Chapter 2

Mobile Communication System and Smart Antennas

2.1 Introduction

Wireless communication has come a long way since the invention of the wireless concept by Marconi in 1897. In recent years there has been an explosive growth in the number of wireless users, particularly in the area of mobile communication. While the step from the first to the second generation of wireless systems mainly brought the transition from analog to digital, the third generation (3G) systems are driven by the fast rise of the Internet and ever increasing need for high-speed data transmission capabilities while on the move. The requirement for high-speed data transmission, especially packet data transmission, brings a whole new set of challenges for 3G systems. With substantially enhanced capacity, quality, and data rates, 3G wireless technologies provides customers with high-speed wireless access to the Internet and multimedia services, anytime and anywhere.

The demand on information exchange has pushed the development of wireless communication systems at an unprecedented pace. In future, wireless mobile systems will be more sophisticated and more widespread. This growth has triggered an enormous demand not only for capacity but also better coverage and higher quality of service [3] [4].

As the wireless network matures and more users are added, a desire for high system capacity is inevitable. The radio spectrum for wireless communications is a limited
resource; it will be stretched out to its limit to accommodate various current and emerging wireless services. To meet the capacity need of the explosive growth of wireless communications, new techniques are required to improve the quality and spectrum efficiency of communications over radio channels. Several new technologies have been explored and deployed in this regard to make effective use of the limited resources. One way to improve capacity is by using the concept of cellular technology, which involves dividing a large coverage zone into small hexagonal cells.

The finite spectrum is made available throughout a geographical area by dividing the region into a number of smaller cells. In analog cellular systems, each cell uses a portion of the spectrum. Cells, which are sufficiently far apart, can reuse the same spectrum resources [5].

Each cell is served by a base transceiver station (BTS), which is responsible for handling communications with mobile users within its respective cell. When a mobile user crosses the boundary of two cells, its communication channel is handed off to the BTS in the new cell. A group of BTSs are connected to a base station controller (BSC), which may be integrated into a cell site. The BSC manages radio resources and network functions between multiple BTSs. The BSC is connected to the mobile switching center (MSC), which is responsible for all call handling as well as interfaces to other switching elements. The MSC exchanges voice traffic with the public switching telephone network (PSTN) or the integrated service digital network (ISDN), or exchanges data traffic with Internet-protocol networks. The top-level architecture of a cellular network is illustrated in Figure 2.1.
In this chapter the overview of Mobile communication system and Smart antenna fundamentals is given, which includes; Discussion on types of mobile communication Systems, Radio propagation, Multipath fading, Digital Modulation, Multiple access, i.e., FDMA, TDMA, CDMA, SDMA, Array Theory, Smart Antenna Technology, Switched Beam antennas, Adaptive Antenna Arrays, Their comparison, and Advantages of Smart Antenna Technology in Wireless Communications.

2.2 Types of Systems

In a mobile communication system at least one of the transceivers is mobile. It may be on board a vehicle that can move at high speeds, or it may be a handheld unit used by a pedestrian. Basic types of systems include base/mobile, peer-to-peer, repeater, and mobile satellite systems. In a base/mobile system, a base station connected to a public network communicates with a mobile unit. This gives the mobile unit access to the public network. More than one mobile at a time can be supported if a different channel is assigned to each user [13]. In most systems, channels are assigned to users as needed rather than giving each user a dedicated channel that is reserved for that user at all times. This is called trunking and allows large numbers of users to be supported.
with a limited number of available channels, with a small probability that any given call will be blocked because all channels are busy.

Cellular telephony uses the base/mobile configuration to give mobile users access to the public switched telephone network, as shown in Fig. 2.2 (a). In peer-to-peer systems, mobile units communicate directly with each other. Mobile units sharing a frequency channel can communicate with one another, and independent conversations can take place on different channels. Many amateurs, and most CB radio contacts fit into this peer-to-peer model, as shown in Fig. 2.2 (b). In peer-to-peer systems, a mobile can sometimes hear only one of two other mobiles that are using a channel, when a total of three users are active [12].

![Diagram of mobile radio systems](image.png)

**Figure 2.2: Mobile radio systems:** (a) mobile/base, (b) peer-to-peer, (c) repeater, (d) mobile satellite

Fig. 2.2 (c) shows a repeater system. In this system, all users transmit on one channel and listen on a second channel. The repeater, a transceiver that is located at a high point, retransmits the signals with greater power on the second channel. In this system, all users can communicate with each other using one pair of frequencies. A repeater system allows communication over a much greater range than in a direct peer-to-peer
system. Repeaters are used for public services and some amateur radio operations at VHF and UHF frequencies. In a mobile satellite system, one or more satellites relays signals between a mobile user and an earth-based base station or “gateway” that connects to the public switched network, as shown in Fig. 2.2 (d). The large distances and high speeds of the satellites introduce some difficulties, but a system of this type can provide worldwide coverage.

2.3 Radio Propagation

The mobile radio propagation environment places fundamental limitations on the performance of wireless communication systems. Signals arrive at a receiver via a scattering mechanism and the existence of multipath with different time delays; attenuations and phases give rise to a highly complex, time-varying, transmission channel. The radio channel in a wireless communication system is often characterized by multipath propagation. A fading signal results from interference between multipath components at the receiver.

Due to multipath propagation, the composite received signal is the sum of the signals arriving along different paths. As shown in Figure 2.3, except for the line-of-sight (LOS) path, all paths are going through at least one order of reflection or diffraction before arriving at the receiver [14].

