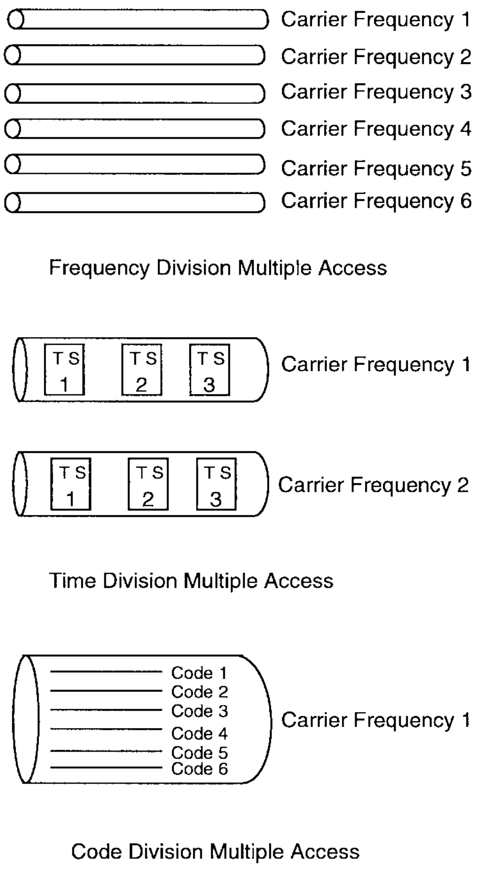


Fig. 2. Channel usage by FDMA, TDMA, and CDMA [12].

The SDMA scheme is based upon the fact that a signal arriving from a distant source reaches different antennas in an array at different times due to their spatial distribution, and this delay is utilized to differentiate one or more users in one area from those in another area. The scheme allows an effective transmission to take place in one cell without disturbing the transmission in another cell. Without the use of an array, this is accomplished by having a separate base station for each cell and keeping cell size fixed, whereas using space diversity, the shape of a cell may be changed dynamically to reflect the user movement. Thus, an array of antennas creates an extra dimension in this arrangement by providing dynamic control in space [20].

C. Propagation Characteristics

An understanding of propagation conditions and channel characteristics is important to the efficient use of a transmission medium. Lately, attention has been given to understanding the propagation conditions where a mobile is to operate, and many experiments have been conducted to model the channel characteristics. Many of the results can be found in recent review papers [5], [21], [22] and the references therein. Some other references for channel measurements and modeling are [23]–[27].

1) Fading Channels: The signal arriving at a receiver is a combination of many components arriving from various directions as a result of multipath propagation. It depends upon terrain conditions and local buildings and structures, causing the received signal power to fluctuate randomly as a function of distance. Fluctuations on the order of 20 dB are common within the distance of one wavelength. This phenomenon is called fading. One may think of this signal as a product of two variables.

One of the components, referred to as the short-term fading component, changes faster than the other one and has a Rayleigh distribution. The second component is a long-term or slow varying quantity and has log-normal distribution [8], [28]. In other words, the local mean varies slowly with log-normal distribution, and the fast variation around the local mean has Rayleigh distribution. The fluctuation in the local mean is caused by shadowing and thus is referred to as shadow fading, whereas the fast change in signal amplitude is caused by the phase differences in signal components and is referred to as multipath fading [5]. A stationary subscriber may also observe fading when the differential phases of various multipath components change fast with frequency [21]. Such fading is referred to as frequency-selective fading. When the fading is independent of frequency, it is referred to as flat fading.

A movement in a mobile receiver causes it to encounter fluctuations in the received power level. The rate at which this happens is referred to in mobile communications literature as the fading rate [29], and it depends upon the frequency of transmission and the speed of the mobile. For example, a mobile on foot operating at 900 MHz would cause a fading rate of about 4.5 Hz, whereas a typical vehicle mobile would produce a fading rate of about 70 Hz.

2) Doppler Spread: The movement in a mobile also causes the received frequency to differ from the transmitted frequency due to the Doppler shift resulting from its relative motion. As the received signals arrive along many paths, the relative velocity of the mobile with respect to various components of the signal differs, causing the different components to yield different Doppler shifts. This can be viewed as spreading of the transmitted frequency and is referred to as the Doppler spread. The width of the Doppler spread in frequency domain is closely related to the rate of fluctuations in the observed signal [5].

3) Delay Spread: Due to the multipath nature of propagation in the area where a mobile is being used, it receives multiple and delayed copies of the same transmission, resulting in spreading of the signal in time. The delay spread may range from a fraction of a microsecond in urban areas to something on the order of 100 μs in a hilly area, which restricts the maximum signal bandwidth between 40 and 250 kHz. This bandwidth is known as coherence bandwidth. The coherence bandwidth is defined as the inverse of the delay spread [30]. For digital modulated schemes, the signal bandwidth is the inverse of the symbol duration.

For a signal bandwidth above the coherence bandwidth, the different frequency components of the signal arrive at a receiver at different times, and the channel becomes frequency selective. Frequency-selective channels are also known as dispersive channels, whereas the nondispersive channels are referred to as flat fading channels. A channel becomes frequency selective when the delay spread is larger than the symbol duration and causes intersymbol interference (ISI) in digital communications. The ISI may be reduced to a certain degree by using equalizers in TDMA and FDMA systems.

4) Link Budget and Path Loss: Link budget is a name given to the process of estimating the power at the receiver site for a microwave link, taking into account the attenuation caused by the distance between the transmitter and the receiver. This reduction is referred to as the path loss. In free space, the path loss is proportional to the second power of the distance, that is, the distance power gradient is two. In other words, by doubling the distance between the transmitter and the receiver, the received power is reduced to one-fourth of the original amount.

For a mobile communications environment utilizing fading channels, the distance power gradient varies and depends upon the propagation conditions. Experimental results show that it ranges from a value lower than two in indoor areas with large corridors to as high as six in metal buildings. For urban areas, the path loss between the base and the cell site is often taken to vary as the fourth power of the distance between the two [5].

Normal calculation of the link budget is made by calculating the C/N ratio where noise consists of background and thermal noise and the system utility is limited by the amount of this noise. However, in mobile communications systems, the interference due to other mobile units is a dominant noise compared to the background and man-made noise. For this reason, these systems are limited by the amount of total interference present rather than the background noise, as in the other cases. In other words, the SIR is the limiting factor for a mobile communications system rather than the SNR, as is the case for other communications systems. The calculation of link budget for such interference-limited systems involves calculating the carrier level above the interference level contributed by all cochannel sources [27].

D. Channel Assignment

The generic term "channel" is normally used to denote a frequency in the FDMA system, a time slot in the TDMA system, and a code in the CDMA system, or a combination of these in a mixed system. Two channels are different if they use different combinations of these at the same place. For example, two channels in an FDMA system use two different frequencies.

Channel assignment is a complex process where a finite number of channels are assigned to various base stations and mobile phones. In a system with fixed channel assignment, channels are assigned to different cells during the planning stage, and the assignment rarely changes to reflect the traffic needs. A channel is assigned to a mobile at the initiation of the call and the mobile communicates with the base using this channel until it remains in the cell.

Dynamic channel assignment, on the other hand, is an efficient way of channel usage in a multiple-user environment. With this arrangement, a channel with the minimum interference is found before assignment. The interference level of all the channels used and unused is monitored periodically, and the channel assignment during the call may be changed from the one with high interference to the one with low interference, the so-called quiet channel [29], [31]. As the interference environment is constantly changing due to the movement of mobiles, this ensures that the performance of the system is not affected adversely as long as there are quieter channels available.

Monitoring traffic and searching for quieter channels is a complex process with heavy computational demand. A study [32] of a dynamic channel-assignment scheme based upon neural networks shows the possibility of reducing this complexity without degrading the handoff performance compared to conventional methods and argues about the suitability of neural networks for dynamic channel assignment. Though it is not necessary that the neural networks always provide the optimal solution to the assignment problem, some improvement in channel utilization is achievable, as reported in [33]. Improvements in performance of mobile communications systems using neural networks for channel assignment have also been discussed in [34]–[38].

There exist a number of other channel assignments between the two extremes of fixed and dynamic, including flexible channel assignment and channel borrowing schemes [39]. Both schemes are a variation of the fixed channel assignment. In the former, the assignment is periodically altered to reflect traffic needs, whereas in the latter, unused channels in a cell are borrowed by a congested cell. The total transmitted power of the base station sometimes is also considered as a criterion for channel allocation [40]. More information on channel assignment and its effect on the performance of the system may be found in [39], [41], and [42] and the references therein.

E. Channel Reuse

The total number of channels in a system is limited, which in turn limits the capacity of the system to sustain simultaneous calls. The capacity may only be increased by using each traffic channel to carry many calls simultaneously. One way of accomplishing this is to use the same channel again and again. To do so, mobile phones using the same channel have to be far away from each other in order to avoid disturbance. A minimum distance between two cells using identical channels is required, known as the channel reuse distance. The capacity of the system depends on this distance.

The concept of channel reuse may be understood from Fig. 3, which shows how three frequencies—A, B, and C—are assigned to various hexagonal-shaped cells. Assignment of frequencies to different cells is accomplished by starting with a cell and assigning it a frequency, for example, A. Then the three branches, which are separated by 120°, are successively assigned frequencies B, C, A, B, C, and so on. Next, a cell with frequency B is taken as a center cell, and frequencies C, A, B, C, A, B, . . . are assigned to the three branches, which are separated by 120°. Similarly, when a cell with frequency C is taken as a center cell, frequencies A, B, C, A, B, C, . . . are assigned to the three branches. The procedure may be repeated if desired to complete the assignment to all cells. For this case, the minimum distance between any two cells using the same frequency is equal to one arm of the hexagon.

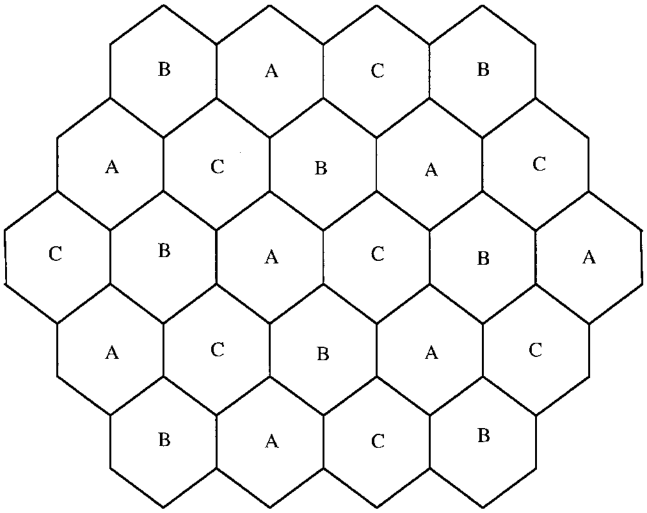


Fig. 3. Frequency assignment for cellular mobile communications.

The cells that use the same set of channels are known as cochannel cells. The cells with frequency A in the figure are cochannel cells. The interference caused by the radiation from these cells is referred to as cochannel interference. For the system to function properly, this interference needs to be minimized by limiting the power transmitted by the mobiles as well as by the base stations in cochannel cells. The amount of transmitted power depends upon the channel reuse distance. For more discussion on this and related topics, see, for example, [11]–[14].

F. Handoff

A mobile phone's movement may cause it to be far away from the original base station through which the phone is connected to the switching center. This distance is detected by the switching center monitoring the signal strength arriving from the phone at the base station. Once the signal becomes too weak, the switching center reassigns a new traffic channel via a base station closer to the phone and asks the phone to tune to this new channel. This is known as handoff or handover, a process that is generally transparent to the mobile user. In a typical call, there may be several handoffs.

The handoff needs to be performed based upon certain established policy, which may involve the measured power level and the quality of reception. The mean signal strength decreases as a mobile moves away from a base, whereas it increases when a mobile approaches a base. A handoff policy based upon this fact may use the relative strength of signals received from various base stations. The measured as well as predicted signal strength may be involved in the decision making. A policy based upon the quality of reception may involve call blocking probability as well as handoff blocking probability [43]. A policy based upon a minimum number of handoffs may lead to poor communication quality. A good handoff scheme should aim to minimize the effects of handoff on calls, including the noticeable disturbances [39] that may be severe in some services, such as live video transmission.

In a system where different cells use different frequencies, the handoff requires switching frequencies and is referred to as a hard handoff. In systems where all cells use the same frequency but different codes, as in the case of CDMA, only codes need to be switched, and the process is known as a soft handoff. Soft handoff can be used between sectors of the same base station. It is also being proposed for satellite-based mobile communications systems [15]. Some discussion on traffic generated by handoffs may be found in [44].

