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Preface

The term *smart antenna* is often used in mobile communications to describe an adaptive process designed to improve the capacity of a base station by focusing the radiated electromagnetic energy on transmit while improving the gain pattern on receive from a mobile system. This is called *space division multiple access*. Here, the transmitted signals from a base station are spatially directed to an intended mobile. In addition, the receive gain of the base station is also increased by spatially forming a beam along the direction of a mobile which is on a transmit mode. In this way the capacity of a base station can be increased, as it can now serve many mobile units simultaneously by directing a beam along each one of them. However, this promise of increased capacity through space division multiplexing can be further enhanced if one understands the true nature of an antenna (the source of radiating and/or the sensor of electromagnetic energy) which is the central point of this methodology. An antenna may be considered to be a device that maps spatial-temporal signals into the time domain, thus making them available for further analysis in a digital signal processor. In this philosophical framework, an ideal antenna is one that converts the spatial-temporal signals arriving at an antenna into a temporal signal without distortion. Hence, there is a tacit assumption that no information is destroyed by the antenna. This may be true when dealing with narrowband signals, but when considering the transmission of broadband signals, even a small radiator called a Hertzian dipole operating in free space behaves differently on transmit than it does on receive. It is important to note that in electromagnetics there does not exist any isotropic radiator, as even a *Hertzian dipole* has a directive pattern. However, along a certain plane the pattern can be omni-directional. On transmit the far field of an antenna (even that of a small Hertzian dipole operating in free space) is the time derivative of the input transient waveform fed to its input terminal. While on receive, the same antenna acts as a spatial integrator of the fields that are incident on it. Hence, the temporal and spatial properties of an antenna are intimately related and it is not advisable to separate them if one wants to realize the full potential of an antenna system. In this book the term *smart antenna* is used to imply that one is dealing appropriately with the dual spatial and temporal properties of an antenna on both transmit and receive.

An admirer of James Clerk Maxwell (the actual discoverer of electromagnetism) or Heinrich Hertz (the true father of radio, as he not only formulated the four equations of Maxwell that are available in electromagnetic textbooks today but also produced an experimental device to generate, transmit, propagate, and receive electromagnetic energy) will realize immediately that antennas act simultaneously as temporal and spatial filters. In addition, an antenna is a spatial sampler of the electric fields. One of the objectives of this book is to explain the basic difference between adaptive antennas and adaptive signal processing. Whereas for the former an antenna acts as a spatial filter, and therefore processing occurs in the angular domain, a signal-processing algorithm is applied in the temporal domain. To identify whether one is dealing with adaptive antennas or adaptive signal processing is to ask the following simple question: For a narrowband communication, can the adaptive system separate a desired signal from its coherent multipath components? In this case, there is not only a signal, but also multipath components that are correlated with the desired signal and interact (in either a constructive or destructive fashion) with the signal. Only an adaptive antenna can isolate the desired signal from its coherent multipath, as the information on how to separate them is contained in the angle of arrival (i.e., in the spatial domain). There is little information in the temporal domain for this case. In a conventional signal-processing algorithm, this type of coherent multipath separation is not trivial, and secondary processing that utilizes spatial concepts from electromagnetics is necessary. The critical point is that temporal processing cannot separate coherent signals spatially, since the differences between the signals manifest themselves in the spatial domain and not in the temporal domain. The signal-processing community sometimes views an antenna as a temporal channel, whereas practitioners of electromagnetics always consider an antenna to be a spatial filter. We want to distinguish between these disjoint temporal and spatial properties by adding the term *smart antennas* which we imply that we are merging these two distinct methodologies to provide better systems. In fact, in an adaptive system, one is shaping the spatial response of an antenna by processing the time domain signal. Hence, we do not treat these two spatial and temporal properties separately. An additional advantage to using this coupled spatial-temporal methodology is that we have a well-established mathematical tool, which treats this space-time continuum in an exact way. This mathematical framework for such a system is described by one of the oldest sets of equations in mathematical physics, equations that have withstood the test of erosion and corrosion of time. Even the advent of relativity has had little effect on them. This analytical framework is given by Maxwell's equations. A related problem that also needs to be addressed is what actually limits the speed of communication: is it based on the channel capacity defined by Shannon which does not include the speed of light or is it based on the dispersion introduced by the propagation medium as per Maxwell's equations? A moment of reflection on this critical question will reveal that we need to develop the problem along the space-time continuum as formulated by the Maxwell's equations.