The average received signal power decreases as the distance from transmitter increases. In addition, phase alignment or cancellation of arriving paths results in considerable amplitude fluctuation of the composite received signal from one location to another. The time dispersion and random amplitude and phase fluctuations in the received signal, a set of characteristics of channel effect, is termed multipath fading.
The multipath channel impulse response is represented by
\[ h(\tau; t) = \sum_{i=1}^{L} \beta_i(t) \delta(\tau - \tau_i(t)) \]
where \( L \) is the number of paths, \( \beta_i \) and \( \tau_i \) represent the complex gain and the delay of the \( i^{th} \) arriving path.

**Delay Spread**: The span of the time dispersion of arriving paths is referred to as *multipath delay spread* of the channel. Taken into account the signal intensity over the delay span, a good measure is the *root mean square (rms) delay spread*, given by
\[ \tau_{rms} = \sqrt{\tau^2 - (\bar{\tau})^2} \]
where,
\[ \tau^2 = \frac{\sum_{i} \tau_i^n |\beta_i|^2}{\sum |\beta_i|^2}, \quad n = 1, 2 \]
The inverse of the rms delay spread is referred to as the \textit{coherence bandwidth} of the channel. Wideband signal has high data rate in comparison to the coherence bandwidth.

\textbf{Doppler Spread}: With the relative motion of the transmitter and the receiver, or the change of the transmission media, e.g. movement of reflectors, the received signal experiences Doppler frequency shift. The spreading within the maximum frequency shift is referred to as the \textit{Doppler spread}. The adaptation time of algorithms used in the receiver must be faster than the Doppler spread of the channel in order to accurately track the fluctuations in the received signal [20].

\textbf{2.4 Multipath Fading Propagation Mechanisms}

Received signals in terrestrial communications typically have several multipath components. Multipath fading occurs when there exist more than one signal component and the relative phases between them change. The causes of the relative phase changes are the positional change of the transmitter (Tx), receiver (Rx), or objects along the propagation path over time. The relative phases of the received signals change as the mobile moves. Depending on the relative phases of the signals, they can reinforce each other or cancel each other. In the latter case a fade results. As the receiver is moved the received signal power undergoes variations, resulting in a fading envelope that can be measured.

Diversity systems that use signals received by two or more antennas can combat this effect. The difference in path length between multipath components causes them to arrive with different delays. This causes intersymbol interference in digital systems, if the difference is significant in relation to the symbol period. Below we review some typical propagation conditions [3].

\textit{Direct Propagation}

When there exists a visible straight path between the base station (BS) antenna and the mobile terminal antenna and no other multipath component exists, as shown in Figure
2.4(a), the received signal power attenuation conforms to free space propagation. This direct signal component is called as a line-of-sight (LOS) component. If the received signal has the LOS component only, it does not experience multipath fading. However, there always exist multipath components other than the LOS component between the transmitter and the receiver in real terrestrial communication systems. Under real propagation conditions, various terrestrial objects such as mountains, buildings, and hills frequently block the LOS component.

**Reflection**

Reflection occurs when a radio wave impinges on an object that is very large compared to its wavelength. Examples of such objects are the earth’s surface, buildings, and walls as shown in Figure 2.4(b).

**Diffraction**

When the radio path between the transmitter and receiver is obstructed, diffraction occurs from edges, such as building corners, causing energy to reach shadowed regions that have no LOS component from the transmitter as shown in Figure 2.4(c).

**Scattering**

Scattering occurs when the wave travels through or reflected from an object with dimensions smaller than the wavelength. If the surface of the scattering object is random, the signal energy is scattered in many directions as shown in Figure 2.4(d). Rough surfaces, small objects, or other irregularities in the channel cause scattering.
2.5 Digital modulation

Digital modulation can be used for mobile communication. In digital modulation formats, the signal to be transmitted is binary data that may or may not represent an analog signal that has been quantized and digitized. At any given time, the transmitter sends one of a discrete set of symbols, each of which represents one or more bits. In digital modulation, each symbol typically occupies a finite time slot, and this requires
the receiver to be synchronized to the transmitter so that the receiver demodulates each symbol in turn [20].

The simplest type of digital modulation is on-off keying (OOK), in which the carrier is turned on and off depending on the value of each bit. In Amplitude-shift keying (ASK), the amplitude of the transmitted signal is varied in discrete steps, with each level representing one or more bits. Frequency-shift keying (FSK) uses discrete frequencies as its symbols. A variation of this is AFSK, in which a carrier is modulated with a base-band FSK signal using one of the analog techniques, typically FM. Phase-shift keying or PSK uses a carrier of a constant nominal frequency and each symbol is represented by a different phase shift from a reference phase that is maintained for the symbol period. Differentially encoded PSK or DPSK is similar to PSK except that each symbol is represented by a phase shift relative to the previously transmitted signal.

This is desirable in mobile systems where the phase of the received signal changes rapidly and it is difficult to maintain a constant phase reference. Quadrature-amplitude modulation (QAM) uses symbols that vary in both amplitude and phase. It can potentially provide many more symbols than the other techniques but it is very sensitive to changes in the channel and thus is difficult to implement for mobile systems. QAM is appropriate for fixed microwave and fiber-optic systems where it can support very high data rates [21].

2.5.1 Spread spectrum techniques

Co-channel interference between digitally modulated signals can be reduced by spreading each signal over a wider bandwidth according to a code that is known by both the transmitter and the receiver. The code is used to extract the desired signal from the interference. Three strategies that can be used are frequency hopping, direct-sequence spread spectrum (DSSS), and ultra-wideband.
In frequency-hopping systems, the transmitter transmits on a predetermined repeating sequence of different frequencies. This includes slow frequency-hopping systems, in which two or more symbols are transmitted on each frequency, and fast frequency hopping systems, in which one or more hops occur for each data symbol.