G. Cell Splitting

Each cell has a limited channel capacity and thus can only sustain so many mobiles at a given time. Once the demand in that cell exceeds this limit, the cell is subdivided into smaller cells. Each new cell has its own base station and frequency allocation. The power of the base station transmitters is adjusted to reflect the new boundaries. The power transmitted by new base stations is less than that transmitted by the old one.

A consequence of cell splitting is that frequency has to be assigned again, which affects neighboring cells. It also increases the handoff rate, as the cells are now smaller and a mobile is likely to cross cell boundaries more often compared to when the cells are big. Due to altered signaling conditions, this also affects the traffic in control channels.

H. Cell Sectorization

Cell sectorization refers to the case where a given cell is subdivided into several sectors, all of which are served by the same base station. This is normally done by employing directional antennas such that the energy in each sector is directed by separate antennas. This has the effect of increased channel capacity similar to cell splitting. The sectors use the same base station, however, and thus do not incur the cost of establishing new base stations associated with cell splitting. This helps in reducing cochannel interference as the energy is directed in the direction of the sector, which does not cause interference in the cochannel cells, particularly in cochannel cells in the opposite direction to the sector. As in the case of cell splitting, this also affects the handoff rate.

I. Power Control

It is important that a radio receiver receive a power level that is high enough for its proper function but not so high as to disturb other receivers. To this end, two methods are used. One is concerned with maintaining a constant power level at the receiver by transmitter power control. In the other, the SNR is kept constant. In both the cases, the receiver controls the power of the transmitter at the other end. For example, a base would control the power transmitted by mobile phones, and vice versa. A receiver monitors its received power—or the SNR, as the case may be—and sends the control signal to the transmitter to control its power as required. Sometimes a separate pilot signal is used for this purpose.

Table 1 Comparison of Microcell and Macrocell System Parameters

Item	**Macrocell**	**Microcell**
Cell Radius	1 to 20 km	less than 1 km
Transmitter Power	1 to 10 W	less than 1 W
Channel Fading	Rayleigh	Nakagami-Ricean
RMS Delay Spread	0.1 to 10 µsec	10 to 100 ns
Max. Bit Rate Per Channel	0.3 Mbps	1 Mbps

Power control reduces the near-far problem in CDMA systems and helps to minimize interference near the cell boundaries when used in forward link [13], [15], [39].

J. Mobile Radio and Cellular System

Conventional mobile radio systems use the highest possible antennas for their base stations and radiate the maximum possible power so that the mobile units can communicate with the base from as far away as possible. In a cellular system, on the other hand, the objective is to divide the area to be served into small cells. Each cell is assigned its own base and frequency for communication. Cells that are far apart use the same frequencies, as previously discussed.

1) Microcell System: As the cells are split by reducing transmitted power and redefining cell boundaries, their size becomes very small. At a radius less than about 1 km, the system is referred to as a microcell system. Conversely, a cellular system with larger cells is referred to as a macrocell system. Various parameters for the two systems are compared in Table 1 [27].

2) Picocell System: When cell sizes are reduced to less than about 100 m, covering areas such as large rooms, corridors, underground stations, large shopping centers, and so on, such cellular systems are sometimes referred to as picocell systems with antennas mounted below rooftop levels or in buildings. These in-building areas have different propagation conditions than those covered by macrocell and microcell systems and thus require different considerations for developing channel models. Details on various models to predict propagation conditions may be found in [22]. Sometimes the picocell and microcell systems are also referred to as cordless communications systems, with the term cellular identifying a macrocell system. Mobiles within these smaller cell systems are termed cordless terminals or cordless phones [1], [3], [45].

Providing in-building communications services using wireless technology and based upon cell shapes dictated by floors and walls is a feasible alternative. It offers many advantages, including cheaper and easier installation, as it does not require the laying of cables, etc. It is argued in [46] that radio frequencies in the 18-GHz band are ideal for such services, as these do not penetrate concrete and steel structures, which eliminates the problem of cochannel

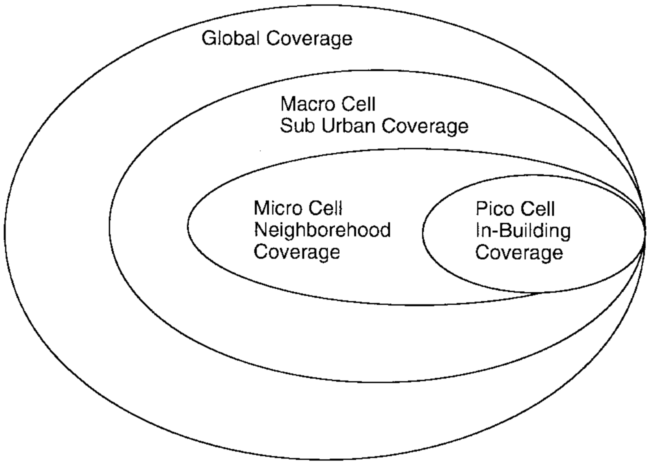


Fig. 4. Concept of overlaying [49].

interference. These frequencies offer huge bandwidth and require millimeter-size antennas, which are easy to manufacture and install.

3) Mixture of Cells and Overlaying: Small cell systems make very efficient use of the spectrum, allowing large frequency reuse and resulting in an increased system capacity. These systems are not suitable for all conditions, however, due to their large handover requirement. A system of mixed cells with the concept of overlaying is discussed in [43], [47], and [48]. In this system, a hierarchy of cells, with their own channel allocation and handover scheme, is assumed to exist. A macrocell system is assumed to be at the top of the hierarchy, with smaller cell systems at the bottom. A mobile with high mobility is assigned to a macrocell system, whereas a mobile with low mobility is assigned to a smaller cell system. Designs incorporating various combinations of different multiple-access schemes reflect the ease of handover and other traffic-management strategies. The SDMA scheme has an important role to play in this concept, with various beams placed at the bottom of the hierarchy. A typical setup [49] showing coverage of various systems is shown in Fig. 4.

K. Satellite Mobile Communications

A variety of configurations involving satellites for wireless communications exists. For example, in global positioning systems, signals received from a number of orbiting satellites are used to determine the position of a receiver. A direct broadcasting system uses satellites to transmit signals to television users. In both of these systems, the transmission is generally one way in nature. For a communications satellite system, on the other hand, a two-way communication is required. Though the requirements for different systems—such as maritime, aeronautical, and land-mobile systems—may be different, the basic principle of operation remains the same. Basically, a satellite acts as a relay station between a mobile and the base station, also known as a hub station. A geostationary satellite may provide a large coverage similar to the large and fixed coverage of a mobile radio communications system, or it may provide a number of spot beams with different beams using different frequencies, as in cellular radio. The communications satellites tend to complement the terrestrial network and play a major role in areas where the latter is not competitive or is underdeveloped.

GEOS's have a number of drawbacks when it comes to global voice communication. These satellites are placed around 36 000 km above the earth, and two-way propagation delay on the order of 0.6 s encountered by a signal makes it unacceptable for voice communication. There also exists a difficulty in covering the area of the globe far south and far north of the equator using GEOS's. There are problems in these regions as the satellite appears close to the horizon. Even using large antennas, communication beyond 75° north and south of the equator is not satisfactory. Blockage of the satellite by large buildings, even when one is situated at about 40–45° north or south of the equator, is also a problem. The communications system requires high-power transmitters with large antennas to overcome the propagation loss suffered by the signal due to a large distance. Such conditions are not practical for mobile systems.

To overcome these problems, a number of low-orbit satellites have been proposed for mobile satellite communications systems. These include LEOS's at an altitude of around 1000 km, MEOS's at an altitude of around 10 000 km, and HEOS's with varying altitudes.

Though LEOS and MEOS require less power and cause less delay, making portable mobiles viable, a large number of satellites are required for global coverage. There is a requirement of fast handoffs, as the satellites move rapidly and are in view only for a short time. There is also a concern of limited lifetime (five–ten years) due to orbital decay, requiring regular replacement [1].

A number of satellite communications systems are planned and will be in operation in the near future [50]. Among these are the ARIES, GLOBESTAR, IRIDIUM, and ODYSSEY systems, which will provide full global coverage with voice, data, and fax services. These are known as big-LEO systems. The word "big" indicates that these satellites would have enough power and bandwidth to provide near toll-quality voice services to hand-held portable and vehicle mobiles, along with other services [50]. Little-LEO systems, such as LEOSAT, STARNET, and VITASET, would provide global coverage with nonvoice services. These would provide low-bit-rate services and are expected to be of small size and low mass. A number of systems along with some other parameters are shown in Table 2 [50], [51].

The IRIDIUM system is briefly discussed here as a typical system to provide a feel for its operation, service provided, and other parameters.

IRIDIUM is proposed by Motorola to provide global coverage for voice, data, fax, paging, and so on. It would have 66 satellites (LEO 780 km) in six polar orbit planes at 86.4° inclination, each with a mass of 700 kg, and would be operational in 1998. Each satellite would provide 48 beams. This gives in total 3168 cells. These would

Table 2 Comparison of Parameters for Some Mobile Satellite Systems

System	No. of Satellites	Muliple Access	Orientation	Altitude (km)
ARIES	48	CDMA	Circular	1020
ELLIPSO	15	CDMA	Elliptical/ Circular	7800-540/ 7800
GLOBESTAR	48	CDMA	Circular	1400
IRIDIUM	66	FDMA/TDMA	Circular	780
ODESSEY	12	CDMA	Circular	10,350
TELEDESIC	840	FDMA/TDMA	Circular	700
ORBCOMM	26	FDMA	Circular	970
STARSYS	24	CDMA	Circular	1000
VITASET	2	FDMA	Circular	800

move over the surface of the earth as satellites move, and 2150 cells would be active at any time to cover the whole earth. The beams would be generated by three phased array panels, each generating 16 simultaneous shaped beams. The system would complement terrestrial systems. It would use 1616–1626.5 MHz for both uplink and downlink and 23 GHz for intersatellite links. A mobile unit would first use the local cellular ground-base system and then a satellite using one of the frequencies. A satellite would demodulate the signal to get the address of the destination and then send the message to that satellite, which is in the viewing area of the destination cell. It would use FDMA for uplink and time division multiplexing for the downlink.

More details on various aspects of mobile communications involving satellites may be found in [50]–[57].

L. Progress and Trends in Mobile Communications

Mobile communications technology has come a long way since the pioneering work at AT&T Bell Laboratories during the 1960's and 1970's. There, researchers coupled the idea of frequency reuse with digital switching, leading to the opening of the first operational cellular system in Chicago in October 1983 [58]. The first-generation analog cordless phones and cellular systems became popular using the design based upon a standard known as AMPS. Similar standards based upon FDMA were developed around the world, including TACS, NMT 450, and NMT 900 in Europe; ETACS in the United Kingdom; C-450 in Germany; and NTT, JTACS, and NTACS in Japan. The handoff decision for these systems is based upon the power received at the base or, in the case of C-450, the round-trip delay.

AMPS systems, used in Australia, the United States, Canada, and Central and South America, use an 824–849 MHz band for transmission from mobiles to base and an 869–894 MHz band for transmission from base to mobiles. There are 832 channels of 30-kHz width. The system typically makes use of 12 frequency reuse plans with omnidirectional antennas or seven frequency reuse plans with three sectors in each cell [1].

In contrast to the first-generation analog systems, second-generation systems are designed to use digital transmission, to have a separate dedicated channel for exchange of control information between base and mobiles, and to employ TDMA or CDMA as a multiple-access scheme. These systems include the Pan-European GSM and DCS 1800 systems, the North American dual-mode cellular IS-54 system, the North American IS-95 system, and the Japanese PDC system. The GSM, DCS1800, IS-54, and PDC systems use TDMA, whereas IS-95 uses CDMA. Both the IS-54 and IS-95 systems are designed to operate in the frequency band used by the AMPS system [1], [59].

The first-generation analog cordless phones are designed to communicate with a single base, effectively replacing a telephone cord with a wireless link to provide terminal mobility in a small coverage area, such as within a house or office. The second-generation digital cordless systems are being developed with the aim of using the same terminal in residential as well as public-access areas, such as offices, shopping centers, and so on, and of being able to receive and originate calls. Digital cordless systems include CT2, a British standard originally adopted in 1987 and later augmented in 1989, the DECT standard, and PHS of Japan. CT2 employs an FDMA scheme, providing one channel per carrier, whereas the DECT and PHS systems are designed to use TDMA, providing 12 and four channels per carrier, respectively [1], [3], [59].

