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Chapter 7: Beamforming, smart antennas, and signal optimization for high-speed wireless communication

7.1. Introduction

The term wireless communication means a communication without wires, cables, or any electrical conductors. Without wires, it is very convenient to carry out communication. The Internet is one of the big developments in the field of data communication that unifies the various services like electronic mail, remote login, file transfer, language translation, calendar, etc. used in data communication. Traditionally, all these services were available, but the development of the Internet and its popularization has massively increased the number of users of data communication services and the volume of data being communicated over long distances. The ever-changing demands and requirements of businesses, industries, and governments have led to developments and advancements in the field of data communication. The introduction of wideband channels has imposed new requirements on the design of data communication devices and systems (Andrews et al., 2014; Boccardi et al., 2014; Gupta & Verma, 2021).

With the changes in the character of communication, the wireless networks have also undergone fast developments. Wireless communication is a field of communication which has developed very rapidly and has drawn the attention of researchers from the various areas of science and engineering. Due to existing limits to increase the bandwidth in the wired systems, and also the advantages of wireless systems over wired systems like mobility, ease of installation and maintenance, popularity, convenience, expansion capability, reduction in cost, etc., wireless communication systems have become increasingly popular. The data rate over fixed telephone lines, especially in developing countries, is still very poor. The mobile communication systems today allow voice transmission over a mobile network with the aid of the wire line network but are not cost-effective for data transmission. Starting with the first generation analog mobile phone system, the second generation digital mobile phone system and short message service, progress has been made to today's third generation mobile communication systems (Zhang et al., 2019; Renzo et al., 2020; Gupta & Verma, 2021).

7.1.1. Background and Significance

Wireless communication enables the transfer of information between different points without requiring metallic conductors, although fiber optics may be utilized for last-mile connectivity. Computer- and telecom networks transmit a variety of information such as data, voice, and video. The continued expansion of the Internet, global connectivity through satellite links, and the increasing usage of wireless networks on land, sea, and in space, are making wireless communication an integral part of everyday life. Wireless communication scientists and engineers work on a variety of technologies to enable the more basic task of transferring information wirelessly — from developing more efficient methods of encoding, decoding, and compressing information, to creating circuit design techniques for extremely high-speed transmit and receive units to be used at both the wireless and wireline ends of the communication system. Electronic circuit techniques proposed and used for high-speed signaling over electromagnetic waves include such varied concepts as pulse coding, nonlinear processing, and subsampling of input signals.