In direct-sequence spread spectrum systems, the bit stream is multiplied by a binary pseudo-noise or PN sequence. The PN sequence is incremented at a rate that is higher than the bit rate and each data bit is broken into several chips, where each chip is the product of the data bit and a digit of the PN sequence. This process spreads the signal power over a wide bandwidth. The signal is recovered by correlating the received signal with an identical PN sequence. When the PN sequence at the receiver is aligned with that of the transmitter, the correlation of the two sequences is high and the product of the two yields an estimate of the transmitted signal. Interfering signals that are not correlated with the PN sequence are significantly attenuated in this process. DSSS can also be used as a form of multiple access by assigning different PN sequences that have low cross-correlations to several users. The users can then share the same frequency spectrum because only the desired transmitter will have a high correlation with the PN code used at each receiver. Another, relatively new technique is called ultra-wideband or UWB. Current systems transmit base-band pulses that have a bandwidth of 1 GHz or more. Pulse-position modulation is used, where value of a given transmitted symbol is given by the precise timing of the pulse.

2.6 Multiple Access (Sharing the Radio Spectrum)

A limited amount of bandwidth is allocated for wireless services. A wireless system is required to accommodate as many users as possible by effectively sharing the limited bandwidth. Therefore, in the field of communications, the term multiple access could be defined as a means of allowing multiple users to simultaneously share the finite bandwidth with least possible degradation in the performance of the system [22]. The four basic schemes of multiple accesses are:

1. Frequency Division Multiple Access (FDMA)
2. Time Division Multiple Access (TDMA)
3. Code Division Multiple Access (CDMA)
4. Space Division Multiple Access (SDMA)

2.6.1 Frequency Division Multiple Access (FDMA)

FDMA is one of the earliest multiple-access techniques for cellular systems when continuous transmission is required for analog services. In this technique the bandwidth is divided into a number of channels and distributed among users with a finite portion of bandwidth for permanent use as illustrated in figure 2.5.

![Figure 2.5: Channel usages by FDMA](image)

The channels are assigned only when demanded by the users. Therefore when a channel is not in use it becomes a wasted resource. FDMA channels have narrow bandwidth (30Khz) and therefore they are usually implemented in narrowband systems. Since the user has his portion of the bandwidth all the time, FDMA does not require synchronization or timing control, which makes it algorithmically simple. Even though no two users use the same frequency band at the same time, guard bands are introduced between frequency bands to minimize adjacent channel interference. Guard bands are unused frequency slots that separate neighboring channels. This leads to a waste of bandwidth. When continuous transmission is not required, bandwidth goes wasted since it is not being utilized for a portion of the time. In wireless communications, FDMA achieves simultaneous transmission and reception by using Frequency division duplexing (FDD). In order for both the transmitter and the receiver to operate at the same time, FDD requires duplexers. The requirement of duplexers in the FDMA system makes it expensive [23].
2.6.2 Time Division Multiple Access (TDMA)

In digital systems, continuous transmission is not required because users do not use the allotted bandwidth all the time. In such systems, TDMA is a complimentary access technique to FDMA. Global Systems for Mobile communications (GSM) uses the TDMA technique. In TDMA, the entire bandwidth is available to the user but only for a finite period of time. In most cases the available bandwidth is divided into fewer channels compared to FDMA and the users are allotted time slots during which they have the entire channel bandwidth at their disposal. This is illustrated in figure 2.6.

![Figure 2.6: Channel usages by TDMA](image)

In TDMA the channel capacity in bits/s is used to the fullest extent possible, and the bit stream is divided into frames and the frames are divided into time slots that are allocated among the users.

TDMA requires careful time synchronization since users share the bandwidth in the frequency domain. Since the number of channels are less, inter channel interference is almost negligible, hence the guard time between the channels is considerably smaller. Guard time is a spacing in time between the TDMA bursts. In cellular communications, when a user moves from one cell to another there is a chance that user could experience a call loss if there are no free time slots available. TDMA uses different time slots for transmission and reception. This type of duplexing is referred to as Time division duplexing (TDD) [29]. TDD does not require duplexers.
2.6.3 Code Division Multiple Access (CDMA)

In CDMA, all the users occupy the same bandwidth, however they are all assigned separate codes, which differentiates them from each other as shown in figure 2.7.

![Figure 2.7: Channel usages by CDMA](image)

CDMA systems utilize a spread spectrum technique in which a spreading signal, which is uncorrelated to the signal and has a large bandwidth, is used to spread the narrow band message signal. Direct Sequence Spread Spectrum (DS-SS) is most commonly used for CDMA. In DS-SS, the message signal is multiplied by a Pseudo Random Noise Code (PN code), which has noise-like properties. Each user has his own codeword, which is orthogonal to the codes of other users. In order to detect the user, the receiver is required to know the codeword used by the transmitter.

Unlike TDMA, CDMA does not require time synchronization between the users. A CDMA system experiences a problem called self-jamming which arises when the spreading codes used for different users are not exactly orthogonal. While dispersing, this leads to a significant contribution from other users to the receiver decision statistic. If the power of the multiple users in a CDMA system is unequal, then the user with the strongest signal power will be demodulated at the receiver. The strength of the received signal raises the noise floor for the weaker signals at the demodulators. This reduces the probability that weaker signals will be received. This problem, known as the near-far problem can be taken care off by using power control. This ensures that all the signals within the coverage of the base station arrive with same power at the receiver [30] [31] [38] [39].
2.6.4 Spatial Division Multiple Access (SDMA)

New technologies are required in the area of mobile communications to accommodate future capacity needs. Space division multiple access (SDMA) has emerged as a key technology and holds a lot of promises for the future of mobile communication. SDMA exploits the spatial domain of the mobile radio channel to bring about increase in network capacity in the existing wireless systems. Unlike wireless systems in the past, which used fixed antenna systems, SDMA based systems uses smart antennas or adaptive arrays that are dynamically able to adapt to the changing traffic requirements. Smart antennas usually employed at the base station, radiates narrow beams to serve different users. As long as the users are well separated spatially the same frequency can be reused, even if the users are in the same cell. This additional intra-cell channel reuse based on spatial separation is the key in achieving an increase in the capacity of the system.