The third-generation mobile communications systems are being studied worldwide under the names of UMTS and FPLMTS. The aim of these systems is to provide users advanced communications services having wideband capabilities and using a single standard. Details on various systems under investigation can be found in [1], [3], [16], [49], [55], and [60]. In third-generation communications systems, satellites are going to play a major role in providing global coverage. Adaptive antenna array processing has the potential to provide designers with an extra dimension of SDMA along with FDMA, TDMA, and CDMA in solving this mammoth task. Details on the use of arrays for mobile communications are provided in the remainder of this paper.

III. ANTENNA ARRAY TERMINOLOGY

This section introduces some common terms relating to antenna arrays.

Antennas in general may be classified as omnidirectional, directional, phased array, adaptive, and optimal. An omnidirectional antenna has equal gain in all directions and is also known as an isotropic antenna. Directional antennas, on the other hand, have more gain in certain directions and less in others. The direction in which the gain of these antennas is maximum is referred to as the boresight direction of the antenna. The gain of directional antennas in the boresight is more than that of the omnidirectional antennas and is measured with respect to the gain of the omnidirectional antennas. For example, a gain of 10 dBi (sometimes indicated by dBic or simply dB) means the

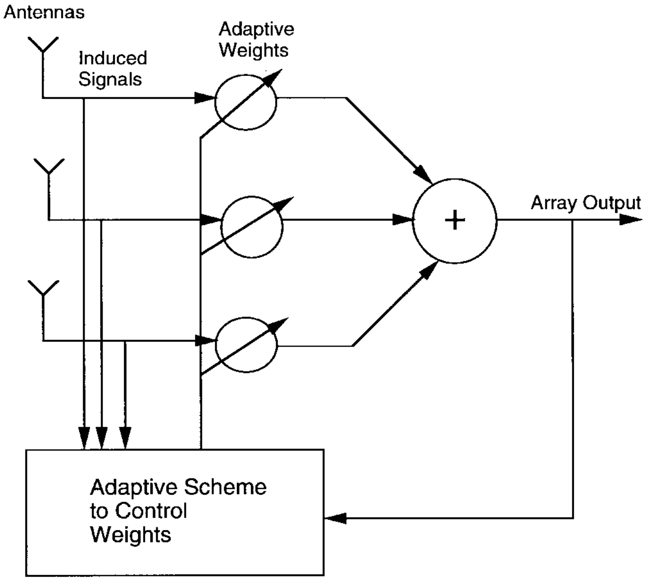


Fig. 5. Block diagram of a narrow-band adaptive antenna system.

power radiated by this antenna is 10 dB more than that radiated by an isotropic one. It should be noted that the same antenna may be used as a transmitting antenna or as a receiving antenna. The gain of an antenna remains the same in both cases. The gain of a receiving antenna indicates the amount of power it delivers to the receiver compared to an omnidirectional antenna.

A phased array antenna uses an array of simple antennas, such as omnidirectional antennas, and combines the signal induced on these antennas to form the array output. Each antenna forming the array is known as an element of the array. The direction where the maximum gain would appear is controlled by adjusting the phase between different antennas. The phases of signals induced on various elements are adjusted such that the signals due to a source in the direction where maximum gain is required are added in-phase. This results in the gain of the array (or equivalently, the gain of the combined antenna) are equal to the sum of the gains of all individual antennas.

The term adaptive antenna is used for the phased array when the gain and the phase of the signals induced on various elements are changed before combining to adjust the gain of the array in a dynamic fashion, as required by the system. In a way, the array adapts to the situation, and the adaption process is normally under the control of the system. A block diagram of a typical adaptive antenna array system is shown in Fig. 5.

An optimal antenna is one in which the gain and phase of each antenna element is adjusted to achieve the optimal performance of the array in some sense. For example, to obtain maximum output SNR by canceling unwanted interferences and receiving the desired signal without distortion may be one way of adjusting gains and phases of each element. This arrangement where the gain and phase of each antenna element is adjusted to obtain maximum output SNR (sometimes also referred to as signal-to-interference-and-noise ratio, SINR) is also referred to as optimal combining in the mobile communications literature [29], [61], [62].

A. Beam Steering and Switching

The signals induced on different elements of an array are combined to form a single output of the array. A plot of the array response as a function of angle is normally referred to as the array pattern or beam pattern. It is also called a power pattern when the power response is plotted. It shows the power received by the array at its output from a particular direction due to a unit power source in that direction. This process of combining the signals from different elements is known as beam forming. The direction in which the array has maximum response is said to be the beam pointing direction. Thus, this is the direction where the array has the maximum gain. For a linear array, when signals are combined without any gain and phase change, this is broadside to the array, that is, perpendicular to the line joining all elements of the array.

The array pattern drops to a low value on either side of the beam pointing direction. The place of the low value is normally referred to as a null. Strictly speaking, a null is a position where the array response is zero. However, the term is generally misused to indicate the low value of the pattern. The pattern between the two nulls on either side of the beam pointing direction is known as the main lobe. The width of the beam (main lobe) between the two half-power points is called the half-power beamwidth. A smaller beamwidth results from an array with a larger extent. The extent of the array is known as the aperture of the array. Thus, the aperture of the array is the distance between the two farthest elements in the array. For a linear array, it is equal to the distance between the elements on either side of the array.

For a given array, the beam may be pointed in different directions by mechanically moving the array. This is known as mechanical steering. Beam steering can also be accomplished by appropriately delaying the signals before combining them. This process is known as electronic steering, and there are no mechanical movements. For narrow-band signals, the phase shifters are used to change the phase of signals before combining them.

The required delay may also be accomplished by inserting varying lengths of coaxial cables between the antenna elements and the combiner. Changing the combinations of different lengths of these cables leads to different pointing directions. Switching between different combinations of beam steering networks to point beams in different directions is sometimes referred to as beam switching.

B. Conventional Beam Forming

Adjusting only the phase of signals from different elements to point a beam in a desired direction is the conventional method of beam pointing or beam forming. The gain of each signal is kept the same. This determines the total gain of the array in the beam pointing direction, also known as the look direction. The shape of the antenna pattern in this case is fixed, that is, the positions of the side lobes with respect to the main beam and their level are unchanged. In other words, when the main beam is pointed in different directions by adjusting various phases, the relative positions of the side lobes with respect to the main lobe do not change. This, however, may be changed by adjusting the gain and phase of each signal to shape the pattern as required. The amount of change depends upon the number of elements in the array.

The gain and phase applied to the signals derived from each element may be thought of as a single complex quantity hereafter referred to as the weighting applied to the signals. If there is only one element, no amount of weighting can change the pattern of that antenna. With two elements, however, changing the weighting of one element relative to the other may adjust the pattern to the desired value at one place, that is, one is able to place one minima or maxima anywhere in the pattern. Similarly, with three elements, two positions may be specified, and so on. Thus, with an L-element array, one is able to specify $L-1$ positions. These may be one maxima in the direction of the desired signal and $L-2$ minimas (nulls) in the directions of unwanted interferences. This flexibility of an L-element array to be able to fix the pattern at $L-1$ places is known as the degree of freedom of the array. For an equally spaced linear array, this is similar to an $L-1$ degree polynomial of $L-1$ adjustable coefficients, with the first coefficient having the value of unity.

C. Steering Vector

The steering vector contains the responses of all elements of the array to a narrow-band source of unit power. As the response of the array is different in different directions, a steering vector is associated with each directional source. The uniqueness of this association depends upon the array geometry [63].

For an array of identical elements, each component of this vector has unit magnitude. The phase of its ith component is equal to the phase difference between signals induced on the ith element and the reference element due to the source associated with the steering vector. As each component of this vector denotes the phase delay caused by the spatial position of the corresponding element of the array, this vector is also known as the space vector. It is also referred to as the array response vector, as it measures the response of the array due to the source under consideration. In multipath situations, such as exist in mobile communications, it also denotes the response of the array to all signals arising from the source [64]. In this paper, the terms steering vector, space vector, and array response vector are used interchangeably.

D. Null Beam Forming

The flexibility of array weighting to being adjusted to specify the array pattern is an important property. This may be exploited to cancel directional sources operating at the same frequency as that of the desired source, provided these are not in the direction of the desired source. In situations where the directions of these interferences are known, cancellation is possible by placing the nulls in the pattern corresponding to these directions and simultaneously steering the main beam in the direction of the desired signal. Beam forming in this way, where nulls are placed in the directions of interferences, is normally known as null beam forming or null steering. The cancellation of one interference by placing a null in the pattern uses one degree of the freedom of the array.

Null beam forming uses the directions of sources toward which nulls are placed for estimating the required weighting on each element. There are other schemes that do not require directions of all sources. A constrained beam-forming scheme uses the steering vector associated with the desired signal and then estimates the weights by solving an optimization problem. Knowledge of the steering vector associated with the desired signal is required to protect the signal from being canceled. In situations where the steering vector associated with the signal is not available, a reference signal is used for this purpose.

E. Diversity Combining

The discussion here concentrates on spatial diversity as provided by an array of antennas. Unless explicitly stated, diversity refers to spatial diversity throughout this paper.

Diversity combining [65] is used to overcome the problem of fading in radio channels and utilizes the fact that the signals arriving at different locations fade at different rates. A system employing a diversity combiner uses signals induced on various antennas placed a few wavelengths apart at different locations and combines these signals in one of many ways [66]. For example, an equal gain combiner adjusts the phases of the desired signals and combines them in-phase after equal weighting. The maximal ratio combiner applies weights in proportion to the SNR and combines the weighted signals in-phase, whereas a selection diversity combiner selects the signal from one of the antennas for processing. The selection may be based upon the power of the desired signal, the total power, or the SIR available at each antenna. The selection based upon the SIR is most effective in combating cochannel interference, whereas the equal gain combiner provides the lowest outage probability (the probability that the channel is not suitable for use).

In general, increasing the number of antennas results in more reduction in channel fading. However, in practice, 10–20 antennas seem to provide satisfactory results [67]. Information on diversity receiver design may be found in [9].

Diversity combining is different from antenna array processing and beam forming. It combines the signals at the baseband or at the IF level to increase the signal level without affecting the individual antenna pattern. Beam-forming techniques, on the other hand, exploit the differential phase between different antennas normally at RF level to modify the antenna pattern of the whole array. In this arrangement, once the signals are combined, the whole of the array has a single antenna pattern.

Diversity combining is useful for combating fading and is efficient in the absence of a common interference on all the antennas. In the presence of cochannel interferences, however, the array processing methods are able to provide better performance by canceling interferences [61]. An overview of array processing schemes will be provided in the second part of this paper.

IV. USE OF ARRAYS IN MOBILE COMMUNICATIONS SYSTEMS

Arrays may be used in various configurations for mobile communications, some of which are discussed here. This section will consider the improvements made possible by using an array. The systems considered include base-mobile, indoor-mobile, satellite-mobile, and satellite-to-satellite communications systems. As no distinction is made between the use of arrays for the purpose of transmission and reception in this paper, a short discussion on transmitting arrays is provided in this section.

A. Base-Mobile System

A general description of the base-mobile system was provided in Section II. The system consists of a base station situated in a cell and serves a set of mobiles within the cell. It transmits signals to each mobile and receives signals from them. It monitors their signal strength and organizes the handoff when mobiles cross the cell boundary. It provides the link between the mobiles within the cell and the rest of the network.

In this section, various scenarios are presented to show how an array could be used in such a system. The discussion will concentrate on the use of an array at the base station as well as at mobiles. Some practical considerations to implement arrays and blind estimation of the cochannel signals are also discussed in this section.

1) Use of Array at a Base Station: In this section, a number of possibilities are discussed where a base station uses an array of antennas. A base station having multiple antennas is sometimes referred to as having antenna diversity or space diversity [68], [69].

a) Formation of multiple beams: In its simplest form, multiple antennas at the base station may be used to form multiple beams to cover the whole cell site. For example, three beams with a beamwidth of 120° each or six beams with a beamwidth of 60° each may be formed for the purpose. Each beam then may be treated as a separate cell, and the frequency assignment may be performed in the usual manner. Mobiles are handed to the next beam as they leave the area covered by the current beam, as is done in a normal handoff process when the mobiles cross the cell boundary.

b) Formation of adaptive beams: An array of antennas with the capability to form independent beams may be used at the base station as discussed in [20], [70], and [71]. The array is used to find the location of each mobile, and then beams are formed to cover different mobiles or groups of mobiles. Each beam may be considered as a cochannel cell, and thus may be able to use the same frequency or code, as the case may be. Fig. 6 shows a typical setup involving different beams covering various mobiles along with the directions of moving mobiles. It illustrates the situation at two time instants.