Another objective of this book is to illustrate procedures for adaptive processing using directive elements in a conformal array. Under the current philosophy, it is uncommon to use directive elements in a phased array or antenna elements that are not uniformly spaced. The current thinking is that if one does not use omnidirectional antenna elements, it may not be possible to scan over wide angles. To increase the directive gain of the phased array, one increases the total number of elements by hundreds or even thousands. This increases the cost significantly, as one needs an analog-to-digital converter at each antenna element in addition to a complete receiver channel for downconversion of the radio-frequency signal to baseband. The complexity of a phased array can also be reduced if we employ directive antenna elements on a conformal surface. In addition, individual antenna elements may be nonuniformly spaced, or the conformal array can even be nonplanar. To treat such general array configurations in this book, we describe an electromagnetic preprocessing technique using an array transformation matrix which broadens the fundamental principles of adaptive antennas. Here we address phased array applications, including direction finding or angle-of-arrival estimation and adaptive processing utilizing directive elements that may be nonuniformly spaced and operating in the presence of near-field scatterers.

We also address problems in radar and mobile communications. To perform adaptive processing we need to have some *a priori* information about the signals that we are trying to detect. For dealing with phased array radars, we generally know or assume the direction of arrival of the signal of interest, as we know *a priori* along which direction the mainbeam of the array was pointing, or equivalently, along what spatial direction the energy was transmitted. Thus in radar, our goal is to estimate the strength of the reflected signal of interest, whose direction of arrival is known. What is unknown is the jammer interference and clutter scenario. Furthermore, we present a direct data domain approach that processes the data on a snapshot-by-snapshot basis to yield the desired information. Here, a snapshot is defined as the voltages available at the terminals of the antenna at a particular instance of time. Since we are processing the data in a batch mode, it is highly suitable for characterizing a dynamic environment where the nature of the interference and clutter may change over time. The direct data domain least squares approach presented in this book estimates the signal in the presence of jammer interference, clutter, and thermal noise. In this technique no statistical information about the clutter is necessary. Also, since no covariance matrix is formed in this procedure, the process can be implemented in real time on an inexpensive digital signal processing chip. We also present an extension of this technique to include traditional statistical processing when dealing with space-time adaptive processing.

Unlike radar, in mobile communications it is difficult to know *a priori* the direction of arrival of the signal. In this case, we exploit the temporal characteristics of the signal through introduction of the principles of cyclostationarity. Again a direct data domain method is presented to solve this problem on a snapshot-by-snapshot basis using the principles of cyclostaionarity. The advantage of exploiting the temporal characteristics of the signals is that the number of interferers can be greater than the number of antennas. However, the number of coherent interferers at the same frequency needs to be no more than half the number of antenna elements. Also shown is a method to incorporate the effects of mutual coupling between antenna elements and the effects of near-field scatterers, to improve the overall system performance.

One unique topic in this book is a multistage analysis procedure that combines electromagnetic analysis with signal processing. Initially, electromagnetic principles are applied to compensate for the effects of mutual coupling between antenna elements, including the effect of nonuniformity in the spacing between the elements and the presence of near-field scatterers. Then a direct data domain methodology is implemented to yield the signal of interest. A deterministic model for the signal of interest yields a lower value for the Cramer–

Rao bound than those using stochastic methods. In this approach, no statistical information about the interference environment is necessary. This makes it possible to perform real-time processing in a dynamic environment. These principles have been applied for space-time adaptive processing of experimental data obtained from an airborne multichannel radar system.