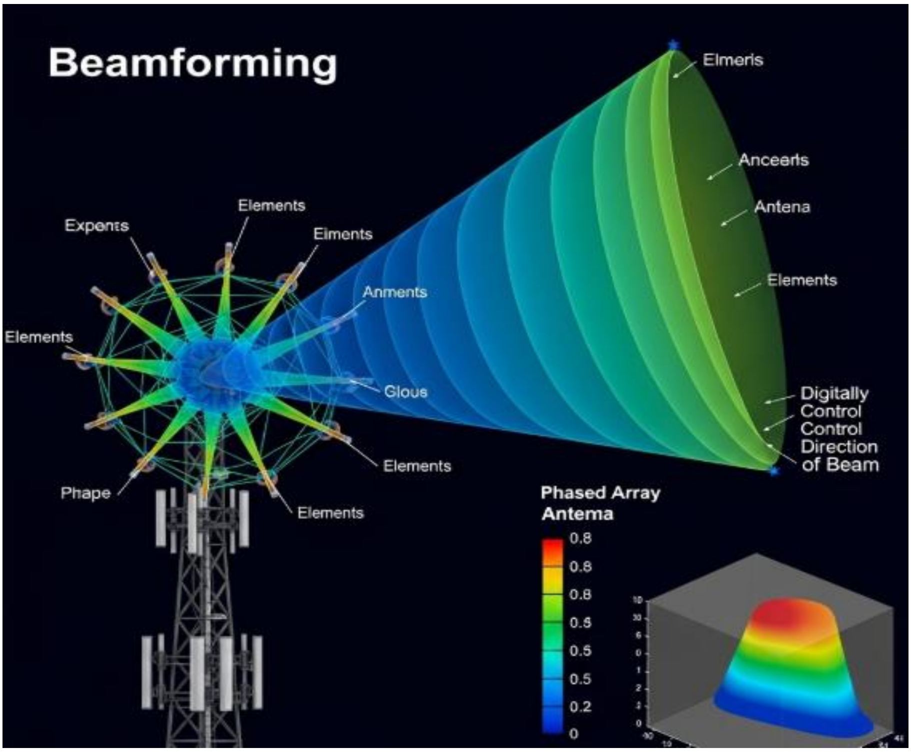

Fig 7.1: Beamforming, Smart Antennas, and Signal Optimization

7.2. Fundamentals of Beamforming

The fundamental principle of beamforming is to employ an antenna array consisting of multiple spatially dispersed antenna elements connected together to reduce or enlarge the level of signals from certain angles of arrival or departure. Typically, such antenna arrays consist of wire-like antenna elements, which are implemented as dipole elements, patch antennas or similar type radiators. The signal levels at multiple antenna elements are combined together in such a way that signals from some particular angles are coherently combined while signals from other directions are destructively cancelled. This process improves the level of signal reception from desired sources while degrading the level of signals from undesirable sources.

In wireless communication, the downstream or forward link is defined as the downlink from the transmitter to the receiver, while the upstream or reverse link is defined as the uplink from the receiver and towards the transmitter. In point to point wireless communication associated with a single pair of transmitter and receiver; the sustainable performance of the communication channel is mainly limited by the level of received Co-Channel Interference, which in turn limits the device specific signal to interference noise ratio. Antenna array techniques allow reduction of the undesired interference from signal sources at specific angles while increasing the desired signals at selected angles. For a point to point communication channel with a single device at either the base station or the mobile unit; it is desirable to use a highly directive narrow beamwidth antenna array. On the other hand, in a multi-user communication environment with many devices at the service intervals of the transmission and reception channel, it is desirable to use a wide beam antenna to enhance the coverage.

7.2.1. Definition and Overview

Beamforming is a technique used in sensor arrays for spatial filtering or directional signal enhancement. The technique has its roots in the electronics, radar, and sonar fields where receiving and transmitting arrays are fairly common. For quite a while, however, array techniques have been largely absent in wireless communications, despite the fact that antennas for mobile applications are typically not isolated and can improve performance via multipath diversity. In the past few years, there has been renewed interest in the use of antenna arrays in wireless communications. While recent work in this area has largely focused on spatial diversity techniques, it is generally believed that larger arrays usable at the mobile unit will implement beamforming to provide increased capacity.

A number of techniques exist for the implementation of beamforming. These include phased arrays and switched beams. Phased arrays require the use of more sophisticated

RF components and extensive calibration. Switched beams employ a number of static beams implemented by a number of antennas. While still requiring an accurate calibration for optimal null placement, they allow the use of simpler RF components. However, switched beams have some disadvantages compared with phased arrays. The placement of beams is static and generally cannot be changed quickly. Switched beams may begin to cover a region in which beamforming is desired, causing reduced gain and increased sidelobe levels. And the side lobes may receive inputs after some delay, increasing the possibility of intersymbol interference.

7.2.2. Types of Beamforming

Beamforming can be classified into different categories according to the following two criteria: (i) whether the beamforming algorithm is designed at the transmitter or the receiver and (ii) whether or not the beamforming algorithm requires channel state information at the transmitter. Based on the first criterion, beamforming can be classified as transmitter beamforming and receiver beamforming. Based on the second criterion, if the beamforming algorithm requires channel state information, it is referred to as open-loop beamforming; otherwise, it is referred to as closed-loop beamforming. For transmitter beamforming, the transmit power is focused on one specific direction. For receiver beamforming, which is also called signal-selection diversity, the receiver selects the signal with the least amount of noise from the different antenna branches.