Adaptive antennas also allow a base station to reuse a frequency to communicate with two or more mobiles if the mobiles are separated in angle from the base station. This approach is called space division multiple access (SDMA). By using highly directional beams and/or forming nulls in the directions of all but one of the mobiles on a frequency, the base station creates multiple channels using the same frequency, but separated in space. This approach is shown in Figure 2.8.

![Figure 2.8: Spatial division multiple access (SDMA)](image)
If SDMA can be achieved, the spectral efficiency can be increased dramatically. There are practical issues that make SDMA difficult to implement. For example, if two mobiles cross paths it may be necessary to hand off one mobile to a different frequency. Also, an adaptive array that can separate NSDMA users must have at least NSDMA+1 elements. Both the number of elements and the array geometry determine the angular resolution that can be achieved by the array. Also in frequency division duplex systems, which use different frequencies for receiving and transmitting, some means must be provided of forming a beam for transmitting that is similar to the beam used for receiving [46].

2.7 Array Theory

An antenna Array is a configuration of individual radiating elements that are arranged in space and can be used to produce a directional radiation pattern. Single-element antennas have radiation patterns that are broad and hence have a low directivity that is not suitable for long distance communications. A high directivity can be achieved with single-element antennas by increasing the electrical dimensions (in terms of wavelength) and hence the physical size of the antenna. Antenna arrays come in various geometrical configurations, the most common being; linear arrays. Arrays usually employ identical antenna elements. The radiating pattern of the array depends on the configuration, the distance between the elements, the amplitude and phase excitation of the elements, and also the radiation pattern of individual elements.

2.7.1 Some Antenna parameter definitions

It is worthwhile to have a brief understanding of some of the antenna parameters before discussing antenna arrays in detail. Some of the parameters are given below.

Radiation Power density: Radiation Power density \( W \) gives a measure of the average power radiated by the antenna in a particular direction and is obtained by time-averaging the Poynting vector.
\[ W_r(r, \theta, \phi) = \frac{1}{2} \text{Re}[E \times H^*] = \frac{1}{2\eta} |E(r, \theta, \phi)|^2 \quad \text{(Watts/m}^2) \]

Where, \( E \) is the electric field intensity; \( H \) is the magnetic field intensity, and \( \eta \) is the intrinsic impedance.

**Radiation Intensity:** Radiation intensity \( U \) in a given direction is the power radiated by the antenna per unit solid angle. It is given by the product of the radiation density and the square of the distance \( r \).

\[ U = r^2 W_r \quad \text{(Watts/unit solid angle)} \]

**Total power radiated:** The total power radiated \( P_{\text{tot}} \) by the antenna in all the directions is given by,

\[ P_{\text{tot}} = \int_0^{2\pi} \int_0^\pi W_r(r, \theta, \phi) r^2 \sin(\theta) d\theta d\phi = \frac{2\pi \eta}{2\pi} \int_0^{2\pi} \int_0^\pi U(\theta, \phi) \sin(\theta) d\theta d\phi \quad \text{(Watts)} \]

**Directivity:** The Directive gain \( D_g \), is the ratio of the radiation intensity in a given direction to the radiation intensity in all the directions. i.e.

\[ D_g = \frac{4\pi U(\theta, \phi)}{P_{\text{tot}}} \]

\[ = \frac{4\pi^2 W_r(r, \theta, \phi)}{\int_0^{2\pi} \int_0^\pi W_r(r, \theta, \phi) r^2 \sin(\theta) d\theta d\phi} = \frac{4\pi U(\theta, \phi)}{\int_0^{2\pi} \int_0^\pi U(\theta, \phi) \sin(\theta) d\theta d\phi} \]
The Directivity $D_0$ is the maximum value of the directive gain $D_g$ for a given direction. i.e.

$$D_0 = \frac{4\pi U_{\text{max}}(\theta, \phi)}{P_{\text{tot}}}$$

Where $U_{\text{max}}(\theta, \phi)$ is the maximum radiation intensity.

**Radiation Pattern:** The Radiation pattern of an antenna can be defined as the variation in field intensity as a function of position or angle. Let us consider an anisotropic radiator, which has stronger radiation in one direction than in another. The radiation pattern of an anisotropic radiator shown in figure 2.9 consists of several lobes.

![Figure 2.9: Radiation Pattern](image)

One of the lobes has the strongest radiation intensity compared to other lobes. It is referred to as the Major lobe. All the other lobes with weaker intensity are called Minor Lobes. The Half Power Beam-width (HPBW) quantifies the width of the main beam, which is the angular separation of the beam between half-power points [33].
2.7.2 Linear Array Analysis

When an antenna array has elements arranged in a straight line it is known as a linear array. Let us consider a linear array with two elements shown in figure 2.10. The elements are placed on either sides of the origin at a distance $d/2$ from it.

![Figure 2.10 A two-element linear array](image)

The electric field radiated by these two elements in the far field region at point P is of the following form.