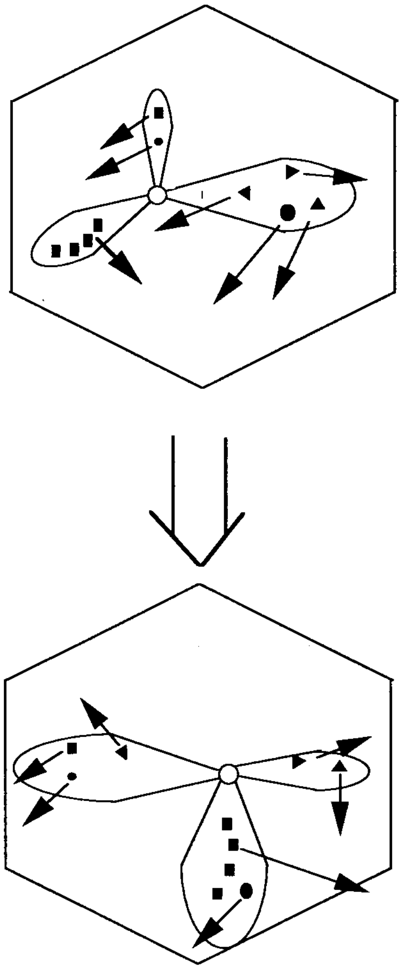


Fig. 6. A typical setup showing different beams covering various mobiles [70].

This setup is different from the one discussed previously, where a number of beams of fixed shape cover the whole cell. Here, the beams are shaped to cover the traffic. As the mobiles move, the different beams cover different clusters of mobiles, offering the benefit of transmitting the energy toward the mobiles. The arrangement is particularly useful in situations where the mobiles move in clusters or along confined paths, such as highways. It is envisaged in [70] that each mobile may be covered by a separate beam. Each beam then would follow the mobile, reducing the handoff problem to the bare minimum.

c) Null formation: In contrast with steering beams toward mobiles, one may adjust the antenna pattern such that it has nulls toward other mobiles. As mentioned, a null in an antenna pattern denotes a zero response. In practice, however, that is seldom achievable, and one creates a pattern with a reduced response toward undesirable interferences.

Formation of nulls in the antenna pattern toward cochannel mobiles helps to reduce the cochannel interference in two ways. In the transmit mode, less energy is transmitted from the base toward these mobiles, reducing the interference from the base to them. In the receiving mode, this helps to reduce the contribution from these mobiles at the base.

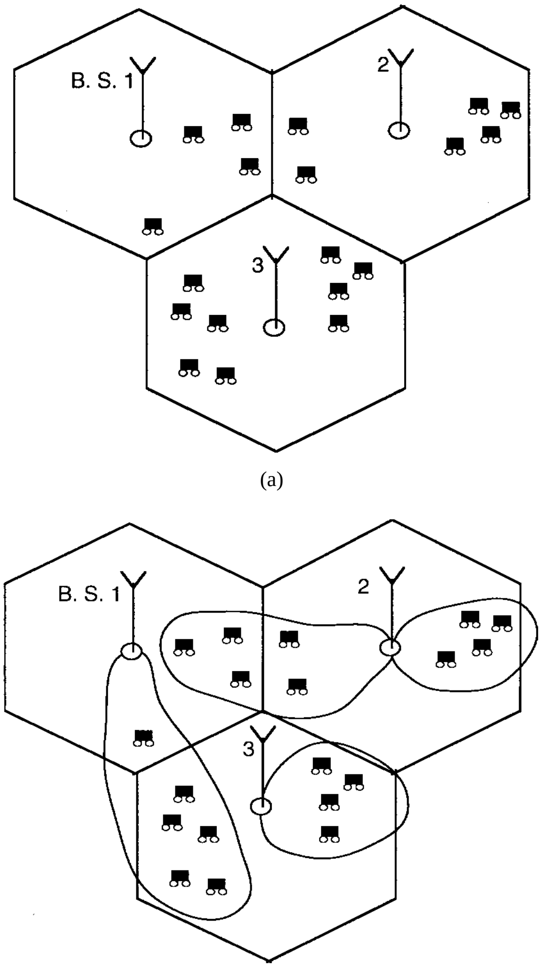
d) Optimal combining: Canceling unwanted cochannel interferences while an array is operating in receiving mode is a very effective use of an antenna array. The process combines signals received on various antennas in such a way that the contribution due to unwanted interferences is reduced while that due to a desired signal is enhanced. Knowledge of the directions of the interferences is not essential to the process's functioning, while some characteristics of the desired signal are required to protect it from being canceled. Discussion on optimal combining to cancel cochannel interferences in digital mobile radio may be found in [29] and [61].

These studies suggest the use of an array at the base station for a TDMA system and adjustment of the array weights during the receive cycle to enhance the signal arriving from a particular mobile. It is argued that a system using the same frequency for receiving and transmitting the signals in different time slots may be able to use the complex conjugate of these weights during the transmit cycle to enhance the signal received at that mobile, simultaneously suppressing this signal at the other mobiles. It relies on the fact that the weights adjusted during the receive cycle to reduce cochannel interference result in an array pattern with nulls in the directions of cochannel mobiles. The use of the complex conjugate of these weights during the transmit cycle produces the same pattern, and thus no energy is transmitted toward the cochannel mobiles.

By using constrained beam-forming techniques, one may be able to combine the formation of nulls in the directions of unwanted mobiles while keeping the specified response in the direction of a desired mobile. The use of constrained beam forming for mobile communications is discussed in [19] and [71]–[73]. For proper operation, the direction of the desired signal is required. It is used for maintaining a specified response in that direction.

Though constrained beam forming is very effective when the desired signal is a point source, its use in mobile communications is limited, particularly in situations of multipaths. Optimal combining using a reference signal is more appropriate for this case. It requires a signal that is correlated with the desired signal. The scheme then protects all signals that are correlated with this reference signal and adds them in-phase to maximize their combined effect. It simultaneously cancels all waveforms that are not correlated with this signal, resulting in a removal of cochannel interferences. Thus, optimal combining using a reference signal is able to make use of multipath arrivals of the desired signal, whereas the constrained beam forming treats them as interferences and cancels them.

A comparative study of a reference-signal-based algorithm and a method using the estimates of directions of sources [71] indicates the superiority of the former when multipaths result in large spread of the desired signal.



(a)

(b)

Fig. 7. Cell shape based upon traffic needs [20]. (a) Cells of fixed shape. (b) Cells of dynamic shape.

A study of optimal combining using a reference signal, presented in [74], indicates that better results are obtained when the weights are estimated using the RLS algorithm than when using the LMS and SMI algorithms.

e) Dynamic cell formation: The concept of adaptive beam forming may be extended to dynamically changing cell shapes. Instead of having cells of fixed size, the use of array antennas allows the formation of a cell based upon traffic needs, as shown in Fig. 7 [20].

An architecture to realize such a base station requires the capability of locating and tracking the mobiles in order to adapt the system parameters to meet the traffic requirements.

Many of the DOA estimation techniques available in the literature assume an existence of point sources. This is not necessarily the case for land-mobile communications, where scattering in the vicinity of a mobile causes a spreading of the source and the signal arrives at the base in the form of multipath, as if there were many radiating sources of varied power in the neighborhood of the mobile. Experiment results [75] indicate that at 870 MHz, the estimated angular spread is around 3° when viewed from a distance of 1 km. This corresponds to a scattering area with a radius of about 50 m around the mobile. Considerations for situations like this need to be given while tracking the mobile and forming the beams of appropriate shapes [19], [71]. Focusing the beam more than necessary may result in a loss of gain, as found in the study reported in [76].

Technology that allows cell shapes and sizes to be changed based upon traffic conditions, channels to be assigned dynamically as per traffic needs, and transmitter power to be adapted according to receiver requirements is referred to as intelligent technology [20]. Apart from variable cell size, adaptive transmitted power, and dynamic channel allocation, this technology also allows for variable speed for transmission and the use of adaptive modulation and demodulation techniques. Discussion on some of these issues can be found in [20] and [77]–[80].

2) Practical Considerations: Some practical situations are considered here for acquiring the knowledge of the DOA, the array response vector, or the reference signal required for the possible implementations of beam-forming techniques using an array.

a) Using DOA information: Many systems use two separate frequencies for transmit and receive modes. The knowledge of the directions of mobiles obtained during the receive mode may be used during the transmit mode to transmit in the directions of mobiles in a multiplexed manner. Once the position of mobiles in a cell is determined during the receive mode, these mobiles are grouped in different clusters, and then the antenna pattern is adjusted such that the main beam is pointed toward one cluster while nulls are formed in the directions of other clusters. The process is repeated to transmit to all the clusters. Transmission could take place simultaneously using parallel transmission circuits or by using a time-sharing arrangement of a single circuit. The nulls may also be directed toward mobiles in other cochannel cells with added implementation complexities caused by the requirement for synchronization [81].

b) Using array response vectors: A base station not requiring the directions of the mobile may be able to form beams by estimating the array response vector corresponding to a mobile, as discussed in [64] for a CDMA system. The system uses two separate frequencies for transmission and reception. In the receiving mode, the base station estimates the array response vector from a signal received from a mobile with whom the base is code locked, whereas in the transmit mode, the same is done by processing the feedback from the mobile to a special tone transmitted by the base. The array response vector may also be estimated from the knowledge of the user code in a CDMA system or from the reference signal if available, as discussed in [29].

c) Using a reference signal: The approach described in [18] suggests that the base station acquires the reference signal from the desired user and uses this to estimate the weighting of each antenna before combining the signals to produce the array output. It suggests that initial weights be estimated by using a specific signal transmitted for this purpose. Once the initial weights are determined, the received signal then may serve as the reference for later updating the weights and tracking the mobile. The user identification may also be used to reemphasize that the current signal is from the desired user. In TDMA systems, a separate signal may be sent for this purpose. Similarly, for the CDMA system, a separate sequence may be transmitted in phase quadrature to the original signal. The synchronization sequence transmitted in some systems may also be used for this purpose.

3) Blind Estimation of Cochannel Signals: A base station employing multiple sensors may be able to exploit the fact that signals arriving from different mobiles follow different paths and arrive at various elements at different times. This allows independent measurements of signals superimposed from different mobiles. This, along with the properties of the modulation technique used, allows separation of signals arriving from different mobiles. Thus, by using the measured signals at various elements of the array at the base, one is able simultaneously to separate all signals. The process is referred to as the blind estimation of cochannel signals. It does not require knowledge of the directions or other parameters associated with mobiles, such as a reference signal or a training sequence, but exploits the temporal structure that might exist in signals inherited from the source of their generation, for example, the modulation techniques used. Many studies on this topic have been reported in the literature [82]–[92].

It has been argued in [93] that most man-made signals encountered in communications exhibit variation in some of their parameters in time, and these signals may be modeled as cyclostationary signals. A random signal whose parameters vary in time with single or multiple periodicity is referred to as a cyclostationary signal. For example, a signal with second-order cyclostationarity is one whose autocorrelation function varies periodically with time. The cyclostationarity property of communications signals has been exploited by many authors [88], [92], [94] for blind signal extraction.

The temporal structure inherent in BPSK signals is exploited in [82] to separate cochannel signals by solving a set of linear equations to obtain the array weights. The method is based upon clustering the received signals as per their delays and reportedly has some implementation advantages over other similar methods [83], [95]. The other properties of signals that have been used for blind signal extraction include constant modulus [96], [97], finite alphabet [84], and higher order statistics [89], [98]. Use of the source correlation compensation technique for blind channel identification is made in [99].

4) Use of Array at a Mobile: There are normally two kinds of mobiles: hand-held portable mobiles and mobiles fixed on vehicles, with differing requirements of the type of equipment they may carry. For example, it is possible for a vehicle mobile to carry an array of antennas and the required processing equipment; however, the same would be difficult for the hand-held portable.

Application of optimal combining at a vehicular mobile is discussed in [62] for a situation where desired signal and cochannel interferences arrive from many directions due to multipaths. It is argued that due to the distributed nature of sources, synthesis of antenna pattern with nulls toward interferences is not practical. It suggests the use of optimal combining of a desired signal arriving from various paths, using a reference signal transmitted from the base in the form of a pilot signal for a spread-spectrum system. An example considering the worst-case scenario indicates that one has about 35 iterations to adjust the weights of the array for the vehicular mobile system and suggests the use of the SMI algorithm for this case. A successful implementation of an antenna array on the roof of a mobile vehicle using a CMA to update the weights for a TDMA system is described in [100]. Developments of a dual antenna system for hand-held portables are reported in [30], [101], and [102].

B. Indoor-Mobile Radio System

In a base-mobile communications system, a number of mobiles communicate through a base station, as discussed. There are, however, a number of differences between a land-mobile system and an in-building mobile system owing to the type of mobiles they serve and the environment in which they operate. For an in-building mobile system, the mobiles are hand-held portables moving on foot, whereas for a land-mobile system, they are generally vehicles. This results in different fading rates for the two cases. The fading rate for the indoor system is much slower than the other, implying that optimal combining could be implemented with ease using adaptive techniques [29], [61].