Open-loop transmitter beamforming does not require the use of feedback to adapt every transmission to the time-variant fading environment, thereby eliminating the penalties associated with the lack of instantaneous channel knowledge. Instead, open-loop transmitter beamforming makes use of time-averaged error rates that coincide with longer-term averages of the channel, making it especially useful in scenarios where the channel coherence time is drastically reduced by extremely fast fading. In addition, open-loop transmitter beamforming can also be used in conjunction with receiver beamforming to further enhance diversity and directivity gain. In either case, both open-loop schemes have the added benefits of only incurring a modest increase in overall transmit power and requiring the most simplistic feedback from the receiver side since only the angle-of-arrival or angle-of-departure information is utilized.

7.3. Smart Antennas: Concepts and Technologies

In wireless communications, the demand for radio resources has predominantly increased stressing the mobile operators to maximize the capacity of wireless links without degrading the quality of services. The cost of radio resources has forced the designers to enhance the performance of the systems. One of the powerful techniques that improves the performance of wireless systems is the spatial diversity gain offered by the multiple antennas at the transmitter and receiver. Though diversity combines the signals over time, frequency and space, the use of additional antennas modulate the signals in space offering capacity of the wireless link compared to the case using a single antenna. Better utilization of the available spectrum can be accomplished using beamforming or focusing techniques since the correlation between different beams is reduced thus allowing the system to use much wider bandwidth for each data stream compared to the case having a single antenna. In a point-to-point communication link, the problem of having increasingly greater demands of capacity per data stream can simply be implemented by the spatial multiplexing approach. Therefore, multiple antenna technology has become of primary importance in the design of future wireless systems.

Smart antennas, also known as adaptive antennas or intelligent antennas, electronically or mechanically dynamically alter their pattern or directive characteristics to maintain optimum signal quality. Smart antennas technology incorporates spatial diversity, rich scattering environment and focus or beamform characteristics to help improve performance. The increased capacity and quality with reduced interference and multipath distortion give cellular engineers the ability to add additional users to an existing cellular network or delay system expansion or upgrade. Smart antennas transceive patterns dynamically modify and improve cellular network capacity and allow future technologies to utilize spectrum efficiently.

7.3.1. What are Smart Antennas?

A Smart Antenna is any antenna system that is capable of controlling the radiation pattern in any desired way for communication purposes. Using an array of antennas is one of the most flexible methods for achieving a desired radiation pattern and is, therefore, the solution exposed in this chapter. A Smart Antenna system or Adaptive Antenna Array is able to control the pattern shape in terms of gain and side lobe levels and also to steer the maximum direction on the fly, overcoming the disadvantages of the traditional fixed pattern antennas. This goal is accomplished by using a Base Station equipped with antennas consisting of N elementary receiving and/or transmitting antennas that are connected to a spatial processor. The transmitted signal, after pass or before the pass through the power amplifiers located at the Base Station, are applied to the elements of the array through a network of correction circuits that take care of the differences of path length with respect to the desired radiation direction and of 3 dB spreads for each antenna elements before and/or after the power amplifiers. A Smart Antenna is a sensor that can continuously change its parameters. In this case the sensor is the array of antennas; it is a multiparameter sensor since it can “see” M desired users and Q undesired users at the same time.

The Smart Antenna continuously computes the weights applied to the channel associated with the wanted users and for reducing the levels of interference in the other channels. The ability of scanning M channels simultaneously is realized if M is smaller than the number N of the possible pattern-causing inputs. The Smart Antenna must compute suitable correction weights continuously in order to have a good performance on the users whom the Smart Antenna has decided to “see” at the initial instant. Smart antennas use advanced digital signal processing algorithms to learn and adapt to the traffic conditions and/or to the environment characteristics: multipath propagation, interference, etc.