Electric field at P due to element 1:

$$
\overline{E}_1 = w_1 f_1(\theta_1, \phi_1) e^{-j(kr_1 - \beta_1/2)} / r_1
$$

Electric field at P due to element 2:

$$
\overline{E}_2 = w_2 f_2(\theta_2, \phi_2) e^{-j(kr_2 + \beta_2/2)} / r_2
$$

Where:

- $w_1, w_2$ are the weights;
$f_1, f_2$ are the normalized field patterns for each antenna element;
$r_1, r_2$ are the distances of element 1 and element 2 from the observation point $P$;
$\beta$ is the phase difference between the feed of the two array elements;
To make the far field approximation the above figure can be re-drawn as shown below in figure 2.11. The point $P$ is in the far field region.

![Figure 2.11 Far-field geometry of a two-element linear array](image)

Following approximations can be drawn from the above diagram:

$\theta_1 \equiv \theta_2 \equiv \theta$;

$r_1 = r_2 = r$ \{ For amplitude variations \}

$r_1 \equiv r - \frac{d}{2} \cos \theta$

$r_2 \equiv r + \frac{d}{2} \cos \theta$ \{ For phase variations \}

Since the array elements are identical we can assume the following:

$F_1(\theta_1, \phi_1) = F_2(\theta_2, \phi_2) = F(\theta, \phi)$
The total field $E$ at point $P$ is the vector sum of the fields radiated by the individual elements and can be illustrated as follows:

$$
\overline{E} = \overline{E}_1 + \overline{E}_2
$$

$$
\overline{E} = w_1 f(\theta, \phi) e^{-j\left(k \left(r - \frac{d}{2} \cos \theta - \frac{\beta}{2}\right)\right)} + w_2 f(\theta, \phi) e^{-j\left(k \left(r + \frac{d}{2} \cos \theta + \frac{\beta}{2}\right)\right)}
$$

$$
\overline{E} = \frac{e^{-jkr}}{r} f(\theta, \phi) \left[ w_1 e^{j\left(k \frac{d}{2} \cos \theta + \frac{\beta}{2}\right)} + w_2 e^{-j\left(k \frac{d}{2} \cos \theta + \frac{\beta}{2}\right)} \right]
$$

For uniform weighting,

$w_1 = w_2 = w$

$$
\rightarrow \overline{E} = w \frac{e^{-jkr}}{r} f(\theta, \phi) 2 \cos \left(\frac{kd \cos \theta + \beta}{2}\right)
$$

The above relation is often referred to as pattern multiplication which indicates that the total field of the array is equal to the product of the field due to the single element located at the origin and a factor called array factor, $AF$. i.e.

(Total) = [E (single element at reference point)] × [array factor]

(Note: The pattern multiplication rule only applies for an array consisting of identical elements.)

The normalized array factor for the above two-element array can be written as follows:

$$
AF_n = \cos \left(\frac{kd \cos \theta + \beta}{2}\right)
$$
Therefore from the above discussion it is evident that the AF depends on:

1. The number of elements
2. The geometrical arrangement
3. The relative excitation magnitudes
4. The relative phases between elements

2.8 Smart Antenna Technology

Though smart antenna techniques are new in the area of mobile communications, the technology itself was introduced in 1960’s. Early smart antenna technology was deployed in military communication systems, where narrow beams were used in order to avoid interference arising from noise and other jamming signals. Extending the smart antenna concept further researchers worked on the technology to apply it to the personal communication industry to accommodate more users in the wireless network by suppressing interference.

Switched beamforming is a smart antenna approach in its simplest form, where multiple fixed beams in predetermined directions are used to serve the users. In this approach the base station switches between several beams that gives the best performance as the mobile user moves through the cell. Most advanced approach based on smart antenna technique, known as adaptive beamforming uses antenna arrays backed by strong signal processing capability to automatically change the beam pattern in accordance with the changing signal environment. It not only directs maximum radiation in the direction of the desired mobile user but also introduces nulls at interfering directions while tracking the desired mobile user at the same time. Multiplying the incoming signal with complex weights and then summing them together to obtain the desired radiation pattern achieve the adaptation. These weights are computed adaptively to adapt to the changes in the signal environment. The complex weight computation based on different criteria is incorporated in the signal processor in the form of software algorithms [14].
Why Now?
In the last couple of years smart antennas for mobile communications have received
everest interest worldwide. So why is the interest appearing now, and not few years
ago? The answer probably lies with the fact that for most operators there has not been
much reason to worry about capacity and spectrum efficiency. Also, as will be
apparent later on, if the base station is to track a large number of users simultaneously,
the computational cost will be large. Only recently are processors with sufficient
power becoming available. In addition to increased capacity, smart antennas also
introduce a number of other advantages to cellular networks, including increased
range, a higher level of security, and the possibility for new services.

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

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

Concepts
Several different definitions for smart antennas are used in the literature. One useful
and consistent definition can be that the difference between a smart/adaptive antenna
and a "dumb"/fixed antenna is the property of having an adaptive and fixed lobe-
pattern, respectively. Normally, the term "antenna" comprises only the mechanical
construction transforming free electromagnetic (EM) waves into radio frequency (RF) signals traveling on a shielded cable and vice versa. We may call it the radiating element.

What are smart antennas?
In the context of smart antennas, the term "antenna" has an extended meaning. It consists of a number of radiating elements, a combining/dividing network and a control unit. The control unit can be called the smart antenna's intelligence, normally realized using a digital signal processor (DSP).