The delay spread problem in the two cases is also different. For a land-mobile system, the signals generally arrive in delayed clusters due to reflections from large objects, such as hills and buildings. For an indoor system, there exist a large number of scattering and reflections inside a building. This causes the impulse response of the indoor radio channel to appear like a series of pulses [103]. The use of adaptive antennas to improve such channels is discussed in [104].

C. Satellite-Mobile System

In this system, the mobiles (in this case mostly vehicles) directly communicate with the satellite, in contrast to a system where a base station acts as a repeater station by communicating with the satellite on one hand and the mobiles on the other. In this case, multiple antenna elements may be utilized on a mobile as well as on a satellite.

1) Array on Satellites: It is possible to use an array on board a satellite and provide communication in a number of ways. For example, different frequencies may be allocated to beams covering different areas such that each area acts as a cell. This allows frequency reuse similar to the base-mobile system discussed previously. The major difference between this and the land-mobile system is the generation of beams covering different cells rather than having different base stations for different cells. An array mounted onboard the satellite provides the beam-generation facility. Depending upon the type of array system utilized, many scenarios are possible.

a) Fixed-shape beams: In a simplistic situation, beams of fixed shape and size may be generated to cover the area of interest, allowing normal handoff as the mobiles roam from one cell to another or as the beams move in a low orbit multiple satellite system covering different areas. Proposed fixed-beam antennas using multibeam phased arrays for mobile communications and featuring frequency-reuse facility and flexibility of variable beam power allocation have been reported in [105].

Traditionally, phased arrays have been used in a feed network to control the beam coverage area. A typical system may consist of a high-gain large reflector antenna along with an array of feed elements placed in the focal plane of the reflector in a particular geometry able to generate a limited number of fixed-shape spot beams. A particular beam is selected by choosing a combination of feed elements. The steering of beams is achieved by controlling the phases of signals prior to the feed elements. Dual circuitry is employed for transmit and receive modes for the signal to flow in both directions. The capability of the system to generate multiple spot beams with independent power control and frequency use makes it attractive for mobile communications. These capabilities, along with a frequency scanning system, have been evaluated for the European geostationary satellite system in various ESA contracts [105], [106].

The frequency scanning system considered in [105] and [106] uses an array of active antennas to provide a high-gain beam with the capability to steer it at any user location using frequency-dependent interelement phase shift. The same array is used for the transmit as well as for the receive mode. In the transmit mode, the signal is supplied to antennas by an array of power amplifiers, whereas in the receive mode, the antennas feed the low noise amplifiers of the receiver. A comparison of the two systems indicates that the frequency scanning system outperforms the conventional multispot system in terms of capacity, required power per channel, and payload mass per channel but requires a complex beam-forming network and mobile terminal location procedures.

b) Dynamic beams: A system using fixed-shape beams does not require knowledge of the traffic conditions, as does a system generating spot beams of varying shapes and sizes dictated by the positions of the mobiles (Fig. 8). For downlink transmission, this helps in transmitting the energy in the direction of mobiles by controlling the shape and coverage of the beams (as discussed in [107]), which in turn reduces cochannel interferences at the mobiles. This also helps reduce the transmitted power due to its directed nature of transmission, relaxing the need to generate large amounts of power onboard a satellite. To generate an arbitrarily shaped beam to be pointed at a desired location, the system architecture requires an advanced beam-forming network with independent beam-steering capability.

Recent developments in monolithic MMIC technology, which allows fabrications of power amplifiers, phase

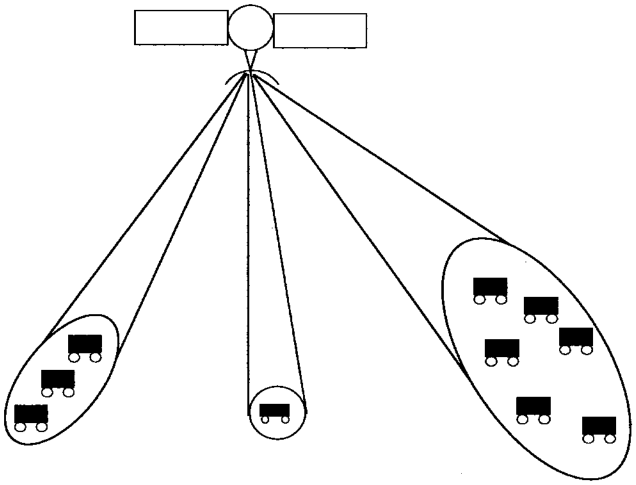


Fig. 8. A satellite system generating spot beams of various shapes to cover clusters of mobiles.

shifters, and low noise amplifiers directly coupled to radiating elements, provides multibeam functionality using a very small space onboard the satellite. The technology enables one to fabricate a large number of active elements that may be independently controlled by digital hardware. This, along with digital signal processing, gives one the capability to generate a large number of independent beams of arbitrary shapes, which may be steered at any desired location.

Such active elements with dedicated high-power and low-noise amplifiers have been used in recent system developments, including the GLOBALSTAR [108] and IRIDIUM [109] systems. Panels containing a large number of elements are mounted onboard the satellite, and these elements are used to generate many fixed-shape beams. These beams form cochannel cells, with each cell supporting a number of communications channels. The system allows normal handoff when mobiles move out of a cell and does not use the knowledge of the positions of mobiles to adapt the beams. Each beam supports a group of mobiles.

c) Separate beam for each mobile: Allocation of separate beams to each mobile is advocated in [110]. A satellite acts as a relay station between mobiles and the base station, with communication between the base station and the satellite being at a different frequency than that between mobiles and the satellite. It is envisaged that each mobile is tracked and the beam is pointed toward the desired mobile, with nulls in the directions of other mobiles operating at the same frequency. Different frequencies are used to communicate with the mobiles in close vicinity. Though the system as described uses different frequencies, the principle of operation remains the same for CDMA and TDMA systems.

It should be noted that the direction-finding and beamforming algorithms in this case operate in a different environment than those operating for the base-mobile communications systems. Due to the distance involved between the satellite and the mobiles, the signals arriving from the mobiles appear more like point sources, which is not the case for the signal arriving at a base station due to spreading of signals caused by reflections in the vicinity of mobiles. The problem of multipath fading and delayed arrival is also not serious in this case.

2) Array on Mobiles: An array of antennas may be mounted on a mobile (vehicle) to communicate directly with a satellite, along with its control circuitry, to steer a beam toward the satellite. As the direction of the satellite with respect to the mobile is changing constantly due to vehicle movement, it requires constant tracking of the satellite and adjusting of the direction of the beam such that it points toward the satellite. Apart from this, the structure of the land-mobile antenna also needs to take into account the aesthetic aspects, which is not the case for base-station antennas. A number of studies have been reported in the literature covering a satellite communications system utilizing multiple antennas for land mobiles, which highlights these and other issues requiring consideration. Some are briefly mentioned here.

The mobile satellite experiment studied in [111] uses a number of antennas mounted on a vehicle. A beam is electronically steered in the direction of a satellite using phase shifters. The system consists of many satellites and a vehicle communicates with the one that is in view at the time, requiring tracking of all the satellites and switching between the satellites as required.

Electronic steering is not utilized for the German TV-SAT 2 system [112] using multiple antennas. It employs four sets of preoriented antenna elements mounted on four faces of truncated pyramids. Fixed beams from each set are formed separately and are switched depending on the orientation of the mobile relative to the geostationary satellite used. The system is useful for larger vehicles, such as buses and trains.

Separate elements are suggested in [113] that are alternately placed side by side in a planar configuration for transmit and receive mode using digital beam-forming techniques for tracking two satellites in multisatellite systems. The system uses low-orbit satellites.

A spherical array mount, useful for ships and aircraft employing digital beam forming to control beam direction, is discussed in [114]. Test results on the characteristics and the suitability of an antenna array mounted on an aircraft to communicate directly with a satellite are reported in [115].

An experimental development of a four-element antenna array to receive a 1.537-GHz pilot tone from the INMARSAT II F-4 geostationary satellite with a fixed position receiver shows that a significant improvement in link reliability can be produced using an adaptive array at a hand-held mobile compared to an omnidirectional antenna [116]. It indicates the possibility of using an array at hand-held mobiles communicating directly with a satellite, provided that the required signal processing could be incorporated somewhere.

D. Satellite-to-Satellite Communications

Intersatellite communications will play an important role in mobile communications, particularly with the use of low-orbit satellites. The position of these satellites changes quickly, which causes a change in their relative directions.

Arrays of antennas can play a major role in this situation by forming beams that always point in the direction of the desired satellite and have nulls in the direction of others operating in the same band. The array may be used for tracking the satellites as well as for canceling interferences arising from the transmission of other satellites. It may also provide protection against unfriendly jamming.

An application of adaptive arrays to cancel interferences in a satellite-to-satellite communications system using direct-sequence spread spectrum is considered in [73]. A constrained beam-forming algorithm, which uses the direction of the desired signal as well as an adaptive beam forming using the reference signal, is studied for this application. The study assumes that the direction of the desired satellite in this case may be obtained from the knowledge of the position of the satellite as it follows a well-defined trajectory.

E. Use of Arrays in Transmit Mode

Antenna arrays have an equal role to play in both the receive and transmit modes. Their use in various configurations, as discussed previously, is applicable for both cases. Conceptually, the ideas of forming multiple beams to cover the cell site as well as pointing independent beams toward a cluster of mobiles, steering nulls toward cochannel mobiles, and forming cells dynamically are equally useful for both the cases. However, the required signal-processing and hardware techniques to implement the array system for the two cases differ significantly. Conventionally, most of the investigations involving adaptive arrays have been for receiving antennas. Some discussion specific to transmitting arrays may be found in [29], [31], [81], and [117]–[123].

The problem of transmitting cochannel signals using an antenna array to several mobiles is addressed in [118] such that each mobile receives its desired signal with minimum cross talk with the other signals. It also proposes the formation of a desired transmitting beam pattern using the knowledge of propagation conditions acquired from the signals transmitted by each mobile for this purpose.

Use of the information gathered during the reception mode may be used during the transmission mode, as advocated in [29], [31], and [121]. It is suggested that the complex conjugate of the array weights, estimated during the reception by optimal combining, be used in transmit mode using different time slots for the two modes. It should be noted, however, that the optimal weights may change substantially, within a dwell time of 5 ms between the uplink and the downlink, causing a severe degradation in the performance of the system, as discussed in [123].

The formation of nulls toward cochannel interferences during transmit mode is described in [81] and [117]. The discussion in [81] is for an element space method, whereas that in [117] uses a beam space technique.

V. PERFORMANCE IMPROVEMENT USING AN ARRAY

An antenna array is able to improve the performance of a mobile communications system in a number of ways [18]–[20], [30], [70], [124]. It provides the capability to reduce cochannel interferences and multipath fading, resulting in better quality of services, such as reduced BER and outage probability. Its capability to form multiple beams could be exploited to serve many users in parallel, resulting in an increased spectral efficiency. Its ability to adapt beam shapes to suit traffic conditions is useful in reducing the handoff rate, which may result in increased trunking efficiency.

This section discusses the advantages of an array of antennas in a mobile communications system and improvements that are possible by using multiple antennas in a system rather than a single one. It provides references to experiments and studies where such improvements have been realized and highlights complexities associated with the implementation of such systems.

A. Reduction in Delay Spread and Multipath Fading

Delay spread is caused by multipath propagation where a desired signal arriving from different directions gets delayed due to the different travel distances involved. An array with the capability to form beams in certain directions and nulls in others is able to cancel some of these delayed arrivals in two ways. First, in the transmit mode, it focuses energy in the required direction, which helps to reduce multipath reflections causing a reduction in the delay spread. Second, in the receive mode, an antenna array provides compensation in multipath fading by diversity combining, by adding the signals belonging to different clusters after compensating for delays, and by canceling delayed signals arriving from directions other than that of the main signal.

1) Use of Diversity Combining: Diversity combining achieves a reduction in fading by increasing the signal level based upon the level of signal strength at different antennas [20], [66], [125], whereas in multipath cancellation methods, it is achieved by adjusting the beam pattern to accommodate nulls in the direction of late arrivals, assuming them to be as interferences. For the latter case, a beam is pointed in the direction of the direct path or a path along which a major component of the signal arrives, causing a reduction in the energy received from other directions and thus reducing the components of multipath signal contributing to the receiver. Techniques to identify a line-of-sight path from a group of received multipath signals have been reported in literature [126].