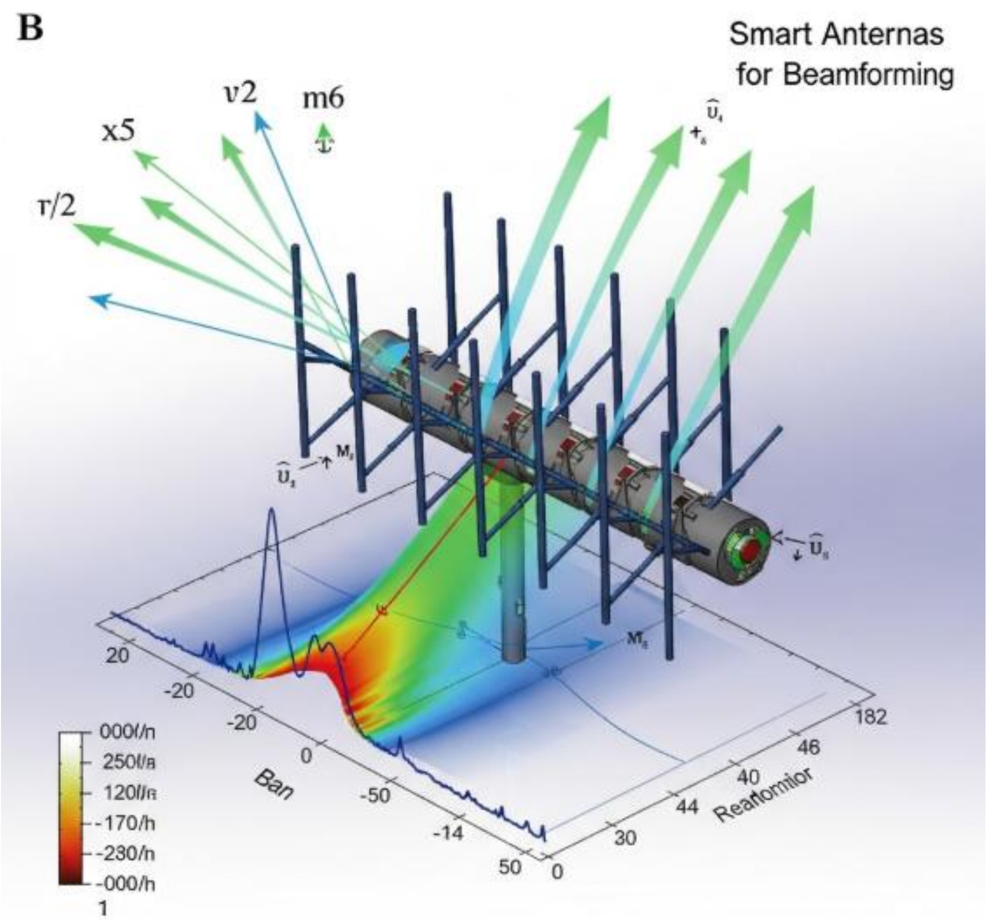

Fig 7.2: Smart Antennas

7.3.2. Types of Smart Antennas

A logical way to categorize smart antennas is based upon their response to the incoming waves. Thus, one classification would be based on whether the antenna is designed to communicate with one user at a time (directive, or switched, antennas) or with several users simultaneously (adaptive antennas). Adaptive antennas, in turn, can be classified based on the requirements cited above into their narrow and wide beamwidth categories. Narrow beamwidth antennas must always scan the directions of the active users, whereas wide beamwidth antennas can initiate communication without performing a scan, but need to possess a higher degree of sophistication.

The alert reader will realize that the above classifications can be combined to create four classes of smart antennas: switched directive antennas; switched broad beamwidth antennas; adaptive narrow beamwidth antennas; adaptive wide beamwidth antennas. The most common example of a switched directive antenna is a parabolic reflector pointed at the desired direction. Such systems can have high gain but must use expensive mechanical hardware to switch the beam toward the required user. Alternatively, two or more sectoral antennas can be used to provide coverage for cell phones.

Switched broad beamwidth antennas have been used extensively for rural telephone service, primarily because of their low cost and ease of construction. An example of switched broad beamwidth antennas is arrays of Yagi antennas used to radiate horizontally polarized beams to provide coverage within isolated rural towns. Transportable small pods of these antennas can be switched to provide telephone service to oil drills located within the offshore waters of remote regions.

