During World War II, the capabilities and usefulness of radars improved significantly. Robert Watson-Watt's radar technology was quickly refined, becoming the British Chain Home air defense radar. This radar helped protect the British from air attacks during World War II. Infamously, the incoming wave of fighters during the Pearl Harbor attack was detected by an early air-surveillance radar, but this information was not used by US military commanders. This lack of appreciation for the value of radar technology changed quickly as the use of radar became pervasive by the military during the war. In fact, many of the radar concepts currently employed were developed during or just after the war, including air defense, ground-approach radar, fire control, and moving-target indication (MTI) radars.

After World War II, radar concepts continued to be developed, although not at the same rapid pace. Not until the advent of synthetic aperture radar (SAR), which became an active area of research during the 1950s [3], was there a significant change in the basic concept originally defined by Hulsmeyer. In the 1960s, the development of phased-array antennas became an important area of research, allowing radars to quickly change search direction. During the 1970s, digital signal processing became viable, and was applied to radar processing, enabling adaptive array processing and the modern radar system. Once again, driven by the advances in computational capabilities, which allow system designers to consider more complicated processing, multiple-input multiple-output (MIMO) radars have become an active area of research.

2.1.2 Definition and Characteristics of MIMO Radar

The notion of MIMO radar is simply that there are multiple radiating and receiving sites [4], as shown in Fig. 2.1. The collected information is then processed together. In some sense, MIMO radars are a generalization of multistatic radar concepts. The underlying concepts have most likely been discovered independently numerous times [5]. While not using the nomenclature MIMO radar, the RIAS and SIAR radars [6,7],

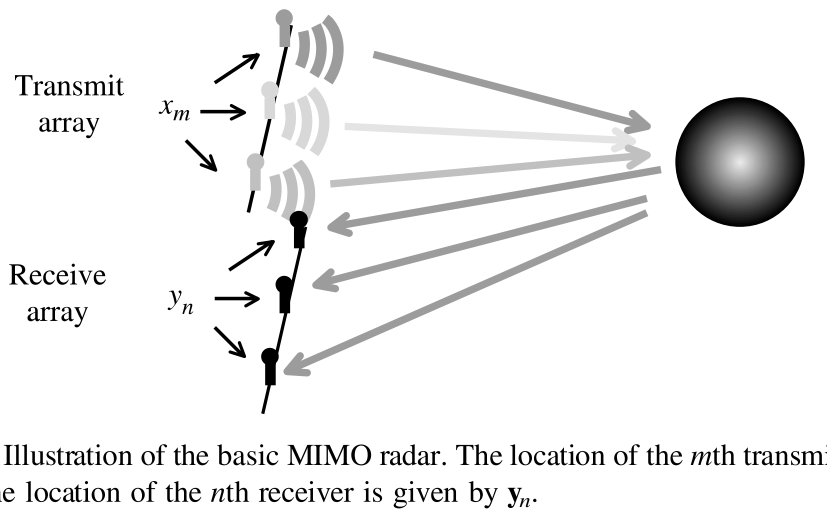

Figure 2.1 Illustration of the basic MIMO radar. The location of the mth transmitter is given by $\mathbf{x}_m$, and the location of the nth receiver is given by $\mathbf{y}_n$.

that are experimental systems developed to study air-surveillance technology, are early examples of systems that could be classified as MIMO radars.

By the most general definition, many traditional systems can be considered as special cases of MIMO radars. As an example, SAR can be considered as a form of MIMO radar. Although SAR traditionally employs a single transmit antenna and a single receive antenna, the positions of these two antennas are translated and images are formed by processing all the information jointly. The significant difference between this radar and a "typical" MIMO radar, which takes full advantage of the degrees of freedom, is that SAR does not have access to channel measurements for all transmit–receive position pairs. Equivalently, one may say that only the diagonal elements of the channel matrix are measured. Similarly, a fully polarimetric radar, that is, a radar that measures both receive polarizations for each transmit polarization, is an example of MIMO radar [4,8]. Clearly, it is a MIMO radar with a relatively small dimensionality. In addition, some spatial interpretations of MIMO radar have to be considered in a different context for polarimetric radars.

Various possible signaling techniques are used for MIMO radar. The transmit antennas radiate signals, which may or may not be correlated, and the receive antennas attempt to disentangle these signals. In much of the current literature, it is assumed that the waveforms coming from each transmit antenna are orthogonal, but this is not a requirement for MIMO radar. However, orthogonality can facilitate the processing. Two simple approaches to obtain orthogonality are to use time division or frequency division multiplexing. However, both approaches can suffer from potential performance degradation (assuming coherent operation) because of the loss of coherence of the target response. The scattering response of the target or background is commonly time-varying or frequency-selective, limiting the ability to coherently combine the information from the antenna pairs. In some applications, it is desirable to introduce correlation between the transmitted signals. For some tracking problems, optimal asymptotic angle estimation performance is given by employing strongly correlated signals [9].