2) Combining Delayed Arrivals: A radiowave originating from a source arrives at a distant point in clusters after getting scattered and reflected from objects along the way [127]. This is particularly true in scenarios with large buildings and hills where delayed arrivals are well separated. One could use these clustered signals constructively by grouping them as per their delays compared to a signal available from the shortest path. Individual paths of these delayed signals may be resolved by exploiting their temporal or spatial structure.

The resolution of paths using temporal structures depends upon the bandwidth of the signal compared to the coherence bandwidth of the channel and increases as this bandwidth increases. In a CDMA system, the paths may be resolved provided their relative delays are more than the chip period [128]–[131]. When these paths are well separated spatially, an antenna array may be used. This could be done, for example, by determining their directions. Spatial diversity combining similar to that used in the RACK receiver [132] may also be employed to combine signals arriving in multipaths.

The signals in each cluster may be separated by user-specific information present in each signal, such as the frame identification number or the use of a known symbol in each frame. A simulation study reported in [133] uses the conjugate gradient method to adjust the array weights for compensating multipath fading in a land-mobile communication. The system uses TDMA, employs known symbols in each frame, and provides satisfactory performance using six elements in the presence of up to 30 scattered waves.

In some situations, it might be possible to separate the signals in each cluster by forming multiple beams in the directions of each component of these clusters, with nulls pointing toward the other ones. Combining signals belonging to different users after compensating for delays not only leads to reduction in delay spread but also reduces cochannel interference.

3) Nulling Delayed Arrivals: A reduction in delay spread using an array by nulling the delayed signals arriving from different directions has been reported in [100] and [104]. The simulation study presented in [104] considers indoor radio channels, uses a PN sequence as a reference signal and the SMI algorithm to estimate the array weights, and concludes that using an adaptive array, a substantial reduction in delay spread is possible. Similar conclusions are reached in [100] using an experimental array of four elements mounted on a vehicle. It shows that using a CMA, the array is able to null the delayed arrival in a time-division-multiplexed channel.

A frequency-hopping system may also be used for correcting degradation due to fading. The system is useful in frequency-selective fading, where the different frequencies fade differently. The frequency-hopping system is a spread-spectrum system where the carrier frequency of transmission is changed in a predetermined manner, in contrast to a direct-sequence spread-spectrum system, where a pseudorandom sequence is used to spread the spectrum. An introduction of enough redundancy in such a system by coding the information before transmission may help the system to correct the loss of reception caused by fading at certain frequencies. A comparison of such systems with a system using antenna diversity of two antennas [134] shows that the performance of the two systems is almost identical. However, there is a cost associated with the coding method. It increases the rate of information due to added redundancy, requiring higher bandwidth. This in turn reduces the capacity of the system.

Application of adaptive arrays for frequency-hopping communications systems is described in [135]–[137], whereas the use of adaptive arrays for direct-sequence spread-spectrum communications systems may be found in [138] and [139].

B. Reduction in Cochannel Interference

An antenna array has the property of spatial filtering, which may be exploited in transmitting as well as in receiving modes to reduce cochannel interferences. In the transmitting mode, it can be used to focus radiated energy by forming a directive beam in a small area where a receiver is likely to be. This in turn means that there is less interference in other directions where the beam is not pointing. An analysis of a base station using multiple beams covering various mobiles indicates that cochannel interference decreases as the number of beams increases [70].

Cochannel interference in transmit mode could be further reduced by forming specialized beams with nulls in the directions of other receivers. This scheme deliberately reduces transmitted energy in the direction of cochannel receivers and requires knowledge of their positions. An implementation of a communications system using an array to cancel the cochannel interference in a UHF broadcasting system is described in [140].

The reduction of cochannel interference in the receive mode is a major strength of antenna arrays and has been reported widely. It does not require knowledge of the cochannel interferences. If these were available, however, an array pattern might be synthesized with nulls in these directions, as discussed, for example, in [141]. In general, an adaptive array requires some information about the desired signal, such as the direction of its source, a reference signal, or a signal that is correlated with the desired signal.

In situations where the precise direction of the signal is known, interference cancellation may be achieved by solving a constrained beam-forming problem, whereas when this is not the case, it may be achieved by using a reference signal as discussed in [73] and [138], where the reference signal for a CDMA system is generated by code synchronization. A comparison of the two schemes [73] for a satellite-to-satellite communications scenario when an approximate direction of the signal is known indicates that the constrained scheme cancels the interference faster than the reference generation scheme.

C. Arrays in Combination with Other Techniques

An antenna array may be used together with other methods to enhance the performance of a system by canceling the interference that might be present in directions other than that of the desired signal.

1) Spatial Diversity and Channel Coding: A combination of channel coding and spatial diversity (two antennas) for a TDMA indoor wireless system [102], [142] shows that the combined scheme provides a better BER than that without coding schemes. This reduces the effective data rate, however, and requires larger bandwidth for a given data rate to be transmitted. This in turn reduces the number of channels available. The problem may be alleviated by using extra antennas to increase space diversity. This and another study [134], which compares a frequency-hopped TDMA system with one using space diversity, show the amount of tradeoff provided by antenna arrays.

2) Diversity Combining and Interference Canceling: An antenna array operating in a combined mode of diversity combining and interference canceling may be able to cancel directional interferences using some degree of freedom and achieve reduction in fading on the order of the remaining degree of freedom [18], thus improving the performance of the system as well as increasing its capacity. This increase depends upon the correlation of fading signals at different antennas [143]. The degradation in the performance, however, is small for correlation up to 0.5.

3) Diversity Combining and Adaptive Equalization: A comprehensive theory and computer simulation are presented in [68] and [69] to demonstrate the potential benefits of a system consisting of diversity combining and adaptive equalization using a tapped delay line filter behind each antenna element. Diversity combining is useful for overcoming the flat fading in mobile communications, whereas the equalizers are normally used to reduce intersymbol interferences in digital data transmission caused by delay spread. Thus, the combined structure offers an effective means to deal with the adverse effects of dispersive as well as flat fading. Many examples are provided to demonstrate the reduction in the average probability of the received bits for a QPSK modulated system using dual diversity and different types of equalizers under various environments. Similar results are also reported in [144]. A survey of adaptive equalization techniques along with their performance characteristics, limitations, implementation complexities, and use in TDMA digital mobile radio may be found in [145].

The importance of an antenna array using the tapped delay line filter to combat fading and to reduce cochannel interference in wideband TDMA mobile communications channels is further emphasized in [102] to increase the data rate beyond about 2 Mb/s. A discussion on the performance improvement of a QPSK modulated system employing an antenna array and a tapped delay line filter to combat multipath fading as a function of the number of taps may be found in [146].

D. Spectrum Efficiency and Capacity Improvement

Spectrum efficiency refers to the amount of traffic a given system with certain spectrum allocation could handle. An increase in the number of users of the mobile communications system without a loss of performance causes the spectrum efficiency to increase. Channel capacity refers to the maximum data rate a channel of given bandwidth could sustain. An improved channel capacity leads to more users of a specified data rate, implying a better spectrum efficiency. In that sense, the two terms are used interchangeably in this paper following the convention used in most of the mobile communications literature.

TDMA and CDMA result in an increase in channel capacity over the standard FDMA, allowing different time slots and different codes to be assigned to different users. Each increase is on the order of five to ten [11], [13], [147], [148]. Many studies have shown that this may be further improved by using multiple antennas and combining the signals received from them. First, the increased quality of service resulting from the reduced cochannel interferences and reduced multipath fading, as discussed, may be traded to increase the number of users. Thus, the use of an array results in an increase in channel capacity while the quality of the service provided by the system remains the same, that is, it is as good as that provided by a system using a single antenna. Second, an array may be used to create additional channels by forming multiple beams without any extra spectrum allocation, which results in potentially extra users and thus increases the spectrum efficiency. Fig. 9 shows a typical scenario of a base-station system employing an SDMA technique to serve many mobiles using only two frequencies [149].

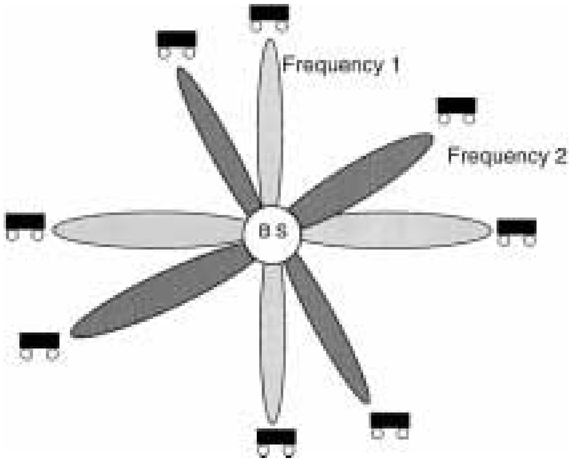


Fig. 9. Base station employing SDMA [149].

Fundamental limits on the maximum data rate and the capacity of a multiple antenna system in a Rayleigh fading environment are considered in [150]. The study concludes that two users with L antennas each, using optimum transmitter/receiver pairs, may be able to establish up to L channels, with each channel having about the same maximum data rate as that of a single channel. This and other studies on the impact of antenna diversity on the capacity of a wireless communications system [18] show the potential for a large capacity improvement in a communications system with the use of an antenna array. Salient features of some of these studies are now described to show the possible improvements in various configurations.

1) Multiple-Beam Antenna Array at the Base Station: A study in [81] indicates that by first using a base-station array in receive mode to locate the positions of mobiles in a cell and then transmitting in a multiplexed manner toward different clusters of mobiles one at a time using the same channel, the spectrum efficiency increases many times over and depends upon the number of elements in the array and the amount of scattering in the vicinity of the mobile. The study concludes that pointing beams with directed nulls toward other mobiles in a cell is a more efficient use of an array than reducing the cell size and the reuse distance. The use of a multiple-beam antenna array at the base station to improve spectral efficiency by resolving the angular distribution of mobiles is discussed in [70], where it is shown that spectral efficiency increases as the number of beams increases. Formulas, which are helpful in predicting interference reduction and capacity increase provided by a switched-beam antenna system employed by a base station, also predict that the number of subscribers in a cell increases as the number of beams increases [151].

2) Antenna Array at the Base Station Employing CDMA System: By using an array of antennas for a CDMA system, the number of mobiles a cell may be able to sustain increases manifold (on the order of the number of elements) for a given outage probability and BER [64], [152], [153]. For example, at an outage probability of 0.01, the system capacity increases from 31 for a single antenna system to 115 for a five-element array. Using an array of seven elements increases the capacity to 155 [153]. The study reported in [64] is for both mobile-to-base and base-to-mobile links and derives expressions for the outage probability considering the effect of cochannel interferences, whereas that reported in [128] is for the mobile-to-base link. The latter uses an RLS algorithm to estimate the weights of the array considered in simulation study and shows that capacity improvements on the order of 60% are possible using a four-element linear array.

3) Antenna Array at the Base Station Employing TDMA System: Examples of a TDMA system employing antenna arrays can be found in [18], [154], and [155]. The study reported in [155] uses the constant modulus adaptive algorithm for updating the weights of the array, whereas that in [18] and [154] uses the SMI algorithm and considers the IS-54 system for its study. IS-54 is the standard for digital mobile radio in North America. It is for a TDMA system where each user's slot contains a 28-b synchronization sequence along with 12-b for user identification and 260 data bits. The study uses the 28-b synchronization sequence as the reference signal and the user identification bits to make sure that the correct user's signal has been acquired. The study concludes that by using optimal combining at the base station with only two antennas, a frequency reuse factor of four is possible except in the worst cases at the boundaries of the cell. This could be further improved to a frequency reuse factor of three using dynamic channel assignment. Furthermore, it argues that frequency reuse in each cell is possible using four or five antennas. This is a substantial improvement compared to a frequency reuse factor of seven proposed for the current system.

4) Base-Station Array for Indoor-Mobile Communications: Multipath fading is a severe problem for indoor-mobile communications. However, due to the slow speed of mobiles, the fading rate is much lower inside buildings than outside, typically on the order of a few hertz. This means that there is enough time to compute antenna weights for optimal combining using slow converging algorithms such as LMS, which offers the advantages of robustness and computational efficiency along with the possibility of its implementation using a single chip, as discussed in [29] and [61]. Using theoretical analysis and computer simulations, it is argued in [29] that using optimal combining at a base station with L antennas may lead to up to L-fold capacity improvement in an indoor-mobile communications system. Furthermore, using a given number of antennas, a substantial capacity increase is also possible with a small increase in the SNR in a system. For example, a system using nine antennas may be able to achieve a six-fold capacity increase from a 10-dB increase in SNR per antenna.

The results presented in [156] indicate that replacing the omnidirectional base-station antenna with an adaptive array capable of forming multiple dynamically allocated beams steered toward the mobiles in a building complex reduces the delay spread substantially. This implies that by using an array, communications services may be extended to areas within buildings where delay spread is a serious problem, such as shopping centers, railway stations, and so on [157].