We also present a survey of various models for characterizing radio-wave propagation in urban and rural environments. We describe a method where it is possible to identify and eliminate multipath without spatial diversity and optimize the location of base stations in a complex environment.

Finally, it is demonstrated that in mobile communication where the transmit and receive ports can be clearly defined, it is possible to direct the signal from base stations to mobile units without having any *a priori* knowledge about their spatial coordinates or knowing the near-field electromagnetic environment in which they are radiating. This is possible through invocation of the principle of reciprocity. This approach will make space division multiplexing more than just an experimental concept but a commercial success.

Every attempt has been made to guarantee the accuracy of the material in the book. We would, however, appreciate readers bringing to our attention any errors that may have appeared in the final version. Errors and any comments may be e-mailed to either author.

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INTRODUCTION

1.1 SOME REFLECTIONS ON CURRENT THOUGHTS

The fundamental bottleneck in mobile communication is that many users want to access the base station simultaneously and thereby establish the first link in the communication chain. The way the scarce resources of the base station are distributed to mobile users is through sharing. This is a technical definition of the term *multiple access*. Therefore, multiple accesses are implemented by sharing one or more of the four resources of the base station by the various mobile users randomly located in space and time. By *time* we imply that different users may start using the system at different times. This sharing can take place in any of the following four ways [1, 2]:

1.) *Bandwidth* (*Frequency Division Multiple Access* or in short, FDMA). Here, the frequency spectrum or the entire bandwidth is portioned off to different users and allocated for that communication duration. Hence each user communicates with the base station over an allocated narrow frequency band for the entire duration of the communication.
2.) *Time* (*Time Division Multiple Access* or in short, TDMA). Here, each mobile has the entire frequency resource of the base station for a short duration of the time (i.e., each user accesses the entire spectrum of the base station for a finite duration in an ordered sequence). With the advent of digital technology it is possible to have an intermittent connection for each mobile with the base station for a short period of time, and in this way the valuable frequency resource of the base station is shared.
3.) *Code (Code Division Multiple Access* or in short, CDMA). In this case, each user is assigned a unique code. In this way the user is allowed to access all the bandwidth, as in TDMA, and for the complete duration of the call, as in FDMA. All the users have access simultaneously to the entire spectrum for all the time. They are interfering with each other, and that is why this methodology was originally conceived as a covert mode

of communication. There are two main types of CDMA. One is called *direct sequence spread spectrum multiple access*, and the other is called *frequency hopped spread spectrum multiple access*. In the first case, two-way communication is accomplished through spread spectrum modulation where each user's digital waveform is spread over the entire frequency spectrum that is allocated to that base station. Typically, on transmit, the actual signal is coded and spread over the entire spectrum, where on receive, the intended user first detects the signal by convolving the received signal with his/her unique code and then demodulates the convolved signal. In the second case the transmit carrier frequency changes as a function of time in an ordered fashion so that the receiver can decode each narrowband transmission. At first glance it appears that CDMA is more complex than TDMA or FDMA, but with the advent of novel digital chip design, it is easy to implement CDMA in hardware.

4.) *Space* (*Space Division Multiple Access* or in short, SDMA). If a base station has to cover a large geographical area, the region is split into cells where the same carrier frequency can be reused in each cell. Therefore, for a large number of cells there is a high level of frequency reuse, which increases the capacity. In this primitive form the transmitted power of the base station limits the number of cells that may be associated with a base station since the level of interference at a base station is determined by the spatial separation between cells, as the mobiles are using the same frequency. This is one of the reasons that microcells and picocells have been proposed for personal communication systems. However, it was soon realized that the capacity of the base station could be increased further by spatially focusing the transmitted energy along the direction of the intended users. In this way, transmission can be achieved at the same carrier frequency simultaneously with different users. This can be accomplished by using an array of antennas at the base station and either a switched beam array or a tracking beam array can be used to direct the electromagnetic energy to the intended users.