7.4. Signal Optimization Techniques

Beamforming enables spatial focusing of communication signals in desired antenna array directions while suppressing them in others, reducing multiuser interference. Smart antennas include beamforming arrays in wireless mobile systems. Antenna patterns are usually made to vary slowly with time, but can in principle be varied from symbol period to symbol period, and even at the symbol rate according to a manifestly time variant signal characterization imposed on the symbols. The signal could be adjusted to match the directional pattern of the array at the time using some adaptive control strategy.

In each case a certain amount of channel stability is required, since the process of carrying out the antenna response legalization involves estimation of channel response and signal optimization. However, if the channel is fairly stable, then the symbol time can be of the order of 10 milliseconds while antenna response functions might only be updated once every 100–1000 milliseconds. Many parameters affecting antenna response do not vary with time, and this relative stability in antenna pattern change may allow signal optimization and response legalization to proceed in cascade fashion, based on predetermined response mapping. The optimal mapping itself, if the antenna response is "fast", may require optimization at a higher rate.

7.4.1. Signal Processing Fundamentals

Despite what may seem on face value, each of the symbols xi in a signalling alphabet X could represent a sizable collection of possible received signals. The nature of received signals emphasizes the huge number of fates, in essence, because there is the collection of all the multipath signals weighted according to the whole probability distribution pertaining to the input signaling arena. It is also emphasized that each symbol xi is not exclusively characterized by a distinctive amplitude value: if we average all the possibly received continuous signals about time, we also obtain a dense collection of delays about which all the probable received signals at time k would have to be centered, weighted according to their respective probabilities.

To describe each of the densified collections of received signals after matching filtering, some statistical tool is necessary. The matched-filtering operation will have to modify the shape of the original signaling waveform. To compute the cracking probabilities which explain how big the influence of noise is, conventional laws of statistical Error Probability Theory are valid. Using a series of simplifying approximations, the classic Theory evaluates the error probabilities, while interestingly, necessities of wireless communications often lead to the very same approximations. The received signal is described at chip-time level and structure of the hopping sequences is analyzed. Here chip-time could be made arbitrarily small and the waveforms involved could be seen as virtually continuous. The chip-timescale is arrived at directly from the requirement of minimizing the bandwidth. In essence this solid basis of chip-time scaling leads to complexity reduction and is conducive to wrong results. A generalized approach using given chip-time levels shows how at macro-diversity level, chip scaling is not a unique factor.

7.4.2. Optimization Algorithms

Signal optimization problems can be solved by several classes of algorithms that differ in nature and globality. They may be classified into gradient, stochastic, or evolutionary algorithms. Gradient algorithms minimize the overall weighted signal error sequentially adapting filter weights along the performance-contour directions. Many different gradient algorithms were derived and modified. However, apart from tensor-factorization methods, they have in general strong limitations for the high-dimensional multimodal performance functions usually met in wireless communications, in particular in the SDMA case. MXE filters can be set using the maximum a posteriori estimation principle. However, the weight-setting algorithms are dictionary specific and hardly applicable to multiplexed signals emitted by antennas with identical polarization.

Stochastic algorithms update the filter weights randomly without calculating gradients. Therefore, they may overcome the possible local minimum limitations of deterministic algorithms as the one in the weight-constraint MMSE case where the filter block error probability is identical to its last term in the sum in the MMSE expression. However, they are slower, since they randomize convergence. Several other general-purpose adaptive global algorithms may be derived from the stochastic algorithm approach. They also randomly switch filter weights, but their switch decision may be based on several heuristic techniques or past selections, including statistics. They are not dedicated to the minimization problem but can be used for any other statistical selection or quality problem such as signal temporal equalization quality, for instance. By definition, the evolutionary optimization methods imitate natural evolution mechanisms to generate better solutions. Stochastic algorithms could be also considered as a specific kind of evolutionary algorithm. Noticeably, some research is targeted at integrating statistics from gradient, stochastic, and heuristic algorithms for better convergence performance and flexibility.