The use of multiple antennas also increases the capacity of the network by allowing many users to operate at the same channels, which then may be separated by blind estimation methods. Depending upon the propagation conditions, a large improvement in capacity is possible [87].

E. BER Improvement

A consequence of a reduction in cochannel interference and multipath fading by using an array in a mobile communications system to improve the communications quality is a reduction in BER and SER for a given SNR, or a reduction in required SNR for a given BER. This relationship has been recognized by many authors [18], [29], [61], [100], [133], [153], [158]–[160].

Experimental results reported in [100] for a high-speed GMSK mobile communications system show that a four-element adaptive array using the CMA is able to reduce the BER substantially compared to a single antenna system in a frequency-selective fading environment. The BER in a system normally reduces as the SNR is increased. These results, however, show that in an irreducible error rate environment, where no amount of SNR increase in a single antenna system would be able to reduce the BER, the system with an adaptive array is able to achieve large reductions.

A simulation study employing a multibeam system with cochannel interference capability [158] indicates that for a QPSK modulated system, the SER decreases as the number of elements in the array increases, and in the presence of multipath arrivals, this decrease is better when there is a dominant path than when there are equal energy paths.

A detailed analysis and computer study of the BER in a PSK system is presented in [61]. The study demonstrates that using an array with optimal combining can achieve a large reduction in BER. Analysis and experimental results reported in [18] indicate that by optimally combining the signals received on multiple antennas at the base station, one is able to cancel the effect of other users in a flat Rayleigh fading environment to such an extent that the average probability of errors behaves as if the other users were not present. Computer simulations show that similar results hold for frequency-selective channels. The use of optimal combining in an indoor environment is studied in [29] to demonstrate its effectiveness in reducing BER for a PSK system. An analysis of a PSK communications system presented in [159] also shows that the use of an adaptive array reduces BER for such a system.

An increase in the number of users in a cell normally causes an increase in the BER. The rate of this increase could be made lower by using an array compared to a single antenna system, as shown in [153]. The computer study uses the RLS algorithm to adjust the weights of an array and uses an expression for BER derived in [161]. For an omnidirectional antenna, it is given by

$$\mathrm{P_e} = \mathrm{Q}\left(\sqrt{\frac{3\mathrm{G}}{\mathrm{K}(1+8\beta)-1}}\right)$$

whereas for multiple antennas it becomes

$$\mathrm{P_e} = \mathrm{Q}\left(\sqrt{\frac{3\mathrm{GD}}{\mathrm{K}(1+8\beta)-1}}\right)$$

where $Q(X)$ is the standard Q-function showing the probability that $x > X$ for a zero mean, unit variance, Gaussian distributed random variable x, G is the processing gain of the CDMA system, K is the number of uses in the cell, $\beta = 0.05513$, and D is the directivity of the beam of the multiantenna system.

A comparison of the BER performance of a system using the conjugate gradient method and the RLS algorithm to adjust the weights of the array indicates the superiority of the former [133]. The BER performance of the adaptive antenna system using the LMS algorithm is compared with the maximum entropy method in [160] and with a method based upon spatial discrete Fourier transform [162] to show that both the latter methods provide better BER performance than the LMS algorithm.

F. Reduction in Outage Probability

Outage probability is the probability of a channel's being inoperative due to increased error rate in the received data. It may be caused by cochannel interference in a mobile communications system. Using an array helps to reduce the outage probability by decreasing cochannel interference. It decreases as the number of beams used by a base station for land mobiles increases in a multibeam adaptive antenna system [70]. The system analysis presented in [70] consists of calculating the outage probability considering one cochannel cell as well as six cochannel cells. The analysis shows that the reduction in outage probability is slightly less in the six-cochannel-cell case compared to the one-cochannel-cell case. Results on the outage probability of the system using an omnidirectional base-station antenna can be found in [28].

A detailed analysis of the outage probability of a system with cochannel interferences in a Nakagami fading environment using diversity combining is presented in [66], [163], and [164]. The study in [66] is done for various combining methods as a function of the number of elements in the array as well as the number of cochannel interferences, and shows that the use of diversity combining reduces the outage probability. The technique to calculate the outage probability of a cellular mobile system presented in [163] appears to be simpler to use than that in [66].

Results on the improvement in the outage probability using an array employing optimal combining are presented in [30] and [69]. The study in [69] concludes by theoretical analysis and computer simulation that the use of diversity combining results in a substantial reduction in the outage probability, whereas the results in [30] are derived from experiments conducted in an open-plan office environment and compare selection diversity and optimal combining, showing that the latter results in a reduced threshold for a given outage probability.

A study [128] of a CDMA system using a base-station antenna array derives equations for predicting the outage probability of the system for the uplink case, that is, by considering the signals arriving from mobiles. The study uses user-specific codes to determine the array response vector by correlating the array output with the code for the desired user. The estimated array response vector is then used for determining the array weight employing the optimal beam-forming technique. Numerical examples confirm that the outage probability increases by an increase in the number of users in a cell as well as by the presence of multipath. Furthermore, for a given outage probability, it shows that the use of an array allows an increase in the number of users in a cell, resulting in an increase in system capacity. The increase in capacity is on the order of the number of elements in an array [152].

G. Increase in Transmission Efficiency

Electronically steerable antennas are directive compared to fixed omnidirectional antennas, that is, they have high gains in the direction where the beam is pointing. This fact may be useful in extending the range of a base station, resulting in a bigger cell size, or may be used to reduce the transmitted power of the mobiles. A laboratory experiment [165] indicates that a reduction from 10 W to 250 mW is possible. This follows from the fact that by using a highly directive antenna, the base station may be able to pick a weaker signal within the cell than by using an omnidirectional antenna. This in turn means that the mobile has to transmit less power [18] and its battery will last longer, or it would be able to use a smaller battery, resulting in a smaller size and weight, which is important for hand-held mobiles.

It is also advantageous to use an antenna array at the base station in transmit mode. In a single antenna system, all the power of the base station is transmitted by one antenna. However, when the base station uses an array of antennas and transmits the same amount of power as that of the single antenna system, the power transmitted by each antenna of the array is much lower compared to the case where the total power is transmitted by one antenna. Furthermore, for a given SNR at the mobile site, the base station using an array has to transmit less power compared to the single omnidirectional antenna case due to the directive nature of the array. This further reduces the power transmitted by each antenna. These reductions in transmitted power level using an array allow the use of electronic components of lower power rating in the transmitting circuitry. This results in a lower system cost, leading to a more efficient transmission system [124].

H. Dynamic Channel Assignment

In mobile communications, channels are generally assigned in a fixed manner depending upon the position of a mobile and the available channels in the cell where the mobile is positioned. As a mobile crosses the cell boundary, a new channel is assigned. In this arrangement, the number of channels in a cell are normally fixed. The use of an array provides an opportunity to change the cell boundary and thus to allocate the number of channels in each cell as the demand changes due to changed traffic situations. This provides the means whereby a mobile or group of mobiles may be tracked as it moves and the cell boundary may be adjusted to suit this group.

Dynamic channel assignment is also possible in a fixed cell boundary system and may be able to reduce the frequency reuse factor up to a point where frequency reuse in each cell might be possible [18]. There may be situations when it is not possible to reduce cochannel interferences in certain channels, and the call may have to be dropped due to large BER caused by strong interferences. Such a situation may arise when a desired mobile is close to the cell boundary and the cochannel mobiles are near the desired mobile's base station [18]. This could be avoided by dynamic channel assignment, whereby the channel of a user is changed when the interference is above a certain level.

I. Reduction in Handoff Rate

When the number of mobiles in a cell exceeds its capacity, cell splitting is used to create new cells, each with its own base station and new frequency assignment. A consequence of this is an increased handoff due to reduced cell size. This may be reduced using an array of antennas. Instead of cell splitting, the capacity is increased by creating independent beams using more antennas. Each beam is adapted or adjusted as the mobile locations change. The beam follows a cluster of mobiles or a single mobile, as the case may be, and no handoff is necessary as long as the mobiles served by different beams using the same frequency do not cross each other. A comparison of the SDMA method with other schemes indicates that the former offers many practical advantages over the other methods of capacity increase [149].

J. Reduction in Cross Talks

Cross talks may be caused by unknown propagation conditions when an array is transmitting multiple cochannel signals to several receivers. Adaptive transmitters based upon the feedback obtained from probing the mobiles could help eliminate this problem [118]. The mechanism works by transmitting a probing signal periodically. The received feedback from mobiles is used to identify the propagation conditions, and this information is then incorporated into the beam-forming mechanism.

K. Cost-Effective Implementation

The use of multiple antennas on direct broadcast satellites leads to a system that is cost effective due to its light weight, reduced power requirements, flexibility and robustness of antenna design, ease of pattern control, and use of more solid-state devices. It also provides a larger aperture and mechanism for error compensation by signal processing [107].

L. Angular Spreading and Its Impact on Performance

Angular spreading refers to a situation where a transmitted signal gets scattered in the vicinity of the source and a signal arrives at a receiver within a range of angles. In a base-mobile communications system, where the base-station antenna is normally high away from the ground and a mobile is close to the ground, the angular dispersion is more pronounced in the vicinity of the mobile and arrives at the base station with an angular distribution. The range of angles becomes smaller as the distance between a mobile and the base increases. Experimental results indicate that an angular spreading of about 3° results from a distance of 1 km [75].

Various models of the scattering situation have been reported in the literature, assuming the multipath signals to be distributed uniformly within the spread angle [71], [143], [166] as well as with the Gaussian distribution [81], [167]. Selection of the distribution function, however, does not appear to be critical as long as the spread is small around the nominal direction [75].

A dispersion of the radio environment results in the distortion of the perceived antenna side-lobe levels at the base station [168] as well as an increase in correlation of fading at different elements of the array [143], both of which affect the performance of the system. The problem of fading correlations is studied in [169]. It is shown by deriving the relationships between the angle of arrival, beamwidth, and correlation of fading that a larger antenna spacing is required to reduce the correlation when the angle of arrival approaches parallel to the array, resulting in a reduction of the beamwidth.

An increased correlation of fading between various elements greater than 0.8 causes signals at all of the antennas to fade away simultaneously, rendering an array in the maximal ratio combining mode ineffective against fading correction [31]. The array, however, is able to suppress interferences, as independent fading is not required for interference suppression [143]. A detailed investigation of the effect of fading correlation on the performance of adaptive arrays to combat fading is carried out in [143]. The investigation concludes that correlation of up to 0.5

causes little degradation, but a higher correlation decreases performance significantly.

Transmission strategies in a multihop packet radio network normally are concerned with designing routing algorithms for sending packets from the source to the destination. A study presented in [170] indicates that fading affects the performance of a multihop system using routing algorithms. This, however, does not seem to be the case for a single-hop system.

M. Cost, Complexity, and Network Implication

It follows from the discussion in previous sections that a system using an adaptive array to improve the performance of mobile communications requires estimation and optimization of numerous time-varying system parameters in a dynamically changing environment.

Though the specific parameters would depend upon the type of system under consideration and the mode of array processing incorporated in the system, it is clear that implementation of such a system would require a complex network and system architecture.

Implementation of schemes such as dynamic handoff, dynamic channel assignment, dynamic beam shaping to incorporate clusters of mobiles, dynamic nulling of cochannel interferences, and procurement of the knowledge of the desired mobile—in the form of a reference signal, its direction, or the array response vector associated with the mobile—for the purpose of beam forming would require a complex control structure. Then there is a question of the time required to update the system parameters.

The system requires quick updates on the positions of fast moving mobiles, whereas its response time is limited by the time required by DOA estimation and tracking schemes to update the positions of mobiles and by the beam-forming algorithms to converge to a satisfactory level. Though some of these algorithms may be implemented in parallel to increase the signal processing power, this adds to the cost of the system.

The system cost includes not only the cost of building hardware to implement the control structure but the cost of building active antennas along with the required phase shifters, high-power amplifiers, and circuitry associated to drive these components. Most of these components are excessively expensive at present and are not required for a system without SDMA. This is currently a disadvantage of using an adaptive array in mobile communications. Apart from the cost of implementation, many reliability questions also need careful consideration.

Some network architecture and traffic-implication issues of mobile communications in general are considered in [48] and [171]–[173]. However, there is no consideration of the complications arising from the use of an array in such systems.

VI. FEASIBILITY OF ANTENNA ARRAY SYSTEMS

In this section, developments in the design of arrays, antenna elements suitable for arrays, tracking systems required for antenna arrays, and experimental studies to demonstrate the suitability of the arrays for mobile communications are briefly discussed.