In current times it appears that further enhancement in the capacity of a communication system can be achieved primarily in the implementation of SDMA. This is generally carried out using an adaptive process where we have a collection of antennas called *phased arrays*. One now dynamically combines the output from each antenna element using different weights. The weights modify the amplitude and phase of the voltages received at each antenna element. Through an appropriate combination of the voltages that are induced in them by the incident electromagnetic fields, one forms an antenna beam. This antenna beam can either be steered continuously or the beam can be switched along certain prefixed directions by selecting a set of *a priori* weights. This can be achieved in either of two ways.

The first way is to design an antenna with a narrow main beam. This is generally implemented by using a physically large antenna, as the width of the main lobe of the antenna is inversely proportional to the physical dimensions.

Hence, an electrically large antenna structure will have a very narrow beam and may also possess very low sidelobe levels. Creation of very low sidelobe levels may require extremely high tolerances in the variability of the actual physical dimensions of the radiating structures. This requires accurate design of the antenna elements in the phased array. Now one can mechanically steer this high-gain antenna to scan the entire geographical region of interest [3, 4]. This is actually done in developing the rotating antenna arrays in AWACS (Airborne Early Warning and Control System) radars [5]. Such a design makes the cost of the antennas very high. The other alternative is to use simple antenna elements such as dipoles, and then form the antenna beam by combining the received signals from a number of them by using a signal-processing methodology. This usually requires a receiver with an analog-to-digital converter (ADC) at the output of every antenna element, which also increases the cost. The signals from the antenna elements are now downconverted and sampled using an ADC, and then a digital beam-forming algorithm is used to form the main beam along the desired direction and to place nulls in the sidelobe regions along the direction of the interferers. The advantage of digital beam forming is that one can form any arbitrary low level of sidelobes with any width of the main lobe along the look direction [3, 4].

Historically, analog beam forming has been going on for a long time. Also, application of the Butler matrix to combine the outputs of the antenna elements is similar in principle to application of the fast Fourier transform (FFT) to the output voltages available at the antenna elements to form a beam [3, 4, 6]. This is because the far field is simply the Fourier transform of the induced current distribution on the radiating structure. Even though there is a one-to-one correspondence between the Butler matrix and the fast Fourier transform, there is an important fundamental difference. The Butler matrix processes the signals in the analog domain, whereas an FFT carries out similar processing in the digital domain. By processing signals in the analog domain, one is limited by the Rayleigh resolution criterion, which states that in order to resolve two closely spaced signals in space (i.e., their directions of arrival at the antenna array are very close to each other), one needs an antenna whose physical size is inversely proportional to the difference in the spatial angles of arrival at the array. Therefore, the closer two signals are located in space, the greater should be the physical size of the antenna in order to separate the two incoming signals. Therefore, the physical length of the array determines the angular resolution of a phased array performing analog processing. On the other hand, digital beam forming allows us to go beyond the curse of the Rayleigh limit if there is adequate signal strength and enough effective bits in the measured voltages (dynamic range) at each of the antenna elements to carry out beam forming [7].

Typically, adaptive beam forming is supposed to be synonymous with digital beam forming and smart antennas [1]. The term *smart antennas* implies that the antenna array can operate in any environment and has the capability to extract the signal of interest in the presence of interference and clutter and thus to adapt to the signal environment. However, a very important factor has been overlooked in the design process of adaptive systems. For example, if one observes a typical cellular phone, the chip and the signal processors that have been used in the system were probably developed within the last year, but the key ingredient (i.e., the antenna) currently used in many systems was developed about 100 years ago by Hertz, as it is a modification of a simple dipole. Nowadays, the dipole is being replaced by some form of helix (bifilar or quadrifilar), which had been used in AM radios for almost 75 years. The same disparity in technology can also be observed in television sets. Even though a modern television set may have advanced components both for video displays and for processing the video and audio signals, the very high frequency (VHF) antenna is still the "rabbit ear"—a dipole, and the ultra high frequency (UHF) antenna is a loop which was developed in the early nineteen hundreds. The principle behind such wide disparities in component technologies of modern communication systems lies primarily in the assumption that an antenna captures a spatial-temporal signal propagating through space and transforms it into a pure temporal signal without any distortion. This assumes that the antennas are essentially isotropic omnidirectional point radiators. That is the reason why in contemporary literature the antenna is often referred to as a sensor of a temporal channel. In electromagnetics, the smallest source is an infinitesimally small dipole and it does not have an isotropic pattern, even though it is omnidirectional in certain planes.