There is a continuum of MIMO radar systems concepts; however, there are two basic regimes of operation considered in the current literature. In the first regime, the transmit array elements (and receive array elements) are broadly spaced, providing independent scattering responses for each antenna pairing, sometimes referred to as *statistical MIMO radar*. In the second regime, the transmit array elements (and receive array elements) are closely spaced so that the target is in the far field of the transmit–receive array, sometimes referred to as *coherent MIMO radar*. Here it is assumed that the target's scattering response is the same for each antenna pair, up to some small delay. While the answer to the question "How large must the angular separation be to get independent scattering responses?" is dependent on the details of the target, a sense of scale is provided by thinking of the target as an array of scatterers with phase responses optimized to focus energy toward one of the antennas. As shown in Fig. 2.2, if an array of appropriately phased scatterers of the physical size of the target can resolve individual locations of the antennas, then independent scattering responses would theoretically be possible. Conversely, if the overall angular antenna separation were small compared to the "beamwidth"

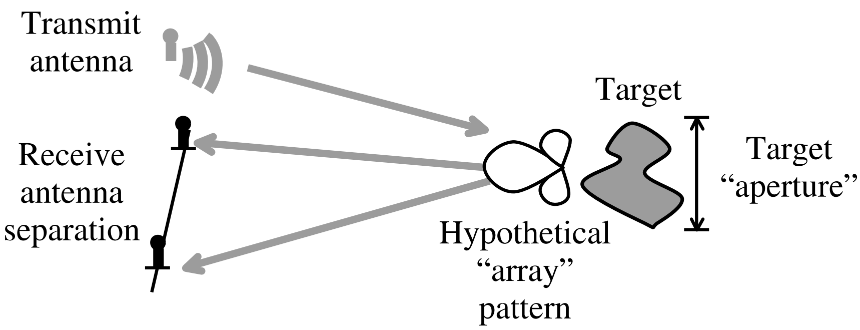

Figure 2.2 Coherent versus incoherent scattering response.

of the scatterer array, then coherent processing would be viable. This analysis is easily interpreted for air-surveillance radars for which a target is well separated from any background. While the discussion is still valid, the interpretation of a target can be less clear in the presence of a background.

2.1.3 Uses of MIMO Radar

There are a variety of potential advantages to using MIMO radar. For given system design choices, some of these advantages can be traded for others:

- Improved target detection performance
- Improved angle estimation accuracy
- Decreased minimum detectible velocity

For the first type of MIMO radar discussed in Section 2.1.2, in which the individual transmit and receive antennas are separated widely, the diversity provided by the multiplicity in transmit and receive angles can be exploited to improve the statistics of the detection performance. Similar to frequency diversity used in some traditional radars, spatial (angular) diversity can be employed to reduce the probability that a "bad" scattering response causes a target to be missed.

For the second type of MIMO radar discussed in Section 2.1.2, in which the antennas are spaced relatively closely, angle estimation performance can be improved. The estimation performance improvement can be dramatic when optimized sparse arrays are used. In some sense, the performance of the MIMO systems can be characterized by a virtual array constructed by the convolution of the locations of the transmit and receive antenna locations. Consequently, a filled virtual array can be constructed by using sparse constituent arrays. In principle, this virtual array can be much larger than the array of an equivalent traditional system; thus, the MIMO system will have much better intrinsic resolution.

Implicitly, with any array design, there is a tradeoff between spatial ambiguities caused by spatial sidelobe levels and the intrinsic spatial resolution. Specifically, in traditional antenna array processing, sparse arrays can provide a larger aperture than can filled arrays, providing improved angular resolution compared to a filled array. However, this performance improvement comes at the expense of increased sidelobe levels. Similarly, MIMO virtual arrays can be constructed to be sparse, filled, or overfilled. MIMO sidelobe levels can be reduced by decreasing the virtual array aperture size. The importance of the trade depends on the application being addressed. For upward-looking radars, such as air-surveillance radars, sidelobes are not a dominating concern. However, for airborne ground surveillance radars, ambiguities with clutter background can be a driving design constraint.

Compared to traditional systems, MIMO ground moving-target indication (GMTI) radars can be employed to improve minimum detectable velocities. Minimum detectable velocity is sensitive to both the aperture size and integration interval. Both of these characteristics can be improved using MIMO radars. There is a question of how to make a fair comparison. Performance criteria are different depending on whether the radar is doing wide-area surveillance or tracking a particular target. For the moment, we consider wide-area surveillance. In this mode, typical GMTI systems either transmit from an single element (or subarray) covering a larger area, or scan a beam from the transmit array over the area of interest. For a comparison with a traditional GMTI transmitting from a single element, the MIMO system may have n_T transmitters illuminating the same area. Assuming that the MIMO system is transmitting independent sequences simultaneously, so that the radiated power combines incoherently, the MIMO system may illuminate the ground with n_T times as much power. If the traditional GMTI system uses the entire transmit array coherently, sweeping a beam to perform its surveillance, as seen in Fig. 2.3,