Smart antennas are an array of antenna elements that change their antenna pattern dynamically to adjust to the noise, interference in the channel and mitigate multipath fading effects on the signal of interest. The secret to the smart antennas' ability to transmit and receive signals in an adaptive, spatially sensitive manner is the digital signal processing capability present. An antenna element is not smart by itself; it is a combination of antenna elements to form an array and the signal processing software used that make smart antennas effective. This can dramatically increase the performance characteristics (such as capacity) of a wireless system. They are usually located at base stations because of the sophisticated signal processing requirements. This shows that smart antennas are more than just the "antenna," but rather a complete transceiver concept [15] [16].

Evolutionary Path
The evolution can be divided into three phases:

Phase 1: Smart antennas are used on uplink only (uplink means that the user is transmitting and the base station is receiving). By using a smart antenna to increase the gain at the base station, both the sensitivity and range are increased. This concept is called high sensitivity receiver (HSR) and is in principle not different from the diversity techniques implemented in today's mobile communications systems.
Phase 2: In the second phase, directed antenna beams are used on the downlink direction (base station transmitting and user receiving) in addition to HSR. In this way, the antenna gain is increased both on uplink and downlink, which implies a spatial filtering in both directions. Frequencies can be more closely reused, thus the system capacity increases. The method is called spatial filtering for interference reduction (SFIR). It is possible to introduce this in second-generation systems.

Phase 3: The last stage in the development will be full space division multiple access (SDMA). This implies that more than one user can be allocated to the same physical communications channel simultaneously in the same cell, only separated by angle. In a TDMA system, two users will be allocated to the same time slot and carrier frequency at the same time and in the same cell.

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

2.9 Types of Smart Antenna Systems

There are basically two approaches to implement antennas that dynamically change their antenna pattern to mitigate interference and multipath effects while increasing coverage and range. They are

- Switched beam
- Adaptive Arrays

The Switched beam approach is simpler compared to the fully adaptive approach. It provides a considerable increase in network capacity when compared to traditional omnidirectional antenna systems or sector-based systems. In this approach, an antenna array generates overlapping beams that cover the surrounding area as shown in figure 2.12.
When an incoming signal is detected, the base station determines the beam that is best aligned in the signal-of-interest direction and then switches to that beam to communicate with the user.

The Adaptive array system is the “smarter” of the two approaches. This system tracks the mobile user continuously by steering the main beam towards the user and at the same time forming nulls in the directions of the interfering signal as shown in figure 2.13.
Like switched beam systems, they also incorporate arrays. Typically, the received signal from each of the spatially distributed antenna elements is multiplied by a weight. The weights are complex in nature and adjust the amplitude and phase. These signals are combined to yield the array output [17] [18]. These complex weights are computed by a complicated adaptive algorithm, which is pre-programmed into the digital signal-processing unit that manages the signal radiated by the base station.

2.9.1 Switched Beam Systems

This type of adaptive technique actually does not steer or scan the beam in the direction of the desired signal. Switched beam employs an antenna array, which radiates several overlapping fixed beams covering a designated angular area. It subdivides the sector into many narrow beams. Each beam can be treated as an individual sector serving an individual user or a group of users. Consider a traditional cellular area shown below in figure 2.14 that is divided into three sectors with $120^\circ$ angular width, with each sector served by six directional narrow beams.
The spatially separated directional beams leads to increase in the possible reuse of a frequency channel by reducing potential interference and also increases the range. These antennas do not have a uniform gain in all directions but when compared to a conventional antenna system they have increased gain in preferred directions. The Switched beam antenna has a switching mechanism that enables it to select and then switch the right beam which gives the best reception for a mobile user under consideration. The selection is usually based on maximum received power for that user. Note that same beam can be used both for uplink and downlink communication.

A typical switched beam system for a base station would consists of multiple arrays with each array covering a certain sector in the cell. Consider a switched beamforming system shown in figure 2.15. It consists of a phase shifting network, which forms multiple beams looking in certain directions. The RF switch actuates the right beam in the desired direction. The selection of the right beam is made by the control logic. The control logic is governed by an algorithm, which scans all the beams and selects the one receiving the strongest signal based on a measurement made by the detector.
Figure 2.15: Block diagram of Switched beam systems

This technique is simple in operation but is not suitable for high interference areas. Let us consider a scenario where user 1 who is at the side-edge of the beam which he is being served by. If a second user were at the direction of the null then there would be no interference but if the second user moves into the same area of the beam as the first user he could cause interference to the first user [19]. Therefore switched beam systems are best suited for a little or zero-interference environment.

In case of a multipath signal there is a chance that the system would switch the beam to the indirect path signal rather than the direct path signal coming from the user. This leads to the ambiguity in the perception of the direction of the received signal, thus, switched beam systems are only used for the reception of signals.

These systems lead to frequent hand-offs when the mobile user is actively moving from the area of one beam to another. Therefore these intra-cell hand-offs have to be controlled. Switched beam systems cannot reduce multipath interference components with a direction of arrival close to that of the desired signal. Despite of all these disadvantages, the switched beam approach is less complicated (compared to the completely adaptive systems) and provides a significant range extension, increase in capacity, and a considerable interference rejection when the desired user is at the center of the beam. Also, it is less expensive and can be easily implemented in older systems.
2.9.2 Adaptive Array Systems

From the previous discussion it was quite apparent that switched beam systems offer limited performance enhancement when compared to conventional antenna systems in wireless communication. However, greater performance improvements can be achieved by implementing advanced signal processing techniques to process the information obtained by the antenna arrays. Unlike switched beam systems, the adaptive array systems are really smart because they are able to dynamically react to the changing RF environment. They have a multitude of radiation patterns compared to fixed finite patterns in switched beam systems to adapt to the ever-changing RF environment. An Adaptive array, like a switched beam system uses antenna arrays but is controlled by the signal processing [20]. This signal processing steers the radiation beam towards a desired mobile user, follows the user as he moves, and at the same time minimizes interference arising from other users by introducing nulls in their directions.