An antenna to a spatial signal is equivalent to what an ADC is to a temporal signal. The purpose of an ADC is to produce high-fidelity temporal samples through the sample-and-hold mechanism of a temporal signal. For an ADC to be of good quality, it is essential that the sample time be much smaller than the hold period so that the sampled values provide a true representation of the analog signal. However, the quality of the ADC becomes questionable if the hold time is comparable to the sample time. In that case the temporal sample obtained from the ADC is not going to be representative of the true signal, as the ADC averages the output over the sample period, during which the signal of interest may have wide variations in amplitude. Under this scenario, where the hold time is comparable to the sample period, unless the effects of the ADC are removed through deconvolution, additional signal and data processing may not produce meaningful results.

This same problem arises in the practical application of antennas. An antenna is a spatial sampler of the electromagnetic fields propagating through space. A receiving antenna generally samples the electric field over its length and produces a voltage at the antenna terminals by integrating vectorially the electromagnetic fields incident upon it. When dealing with narrowband electromagnetic signals, a high-quality receiving antenna is often composed of an array of half-wavelength dipoles, typically spaced a half-wavelength apart [3–5]. So in an adaptive antenna environment, we are assuming the integrated value of the electrical field over a half wavelength to be equal to the actual value of the electric field at a point in space which corresponds to the feed point of the antenna. In other words, we are replacing the value of the incident electromagnetic field at the feed point of the antenna by a quantity that is the integral of the electromagnetic fields over a half wavelength in space. Thus by comparing the performance of a finite-sized antenna in spatial sampling of electromagnetic fields to that of temporal sampling of a signal by an ADC, it is quite clear that unless the effects of the antenna are removed from the measured data, signal and data processing may not result in the desired output. This is due to the basic premise that the spatial integral value of the electric field along the half-wavelength antenna is representative of the actual value of the electric field at the antenna feed point. This is not correct. Hence, one of the objectives of this book is to merge the electromagnetic analysis with the signal processing [7–11]. Now one can implement adaptive processing using realistic antenna elements operating in close proximity and incorporate mutual coupling effects. Moreover, there may be coupling between the antenna elements and the platform on which it is mounted. In addition, there may be near-field scatterers, including other antennas, buildings, trees, and so on, near the array that may again distort the beam. In this book we present and illustrate methods for adaptive processing incorporating near-field electromagnetic effects.

When dealing with broadband signals, we often assume that the omnidirectional isotropic point radiators have no effects on the signal. Such a simplistic assumption is seriously flawed. An antenna is not only a spatial sampler of the propagating electromagnetic field, it has a temporal response as well. It has a unique transfer function. For example, the far-field response from even an electrically small antenna is the result of a temporal differentiation of the driving time domain waveform. In addition, the radiated waveforms will have different signal shapes along different spatial directions. Moreover, an antenna of finite size will not mimic an omnidirectional point radiator in performance. On receive, an antenna vectorially integrates the spatial-temporal waveform that is incident on the structure. Therefore, unless the transfer function of the antenna is removed from the measured data, carrying out additional signal processing may not lead one to the correct solution to the problem at hand. This is not a simple problem, as the impulse response of both a transmitting and a receiving antenna of finite size is dependent simultaneously on both azimuth and elevation look directions. In a practical situation it is difficult to characterize the impulse response of either a transmitting or a receiving antenna, as it is difficult to know *a priori* at what azimuth and elevation angles the coupling is taking place. In broadband applications, the antenna responses must be accounted for. The easy way out in most practical systems in theory and in practice is to deal only with narrowband signals. One of the objectives of this book is to initiate a dialogue so that adaptive processing of the data collected through an antenna is performed in the correct fashion. Thus by combining electromagnetic analysis with signal processing, one can build toward a much more effective solution to the problem at hand.