A. Developments of Antenna Elements and Arrays

Antenna design is one of the biggest challenges in mobile communications system development. An antenna mounted on a vehicle has stringent requirements. Mechanically, it must conform with the vehicle as much possible for aesthetic and aerodynamic reasons. It must be cheap and suitable for mass production, easy to install, strong enough to withstand forces during vehicle movement, light weight, and compact. Electrically, it should have the required gain, bandwidth, wide-angle scanning capability, and low losses.

The gain of an antenna is at its maximum in the boresight direction of the antenna and drops off in directions away from the boresight direction. The amount of gain required depends upon the C/N ratio available at the antenna sight for receiving antennas, the C/N ratio required by the receiver, and the losses caused by cables, mixers, and the receiving circuitry in general as well as the noise generated therein. All of these losses and noise in the receiving systems are normally specified by the system noise temperature. It is not the physical temperature of the system but indicates that a noise source at this temperature would generate the same amount of noise as that generated by the system referred to at the antenna terminal.

The concept of noise temperature follows from the fact that a noise source at temperature T (absolute temperature) would generate the noise power $N = kTB$, with k denoting Boltzmann's constant and B the bandwidth of interest. Thus, a device of bandwidth B generating this much noise is said to have the noise temperature T. In view of this, the receiving antennas are also specified by their gain-to-noise temperature ratio, in short G/T dB/K. An antenna used for voice and high-speed data around 20 Kb/s typically is of a medium gain around 11 dBi, which amounts to G/T around -13 dB/K.

For transmitting antennas, the antenna gain and amount of power supplied to the antenna are combined, and EIRP is normally used to specify it. It is a product of the supplied power and the antenna gain and indicates that for the calculation of the flux density at R distance away from this source, the EIRP is the power radiated by an isotropic source, that is, a source radiating uniformly in all directions. The flux density at a point R distance away from an isotropic source is given by the transmitted power divided by the surface area of a sphere of radius R centered at the source, $4\pi \mathrm{R}^2$.

In recent years, there has been a wide range of interest in developing antenna elements, arrays of antennas, feed systems suitable for such arrays, and other related components covering a wide range of frequency bands. The frequency bands in satellite communications literature are normally referred to by letters. The frequencies for L-band typically are around 1.5 GHz for downlink and 1.6 GHz for uplink. The band is denoted as a 1.6/1.5 GHz band. Higher frequencies are used for uplink and lower ones for downlink

Table 3 Letter Designation for the Frequency Spectrum

Letter Band	Nominal Frequency Range
HF	3-30 MHz
VHF	30-300 MHz
UHF	300-1000 MHz
L	1-2 GHz
S	2-4 GHz
C	4-8 GHz
X	8-12 GHz
Ku	12-18 GHz
K	18-27 GHz
Ka	27-40 GHz
V	40-75 GHz
W	75-110 GHz
mm	110-300 GHz

because transmission loss increases as the frequency of transmission increases, requiring more transmitted power, and the fact that it is easy to generate power at the ground compared to onboard a satellite.

The other bands include the S-band covering 2.5/2.4 GHz, C-band covering 6/5 GHz, Ku-band covering 14/12 GHz, and Ka-band covering 30/20 GHz. Letter designation for the entire frequency spectrum as defined by IEEE Standard 521 [174] is provided in Table 3.

An excellent treatment of vehicle antennas for mobile communications is provided in [175] and concludes that the MMIC phased array antenna technology will play a key role in future mobile communications. Using this technology, a hand-held portable monitor consisting of an antenna array along with its feed circuitry, low noise amplifiers, power amplifiers, phase shifters, and so on will be able to access a satellite in the Ka-band [176].

Current developments in basic antenna elements suitable for building an array for vehicle antennas in a satellite-to-mobile communications system include microstrip patch antennas [177]–[180], a ring patch [181], slot antennas [182], [183], crossed dipole antennas [184], traveling-wave-type antennas [185], and spiral-shaped antennas [186]. Many of these variously shaped building-block antennas are fabricated using microstrip technology. A microstrip consists of a nonconducting surface referred to as a substrate covered with a conductor. The shape of an antenna is formed by an etching process to remove the unwanted conductor. The thickness of the substrate, number of layers, and type of material used for the substrate are among the parameters to control the radiation properties of the antenna. Vehicle antennas for a base-station communications system providing space diversity include a trunk lid antenna and a disk-loaded monopole antenna [187] operating at 900 MHz.

A slotted disk antenna is made up of circular rings of slots. The circular rings are not made of continuous conductors but have gaps at regular intervals. The inter-ring spacing, gap size, and slot width are the design parameters. A center-fed slotted disk antenna suitable for vehicle mounting is reported in [183]. Discussions on a linear tapered slot antenna may be found in [188]. A variation of the linear tapered slot antenna reported in [182] has the capability of easy packaging and integration with MMIC devices with a gain of 9 dBi at the design frequency of 10 GHz.

A circular patch antenna featuring a gain of 8.5 dBi, compensated by an inductance–capacitance circuit to increase its band, and placed in a cavity to isolate it from other antennas has been reported in [177]. The patch antennas may be stacked to increase the gain, as demonstrated in [181], by using two sets of ring antennas to obtain a gain of around 9 dBi. The development and fabrication of arrays using circular patch antennas has been discussed in the literature, including conformal arrays of semispherical and partially spherical shapes using 16 elements [180] and a planar array using alternative elements for transmitting and receiving a signal [178].

Array design suitable for mobile communications is an active area of research, and many prototypes have been built, analyzed, and tested. These designs include:

- an eight-element array of spiral antennas with a mechanical steering capability with a gain of 15 dBi [186];
- a 12-element array mounted on a truncated pyramid with electronic steering capability with a gain of 10 dBi [185];
- a single-layer slotted leaky waveguide array with 16 waveguides suitable for direct broadcast reception from a satellite in Japan [189];
- a spherical array with beam-forming capabilities [180];
- a set of four planar arrays, each with 32 patch antennas suitable to operate at 12 GHz for mobile reception of direct broadcasting satellites in Germany [112].

An analysis of the slotted leaky waveguide array system can be found in [190]–[192]. These and other array design activities [109], [111], [193], [194] demonstrate the suitability of antenna arrays for mobile communications systems from an antenna-design point of view.

B. Tracking System

Land-mobile satellite communications using a directional antenna requires knowledge of the direction of the satellite to steer the beam toward it. As the vehicle moves, tracking the satellite becomes important. The accuracy of the tracking depends upon the type of antenna system. For example, in a system where the shape of the antenna pattern remains fixed during the steering process—such as a mechanically steered array, where the boresight direction of the array is pointed toward the satellite, as well as an electronically steered array, where only phase is adjusted to steer the beam—the accuracy required in the direction of the satellite is on the order of a half beamwidth, as any higher error would put the satellite out of the main lobe. It is argued in [111] that the maximum acquisition time permitted for an electronically steered array is 10 s and the time required from acquisition to optimum pointing is less than 2 s. A tracking system needs to take into account the maneuvering of vehicles resulting in velocities on the order of 45°/s and accelerations up to $45°/s^2$ [111], as well the convergence speed of the algorithm used when an adaptive scheme is employed to adjust the array weights [154].

Two types of systems are normally used for satellite tracking purposes: a closed-loop system where the received signal from a satellite is used and an open-loop system, which does not require this signal.

A classical closed-loop method known as a monopulse scheme generates two signals, sum and difference, from the signal received from a satellite. A sum signal is generated by adding the two signals in phase and is used to recover information. The difference signal is generated by adding the two signals from symmetrical elements in the array out of phase, such that when the beam is pointing to the satellite, a null is formed. A number of null steering algorithms exist in the literature [195], [196]. In the course of vehicle movement when the beam is not pointing correctly, the array is steered to achieve the perfect null in the difference beam. A variation on this scheme is implemented in [185] using an array operating at L-band. The results of the field trial indicate the feasibility of a low-cost antenna system [185].

An open-loop system does not require the signal from the satellite in the form of feedback. It uses the output from sensors such as a magnetic compass and optical fiber gyro and is useful in situations where the satellite signal is not stable. This is the case for a land-mobile communications system compared to a maritime communications system [197]. A phased array tracking system using a hybrid of geomagnetic sensors and optical fiber gyro shows a good performance, as discussed in [197] and [198]. Geometric sensors provide the absolute direction, whereas the gyros provide the relative variations in direction and are useful to compliment the sensors when their capabilities are hindered by local environment conditions such as buildings, bridges, and power poles [197].

C. Experimental Systems

A number of projects have been undertaken to conduct experiments involving antenna arrays by developing systems and designing hardware. The results of the field trials have been reported in the literature.

A project [30] known as the Smart Communication Antenna Research Program (SCARP) has been undertaken by ERA Technology, U.K., and supported by many industrial organizations in the United Kingdom. It involves eight dipole antennas mounted on an eight-faced pyramid to provide hemispherical coverage and has studied the performance of a system in the fading channels using a reference signal to update the weights of optimal combining. The weights are updated using normalized least-squares algorithms from a set of 100 snapshots. The results indicate that the optimal combiner is able to track the time-varying environment without degrading the signal quality. Furthermore, a comparison of diversity combining and optimal combining shows that an eight-element array provides an improvement in SNR of around 5 dB compared to a single antenna using diversity combining and a further 5 dB using optimal combining. The system is designed to operate at 1.89 GHz and concludes that the adaptive antenna array techniques have now reached a stage where they may be considered for commercial mobile radio communications.

An experiment conducted in central Tokyo using a four-element antenna array mounted on the roof of a van shows that when weights are updated using the CMA, the antenna pattern may be adjusted by digital beam-forming concepts to cancel delayed signal to overcome multipath fading [100], [125]. The system employs a TDMA scheme and uses Gaussian-filtered minimum shift keying transmission at a rate of 256 Kb/s. The system operates at 1.5 GHz, and the experimental results demonstrate that the array is successful in directing nulls toward the delayed signals due to multipath. The study concludes by suggesting that the adaptive arrays are expected to function well as a countermeasure to selective fading in a high-speed communications environment.

An experiment conducted in south France using arrays of elements operating at L-band used a circular as well as a pyramid-shaped array of five patched elements [199]. It used a reference signal generated from the demodulator and used the matrix inversion algorithm to update the weights. The results at the transmission rate of 200 Kb/s indicate that the digitally implemented algorithm is able to adjust the weights in multipath conditions. The experimental and simulation results show the tracking, jammer canceling, and multipath correcting properties of the algorithm. The study concludes that for a further improvement in the receiver performance, the array needs to be enlarged using more elements.

The other system developments and experiments to carry out the feasibility studies of antenna arrays for mobile communications include the study of an array mounted on an aircraft using the ETS-V satellite in Japan [115], the study of an array mounted on the roof of a car to receive the German SAT-2 [112], a feasibility study of a frequency scanning satellite system [105], [106], hardware implementation of a four-element adaptive array for high-speed digital mobile communications [125], and a laboratory prototype of a low-power system for mobile communications [165]. The setting up of a consortium to investigate the feasibility of adaptive array technology in third-generation mobile communications systems in Europe is reported in [157].

Some other developments reported in the literature related to systems employing adaptive antennas include a multiway power divider for a planar slotted waveguide array suitable for vehicles to communicate with direct broadcasting satellites [190], a digital demultiplexer for an adaptive satellite array [110], a Ku-band solid-state power amplifier for European satellite systems, and a low-cost feed system suitable for vehicle antennas, which does not require the use of phase shifters at each element [111].

An interesting overview of key payload technologies for future satellite personal communications, dealing with payload architectures involving onboard digital signal processing and narrow-band beam forming suitable for MEO and GEO satellites, is provided in [200]. It discusses many implementation issues relevant to present and future activities of the ESA.

VII. CONCLUDING REMARKS

This paper has attempted to provide a snapshot of a dynamic and fast-growing industry at a level where nonexperts in the field are able to appreciate it. After presenting an overview of mobile communications, this paper showed the current state of research in the use of antenna arrays to meet the projected demand of increased channel capacity by describing how an array may be used in various mobile communications systems and what improvements may be expected using such systems. Many theoretical, experimental, and computer-simulated studies were cited to show the feasibility of such systems.

This paper has painted a very bright picture of the field and at times appears ambitious. Even though many studies point toward the feasibility of such systems, the systems are in their infancy, particularly when it comes to implementation issues. Many questions related to network architecture, system architecture, and required control strategies need answering before cost-effective mobile communications systems using adaptive antenna arrays can be developed.

ACKNOWLEDGMENT

The author wishes to thank Lt. Col. M. Ryan for providing the software to manage the reference list contained in this paper, J. Calder for his constant encouragement during the course of writing this paper, and the anonymous reviewers for their helpful comments.

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