7.5. Integration of Beamforming and Smart Antennas

Traditionally, most research on both beamforming and smart antennas has been carried out separately, in different communities of Electrical Engineering. However, it is clear that the two areas are similar and share important similarities, and also some differences. Both beamforming and smart antennas have made significant advances, and many both have, or are close to being, deployed. In addition, several commercial products are now available that implement some combination or variant of beamforming or smart antennas.

Interest in beamforming and smart antennas has been growing recently for a number of reasons. It is well recognized that mobile communication performance can be significantly enhanced by the use of smart antennas or beamforming. In addition, both beamforming and smart antennas are useful in wideband wireless communications. The synergy between the two technologies and their combined functionality has also been advocated in the context of sensor array processing, wireless local area networks, and broadband mobile systems. The integration of advances in both beamforming and smart antennas can take advantage of new concepts and recent developments available in one technology for the other technology. However, such integration on new systems and standards is difficult because of the lack of common understanding across the two communities, disparate viewpoints, and cost innovations.

In this chapter, we first summarize the similarities and differences between beamforming and smart antennas. We also examine the synergy between the two technologies and their combined functionality in terms of wireless channel, signal model, and transport architecture. Then, using a few case studies, we illustrate various approaches to the integration with both technologies and new concepts and integration in recent developments available in beamforming and smart antennas.

7.5.1. Synergistic Effects

Recently, the fields of smart antennas and beamforming for wireless and mobile systems have entered a phase of synergy. Smart antennas use different gain patterns to simulate spatial filtering which combined with diversity effects do improve mobile communications system performance.

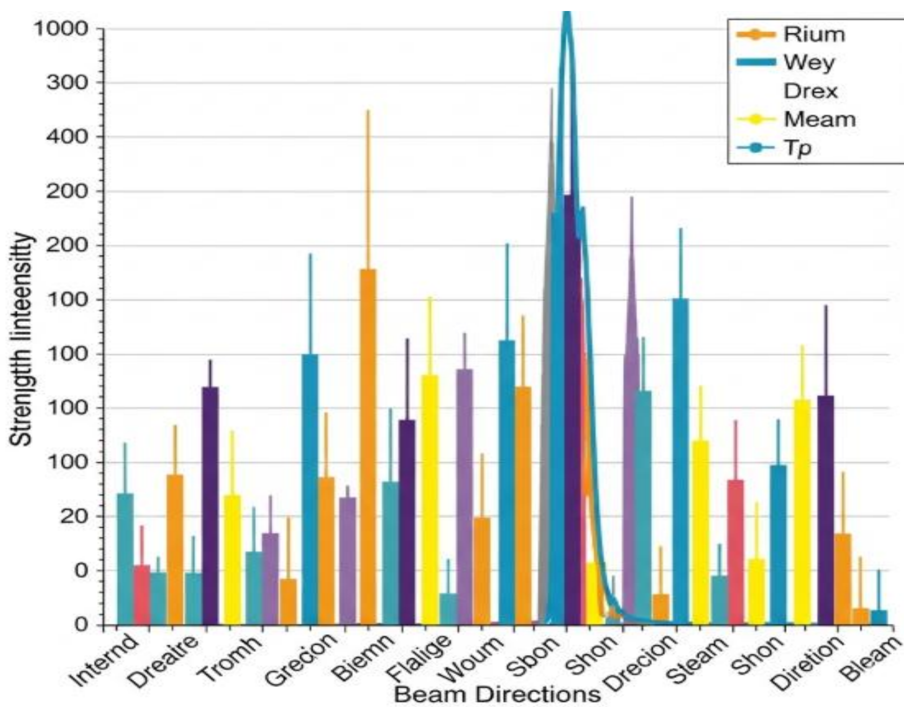

Fig 7.3: Optimization for High-Speed Wireless Communication

These patterns typically use a multi-element sensor configuration which can cause high spatial resolution sensing loss. Beamforming algorithms improve the spatial resolution but perform adaptive filtering on a single channel, thus avoiding high data rate slippage in time and frequency multiplexing. In practice, these ideas complement each other very well. Smart antennas provide gain, spatial diversity, multipath suppression and improved data handling capacity to wired and wireless infrastructures. Beamforming is a means to achieve better performance of antenna arrays in mobile communications. It also reduces hardware and sensor requirements. Beamforming arrays and smart antennas use adaptive filtering in different domains. Smart antennas reduce the spatial diversity of the problem to a number of channels, while beamforming arrays reduce the number of channels necessary for adaptive filtering to one by performing signal enhancement and interference exclusion in the spatial domain. This section summarizes some integrations of these two techniques and describes some ideas for the future use of hybrid systems.