The adaptive array systems are really intelligent in the true sense and can actually be referred to as smart antennas. The smartness in these systems comes from the intelligent digital processor that is incorporated in the system. The processing is mainly governed by complex computationally intensive algorithms.

2.9.2.1 Smart antenna concept

The smart antenna is basically a set of receiving antennas in a certain topology. The received signals are multiplied with a factor, adjusting phase and amplitude. Summing up the weighted signals, results in the output signal. The concept of a transmitting smart antenna is rather the same, by splitting up the signal between multiple antennas and then multiplying these signals with a factor, which adjusts the phase and amplitude. Figure 2.16 represents the concept of the smart antenna. The signals and weight factors are complex.
An adaptive antenna array or a smart antenna is also named a "Software antenna" because it can form a desired antenna pattern and adaptively control it, if an appropriate set of antenna weights is provided and updated in software. The radiation pattern can be adjusted to place nulls in the paths of interferers as shown in figure 2.17.

The interferer's direction is tracked via a Direction of Arrival algorithm. The antenna array can also combine multipath signals using space diversity techniques; they in effect maximize the signal to interference ratio (SIR).
An adaptive antenna array can be considered as an adaptive filter in space and time domains for radio communications, so that a communication theory can be generalized from a conventional time domain into both space and time domains.

2.9.2.2 Smart Antenna Combining Schemes

Smart antennas employ two different combining schemes:
Diversity combining
Adaptive combining

Diversity Combining:
It is a combining technique that combines the signals from multiple antennas in a way that mitigates multipath fading. The diversity-combining scheme exploits the spatial diversity among multiple antenna signals. So the diversity combining achieves higher performance when multiple antenna signals are less correlated. If each antenna signal undergoes independent fading, the diversity-combining scheme would perform well.

The adaptive combining scheme adjusts the antenna weights dynamically to enhance the desired signal while suppressing interference signals. Since the adaptive combining scheme aims to add multiple antenna signals, the scheme performs better for correlated antenna signals. Thus, if multiple antenna signals are exactly the same except the phase difference, the adaptive combining achieves the highest performance.

Adaptive Beamforming:
It is accomplished using software and advanced signal processing. The technology combines the inputs of multiple antennas (from an antenna array) to form very narrow beams toward individual users in a cell. The concentrated energy of the focused beams creates significant gain and allows signals to extend farther [22]. The narrow beams get rid of interference, allowing many users to be connected within the same cell at the same time using the same frequencies.
Adaptive beamforming requires sophisticated signal processing, which until today was considered too expensive for commercial application. The cost of processing has immensely reduced, making beamforming relevant to the commercial market as a cost effective solution for wide-scale deployment of broadband wireless networks.

Beamforming gives significant improvement in link budget. It can be used in conjunction with other techniques, such as adaptive modulation, frequency diversity or forward error correction to enhance overall system gain. With adaptive beamforming, spectral efficiency of the cell could be multiplied at least ten times.

2.9.2.3 Basic Working Mechanism

A smart antenna system can perform the following functions: first the direction of arrival of all the incoming signals including the interfering signals and the multipath signals are estimated using the Direction of Arrival algorithms. Secondly, the desired user signal is identified and separated from the rest of the unwanted incoming signals. Lastly a beam is steered in the direction of the desired signal and the user is tracked as he moves while placing nulls at interfering signal directions by constantly updating the complex weights.

It is quite evident that the direction of radiation of the main beam in an array depends upon the phase difference between the elements of the array. Therefore it is possible to continuously steer the main beam in any direction by adjusting the progressive phase difference between the elements. The same concept forms the basis in adaptive array systems in which the phase is adjusted to achieve maximum radiation in the desired direction. To have a better understanding of how an adaptive array system works, let us consider a typical adaptive digital beamforming network shown in figure 2.18.
In a beamforming network typically the signals incident at the individual elements are combined intelligently to form a single desired beamformed output. Before the incoming signals are weighted they are brought down to baseband or intermediate frequencies (IF’s). The receivers provided at the output of each element perform the necessary frequency down conversion. Adaptive antenna array systems use digital signal processors (DSP’s) to weight the incoming signal. Therefore it is required that the down-converted signal be converted into digital format before they are processed by the DSP. Analog-to-digital converters (ADC’s) are provided for this purpose. For accurate performance, they are required to provide accurate translation of the RF signal from the analog to the digital domain. The digital signal processor forms the heart of the system, which accepts the IF signal in digital format and the processing of the digital data is driven by software [27]. The processor interprets the incoming data information, determines the complex weights (amplification and phase information) and multiplies the weights to each element output to optimize the array pattern. The optimization is based on a particular criterion, which minimizes the contribution from noise and interference while producing maximum beam gain at the desired direction. There are several algorithms (discussed in the next chapter) based on different criteria for updating and computing the optimum weights.
2.9.3 Switched beam and Adaptive antenna array technologies: A comparison

