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.