Issues such as high multipath present in urban and rural areas, with scattered large amplitude reflected signals, poorly realized channel equalization, siting of antennas and filters, and ill concentration of samples, cause fast fading, which can result in very important errors in the process of detection or demodulation of signal and in estimation of desired signal parameters. On the other hand, smart antennas improve mobile channels using special gain shapes which have broad features necessary for detecting mobile signals. If these changed gain patterns were applied before demodulation, detection and channel equalization performances would also improve.

7.5.2. Case Studies

Several studies have recently examined some potential advantages of integrating smart antennas and beamforming literally. Studies report significant user throughput and/or capacity improvements in broadband and multirate wireless systems. A multiuser detection (MUD)-based approach was taken to study the joint MUD optimization of spatial signature designs and transmitter power allocation for code-division multiple access with beamforming antennas. It was noted that smart antennas at the base station (BS) increase the overall capacity and allow for a larger number of users in the system, which improves beamforming-gain diversity at the BS. Similar capacity, throughput, and multirate user experience assertions were made, specifically noting that antenna beamforming helps boost the performance of the users in poor conditions, which, in turn, helps increase the total capacity of the system. Another study reported performance improvements in terms of both radiated power and overall system performance by using smart antennas with error control coding for broadband wireless systems.

Design issues were considered to support the incorporation of beamforming into downlink space-time block-coded CDMA systems. The theoretical and simulation results point to promising performance gains with implementations of the incorporation of beamforming in the system. It was shown that beamforming in integrated multirate systems under certain conditions significantly enhanced the diversity. It was noted that in mobile multipath areas, random traffic patterns could create deep fades and that proper power assignment and frame structure design can eliminate possible deep fades. Another study demonstrated that space-time coding techniques for MIMO systems can be applied to multicarrier CDMA systems with beamforming to yield diversity gains.

7.6. Challenges in Implementation

We have already seen that smart antennas, when combined with the recent high-speed wireless systems, can considerably improve their performance and capabilities. However, the realization of smart antennas entails many challenging issues and problems. Certain factors such as the architecture and technology presently used, the RF and microwave electronics needs, system calibration, system size and weight and other physical factors, cost, computational complexity and speed, operative environment etc., need to be carefully studied and optimized for a successful implementation. The prerequisites needed to solve the above problems may be totally different from those needed for other applications. The addressing of the following main issues and questions will play an important role in realistic smart antenna system implementations: What are the principal smart antenna technologies? Are they realizable? What are the basic hardware components needed? What are their limitations? What is architecture and technology? Is it standard or non-standard hardware? What is the size and weight? How many antennas, transceivers and PLL synthesizers are needed? What is the electrical specification? Are the present RF/microwave technologies able to provide the needed capabilities? If not, what new technologies or solutions are needed and for what specific application? What functionalities need electronic hardware implementation? What are the hardware limitations as far as cost, power, weight, size etc.? What specialized signal processing algorithms, computing power and speed are needed? What are the specific implementation costs for each application?

If smart antennas are to become omnipresent within the near future, and thus, their implementation is important, care must be taken to answer the above questions and provide technology that has all the attributes that are advantageous for successful and cost-effective implementation. In other words, the implementation pathway must be specific to an application.

7.6.1. Technical Challenges

The implementation of adaptive algorithms for mobile communication, especially high-speed communication with mobile terminals, has met both hardware and theoretical challenges. Theoretical challenges include the speeding up of recently developed multichannel adaptive algorithms, the study of adaptive multiuser detection for communications with more than one target user, the corruption of the received signals by some unknown additive noise, the development of robust modeling techniques, and the development of algorithms for blind detection or classification capability. Additional theoretical challenges relate to the problem of operating under austere conditions, such as when there is very high multipath fading, the possibility of deep message signal fading, near-far effects, an unknown additive noise, and the presence of more than one target user as well as other non-target users.