A related problem in adaptive processing is that one often uses antenna elements that are very close to omnidirectional in nature. Even a dipole may have some directivity in elevation, but in azimuth it is still omnidirectional. This may not be an intelligent choice for cellular telephony, since a mobile will radiate most of the power in azimuth directions away from the intended user. The efficiency of a mobile communications system can be improved by using directive elements in a phased array. However, the problem with using directive elements is that it is not clear how to apply classical adaptive processing. Beamspace solutions offer one answer, but there may be others. One of the objectives of this book is to suggest adaptive systems with directive antenna elements and to illustrate how the measured outputs from directive elements can be combined when the directive element patterns of the antenna elements are properly oriented. Equivalently, the antenna elements in an array can be distributed nonuniformly to cover the physical structure and thereby further increase the radiation/receive efficiency. This is particularly useful in mobile systems, where the electromagnetic environment is not predictable nor may it be characterized in an accurate fashion. We address these issues and more in the following chapters.

1.2 ROADMAP OF THE BOOK

The book is organized as follows:

Chapter 2 provides a historical overview of Maxwell's equations and presents some simple formulas to calculate the impulse response of selected canonical antennas. Our purpose is to demonstrate that even an infinitesimally small point source radiating a broadband signal in free space has a nontrivial impulse response and that their effects must be included in channel characterization. Measured results are also provided to illustrate impulse responses of some typical antennas and physical platforms over which they may be mounted.

In Chapter 3 we describe the anatomy of an adaptive process and present classical historical developments (i.e., statistically based methodologies where one needs to have an aggregate of the voltages at the antenna elements over some spatial-temporal duration). Appendix A further delineates the differences between a deterministic approach and a stochastic approach and illustrates the strengths and weaknesses of each.

In Chapter 4 we describe a direct data domain least squares (D^3LS) approach, which operates, on a single snapshot of data. The advantages of using a D^3LS over conventional stochastic methodologies are explained in Appendix A. There are various compounding factors such as nonstationarity of the data and real-time signal processing issues that are aided by a deterministic model, as it is well suited to applications in a highly dynamic environment where processing data on a snapshot-by-snapshot basis is appropriate. In addition, there is no need to develop a stochastic model for clutter, which in a direct data domain approach is treated as an undesired signal just like interferers and thermal noise. For a conventional adaptive system a *snapshot* is defined as the set of voltages measured at the terminals of the antennas. Both the interference and clutter in this algorithm are treated as undesired electromagnetic signals impinging on the array. Since no covariance matrix is formed in this method, a least squares method operating on a single snapshot of the data can be implemented in real time using a modern digital signal-processing device. To this end a survey of the various forms of the adaptive conjugate gradient (CG) algorithm are presented in Appendix B. Their suitability when dealing with adaptive problems is also illustrated. In addition, several variants of this direct data domain least squares method can be implemented in parallel so that independent estimates of the same solution can be obtained. In reality, where the actual solution is unknown, different independent estimates can increase the level of confidence of the computed solution.

In Chapter 5 we illustrate how electromagnetic analysis can be utilized to correct for mutual coupling in an adaptive algorithm. Computed results with and without mutual coupling effects between the antenna elements are presented to illustrate the point that in a real system the finite size of the antenna must be accounted for. The efficiency of using a single snapshot of data for real-time processing is also discussed. It is shown that use of a direct data domain approach such as the Matrix Pencil along with an electromagnetic compensation technique leads to an accurate determination of the directions of arrival in a CDMA environment. The Matrix Pencil technique for both the one- and two-dimensional cases are described in Appendix C.