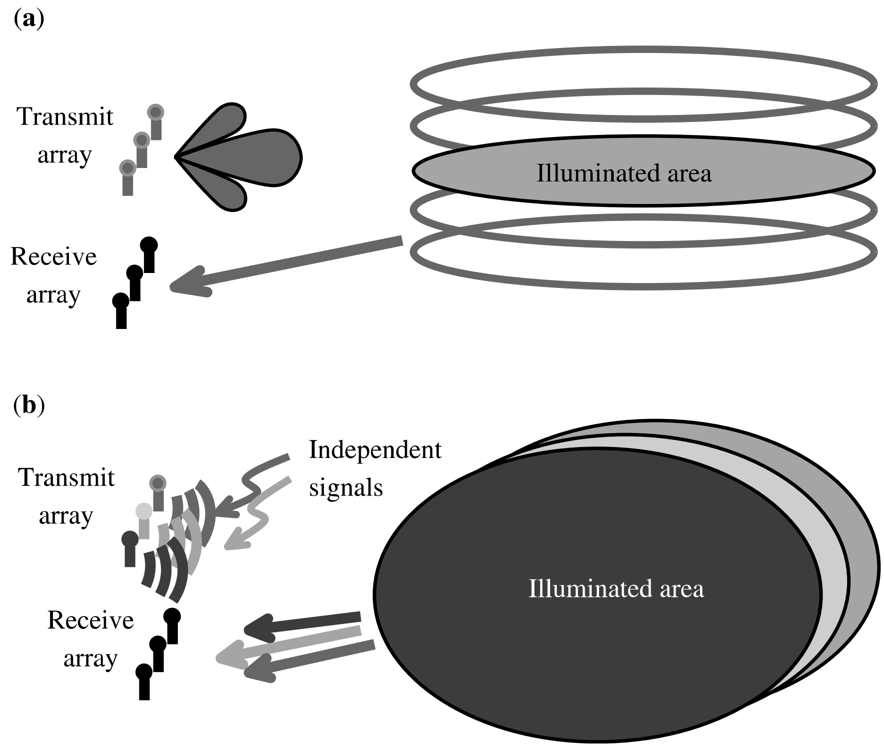

Figure 2.3 Illumination patterns of (a) traditional scanning radar and (b) MIMO radar assuming independent transmit signals.

then the traditional system illuminates the ground with n_T^2 as much power as that of a single antenna. However, the beam must be swept over the region of interest. The integration interval is about $1/n_{\text{beams}} \approx 1/n_T$. As a consequence, the integrated power is proportional to n_T^2/n_T. The MIMO system would illuminate this same total region continuously, so that the average power on the ground for the MIMO system and the swept beam is approximately the same. The combination of the longer illumination and the larger aperture of the MIMO radar provides for the possibility of improved minimum detectable velocity for GMTI systems.

2.1.4 The Current State of MIMO Radar Research

The field of MIMO radar is growing rapidly. It would be nearly impossible to cover every paper on this topic. However, here we attempt to provide a snapshot of the state of MIMO radar research.

2.1.4.1 Statistical MIMO Radar While it is not the focus of this chapter, it certainly is worth mentioning some of the research in diversity-oriented MIMO radar. Fishler [10] and Lehmann et al. [11] discuss the benefits of spatial diversity enabled by using MIMO radar. Dai et al. [12] discuss variations on this theme, in which “closer” antenna spacings are allowed. In general, these papers discuss improvements in detectability of a target because of the multiple bistatic viewing angles enabled by widely separated transmit and receive antennas.

2.1.4.2 Coherent MIMO Radar The notion of MIMO radar using closely spaced elements is discussed in Refs. 4, 14, and 15. The degrees of freedom and virtual array interpretation of MIMO radar are discussed in Refs. 4, 14, and 16, which includes a discussion of detection performance. In Ref. 4 the construction of filled or nearly filled virtual antennas arrays given sparse transmit and/or receive arrays is presented. For array design, given a certain number of antennas, there is often a tradeoff between aperture, and spatial sidelobe level. The same is true for MIMO radar. The height of these sidelobes determines the threshold point. The threshold point is the SNR at which an estimator will diverge from the Cramér–Rao bound [17], as seen in Fig. 2.4. Tools for studying this effect are introduced in Ref. 18. A study of adaptive techniques for processing MIMO radar data is considered in Ref. 19.

2.1.4.3 Waveform Optimization In general there are two views of waveform design. In the first view, the design of the details of the time series transmitted from each transmitter is considered. In Refs. 20 and 21 using simulated annealing and genetic algorithms, respectively, time series are designed for good cross-transmitter and range estimation characteristics. In Ref. 13, Doppler characteristics are added to the set of design criteria. General MIMO ambiguity function tools are considered in Ref. 22.

In the second view, which is the approach used in this chapter, the details of the time series are not considered. Rather, only the intertransmitter signal correlation is