7.6.2. Environmental Factors

The influence of environmental factors, such as other antenna users, natural or artificial obstacles and radiation, other than the desired signals in the mobile communication environment, complicates the signal capturing. Because of continuous variation of both temporal and spatial channel structures, only tracking of a narrowband signal with specific direction characteristics is possible. There are several specific propagation phenomena, such as multi-path propagation, multi-path effect, and the Doppler effect, which have to be considered in tracking the narrowband signals for code phase search. The spatial-selectivity property of a smart antenna can be used in suppressing the undesired signal multipath components travelling along a different direction and enhancing the desired signal multipath components travelling along a specific direction. Simultaneously, due to the mobile environment, the antenna user creates a dot-like, moving source. The output pattern, such as a pencil beam as narrow as a few degrees, is made with many artificial arrays which may not be possible for a mobile environment, and consequently a wide pattern is desired for antenna steering for mobile users. For DHOFC or multiplication of the mobile user speckle time function, it suggests design directions for bandwidth to integrate for the model case, as well as the design directions for the bandwidth to integrate paths. The design of the larger band signals depends on the lower bandwidth requirement of the mobile channel, to compare all time-delay paths with code routers. Specifically, mobile propagation data stored in the code cordless phones in the time domains have the impulse type or almost periodic-like effects, causing Doppler Main Lobe properties to have the codes periodic, frequency spread comet, and oblateness properties.

7.7. Conclusion

The cooperation allowed by an intelligent envelope and large arrays removes the old tradeoff existing between size and gain, in the sense that a large array of small antennas provides far higher gains at very low cost than do large radiators. The more complex and multi-dimensional channel models are truly required for this case and the larger available bandwidths are probably needed in any event in order to increase the data rates. The ability of exploiting the direction of arrival of currently used communication waveforms opens a rich set of possibilities in the design of wireless transceivers aiming at high data rates but the proper exploitation will require many empirical studies and new theories.

While the general concept of using space and array techniques to increase the number of users for given ISI conditions and/or allow communication at greater rates is deeply rooted in the history of wireless communications, the specific new multi-dimensional techniques being used and planned are different from the prior art. The growing set of available system and technology concepts, embedded typically in large silicon chips, will increase the flexibility in the design of new microwave wireless transceivers. While the history of microwave wireless communication systems points to the possibility of vast systems able to exploit all of the various potential benefits discussed previously, such as large capacity, increased range, low cost, low power, long battery life, the economics of mass production for the large ISM low power wireless products will undoubtedly dictate the scales and sizes of the new wired relatives.

7.7.1. Future Trends

Smart antennas are an important component in the realization of high-speed wireless communication networks. They can enable mesh cellular networks as well as facilitate the provision of broadband services to rural areas without the deployment of expensive cable and fiber systems. For example, wireless on broadband access networks creation, satellite communication networks, ATM B-ISDN extensions over wireless, and mobile wireless LANs and MANs with high data rates and low delays require enhanced wireless communication system features such as: (1) dynamic real-time channels defined by location, (2) high capacity through spatial division multiplexing, (3) mobile-to-mobile communications, (4) spatial processing of each link in a wireless multipoint to multipoint communication system, and (5) multiband terminal with no primary known location, fixed distributions, and requires either asynchronization capabilities.

Antennas with compact size, light weight, and ergonomically acceptable terminal configuration to enable easy operation are the future requirement of the smart antennas for high-speed communication systems. The antenna radiation patterns must possess high directives and low-side lobes to lower the cross-coupling associated with spatial diversity. Antennas providing these types of radiation patterns will be difficult designs because of the small circuit size and limited effective area available when the applied multi-band dipole technology is used. Moreover, where required to support an intelligent limitation of the diversion, developed smart antennas must be submitted to specific control rules that take into account the form of the controllers used in the smart antenna application. Antenna should be programmed to follow those control rules.

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