Chapter 6 demonstrates a two-step process implemented to extract the signal of interest in the presence of interferers and clutter when the antenna elements in the receiving array are nonuniformly spaced and operating in the presence of other near-field scatterers. The placement of the antenna elements in the array need not be coplanar. In addition, we illustrate how a conformal nonuniformly spaced microstrip patch array located on the side of an aircraft can be used for both direction finding and adaptive processing. Even though significant amounts of scattered energy are incident on the array from the wing and the fuselage, performance is not degraded and processing is carried out on a snapshot-by-snapshot basis. For these classes of radar-related problems, we generally assume that the direction of arrival of the signal of interest is known *a priori*. Additional examples are presented to illustrate how direction-of-arrival angle estimation can be carried out using conformal arrays on hemispherical and cylindrical surfaces having directive antenna elements with polarization diversity.

However, in a mobile communication environment we do not know *a priori* the direction of arrival of the signal of interest, and hence a different type of *a priori* knowledge about the signal is required. Chapter 7 describes the concept of cyclostationarity to illustrate how the D^3LS method can be applied to a set of received voltages at an antenna array which need not be coplanar and operates in the presence of mutual coupling and near-field scatterers. These techniques are called *blind methods*, as no training signals are necessary. We still carry out processing on a snapshot-by-snapshot basis, so this adaptive procedure is highly suitable in a dynamic environment.

Chapter 8 provides a survey of the various propagation models currently used in characterizing mobile communication channels. It includes both stochastic and numerical models.

Chapter 9 describes methods for optimizing the location of base stations for indoor wireless communications subject to a certain quality of service in a given environment. A survey of the various optimization techniques is presented to illustrate what class of methods is well suited for these types of problems.

In Chapter 10 we present a frequency diversity technique that can identify and eliminate various multipath components without spatial diversity.

In Chapter 11 we describe a methodology for directing the signal from a base station to a specified mobile user while simultaneously placing nulls along the direction of the other mobiles utilizing the principles of reciprocity. The advantage of this technique is that directing the electromagnetic signals to an intended user is possible without any knowledge of the physical location of the antennas or the electromagnetic multipath environment in which the system is operating. It is not even necessary to know the spatial coordinates of the transmitter or receiver.

Chapter 12 illustrates the extension of the D^3LS method to space-time adaptive processing (STAP). In this section the single snapshot-based direct data domain methodology is applied to the data collected by a side-looking airborne radar to detect a Saberliner aircraft in the presence of terrain and sea clutter. Several variations of the direct data domain methods are presented. Here also we use a single snapshot and model clutter in a deterministic fashion as unwanted electromagnetic signals. The voltages received at each antenna element in space and sampled in time corresponding to a single range cell characterize a single space-time snapshot corresponding to a specific range cell. Hence, in this approach we process the data on a range cell-by-range cell basis. Comparisons are also made with conventional statistical methods to illustrate the quality of the solution that can be obtained by applying this method to measured radar data. Another important factor is that direct data domain procedures require far fewer computational resources than a conventional stochastic covariance-based methodology. The direct method is further extended to carry out STAP using data from a circular array. Next, a hybrid STAP technique is described which utilizes the good points of both a direct method and a stochastic method. Finally, a knowledge-based STAP is described which is capable of automatically selecting the most appropriate method for a given data set.

The unique features of this book are:

1.) Electromagnetic analysis and signal-processing techniques are combined to analyze and design adaptive systems. Thus the presence of mutual coupling between antenna elements and the presence of near-field scatterers can be incorporated in the analysis.
2.) A direct data domain least squares algorithm is developed which processes the data on a snapshot-by-snapshot basis. Thus it is quite suitable for real-time implementation the use of *a priori* information either through the direction of arrival or through use of the concept of cyclostationarity and processing a single snapshot of data.
3.) The principle of reciprocity is exploited to direct a signal to a mobile user while simultaneously placing nulls along other directions without any spatial information about the base station or the mobile user or exact characterization of the electromagnetic environment in which they are operating.

4.) The direct data domain approach is extended to include space-time adaptive processing for dealing with side-looking radars to carry out filtering in space and time to detect weak signals in the presence of terrain and sea clutter using either linear or circular arrays. A knowledge-based STAP approach is described which is quite suitable for making use of a variety of algorithms, depending on the given data set. One advantage of this methodology is that it is transparent to a user.

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