<table>
<thead>
<tr>
<th>Switched beam technology</th>
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<tbody>
<tr>
<td>- Give high gain, narrower bandwidth azimuth beamwidths</td>
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<tr>
<td>- Butler Array matrix technology</td>
</tr>
<tr>
<td>- Multiple fixed directional beams used</td>
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<tr>
<td>- Uses algorithms for beam selection</td>
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<tr>
<td>Advantages:</td>
</tr>
<tr>
<td>- Require only moderate interaction with the base station receiver as compared to adaptive antenna systems</td>
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<tr>
<td>- Is a relatively low technology approach so has lesser cost and complexity</td>
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<tr>
<td>Disadvantages:</td>
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<tr>
<td>- Intra-cell hand-offs between beams have to be handled</td>
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<tr>
<td>- Cannot mitigate multipath interference components with DoA close to that of the desired signal</td>
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<td>- Is unable to take advantage of path diversity by combining coherent multipaths</td>
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<table>
<thead>
<tr>
<th>Adaptive antenna array technology</th>
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<tbody>
<tr>
<td>Advantages:</td>
</tr>
<tr>
<td>- Antenna beams adaptively track signal direction; a null can be placed in the direction of an interferer</td>
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<tr>
<td>- No intra-cell hand-off problems since beams continually track user</td>
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<tr>
<td>- May have greater capacity increase when compared to switched beams</td>
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<td>- More intensive signal processing needed via DSPs</td>
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<tr>
<td>Disadvantage:</td>
</tr>
<tr>
<td>- Is more expensive to install; a base station with traditional antennas can more easily be upgraded to use switched beam antennas</td>
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</table>
2.10 Advantages of Smart Antenna Technology in Wireless Communications

The various factors that have to be considered in designing a wireless system and the challenges to be met can be listed as follows:

- A multipath time-varying propagation environment
- Limited radio spectrum
- Batteries - size and the duration they operate
- Dropped calls
- Co-channel interference
- Capacity of the system in terms of traffic it can handle and subscriber base

The main advantages of using adaptive antenna arrays in a wireless communication system are listed below. Their implementation will have a large impact on the performance of cellular networks. It will also affect many aspects of both the planning and deployment of mobile systems.

(i) They enhance the range of coverage and thus reduce the initial deployment cost of a wireless system

In rural and sparsely populated areas, a range increase potential is available because smart antennas are more directive than traditional sector or omni-directional antennas. Since smart antennas employ collection of individual elements in the form of an array they give rise to narrow beam with increased gain when compared to conventional antennas using the same power. The increase in gain leads to increase in range and the coverage of the system. Therefore fewer base stations are required to cover a given area.
(ii) Reduction in co-channel interference

Smart antennas have a property of spatial filtering to focus radiated energy in the form of narrow beams only in the direction of the desired mobile user and no other direction. In addition they also have nulls in their radiation pattern in the direction of other mobile users in the vicinity. Therefore there is often negligible co-channel interference.

(iii) Can be applied to the various multiple-access schemes such as TDMA, CDMA and FDMA.

(iv) Help mitigate the effects of multi-path and improve Quality of service as compared to the scenario when conventional antennas were used.

By using a narrow antenna beam at the base station the multipath propagation can be somewhat reduced.

(v) Improve system capacity

In densely populated areas, interference from other users is the main source of noise in the system. This means that the signal to interference ratio, SIR, is much larger than the signal to thermal noise-ratio, SNR. Adaptive antenna arrays increase the received SIR by simultaneously increasing the useful received signal level and lowering the interference level. In TDMA systems, the implication of the increased SIR is the possibility for reduced frequency reuse distance. In CDMA too, the main source of noise in the system is the interference from other users. This means that the expected capacity gain is even larger for CDMA than for TDMA [30].

(vi) Can lead to new services

Smart antennas can give wireless networks access to spatial information about the users. This information can be used to estimate the positions of the users much more
accurately than in existing networks. Positioning can be used in services such as emergency calls and location-specific billing.

(vii) Increased security

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

(viii) Reduction in transmitted power

Ordinary antennas radiate energy in all directions leading to a waste of power. Comparatively smart antennas radiate energy only in the desired direction. Therefore less power is required for radiation at the base station. Reduction in transmitted power also implies reduction in interference towards other users.

(ix) Lower handset power consumption

(x) Increased data rate

(xi) There is lower specific absorption rate (SAR)

(xii) Improved spectral efficiency

(xiii) It combines the signal it receives directly from the base station with the reflections of the same signal whereas a conventional handset normally tunes into the strongest signal it can find.

(xiv) It is possible to combine the signals from the antennas in a particular way that both the SNR (signal to noise ratio) and CIR (carrier to interference ratio) levels are improved.

(xv) Research done on outdoor mobile communication systems indicates that addition of adaptive circuitry can overcome most of the impairments by the effects of multipath fading.
2.10.1 Role of Smart Antennas in CDMA Systems

A CDMA smart antenna system can be used at existing CDMA base stations to increase cell capacity up to 50 percent. A multibeam, phased-array antenna is most commonly used for this purpose.

- Sector Synthesis
  The phased-array antenna can create custom antenna patterns to serve users within a cell. The narrow antenna beams increase carrier-to-interference (C/I) ratios, which improves call quality and allows the implementation of tighter frequency reuse patterns. CDMA smart antennas offer greater flexibility in optimizing the use of CDMA cell site capacity.

- Capacity gain
  They come from two primary sources: peak load reduction and reduction in the number of handoffs. Capacity of a cell is usually not efficiently used due to imbalances in loading. By manipulating the site's sector patterns, smart antennas can balance traffic loads among sectors, shifting traffic from a sector that is capacity constrained to sectors that have excess capacity because of lighter traffic loads.

- Reduced handoffs
  Smart antennas can give greater capacity gains via reduced handoff overhead. As the number of handoffs increase, capacity decreases. CDMA's soft handoffs provide for high quality make-before-break transitions. Handoffs can also be positioned in low traffic areas to mitigate excess interference [31].

Thus, smart antennas extract more capacity from current CDMA network resources and their implementation at base stations results in a more efficient network.