Abstract—This paper establishes the classical linear model of signal of the multiple-input multiple-output (MIMO) radar system with distributed apertures, the problem of radar waveform design for target identification and classification. Both the ordinary radar with a single transmitter and receiver and the recently proposed MIMO radar are considered. Most radar systems operate by radiating a specific electromagnetic signal into a region and detecting the echo returned from the reflecting targets. A random target impulse response is used to model the scattering characteristics of the extended (nonpoint) target, and two radar waveform design problems with constraints on waveform power have been investigated. The first one is to design waveforms that maximize the conditional mutual information between the random target impulse response and the reflected waveforms given the knowledge of transmitted waveforms. The second one is to find transmitted waveforms that minimize the mean square error in estimating the target impulse response. MIMO radar has the potential to significantly enhance the flexibility and performance of radar technology.

Keywords—Beamforming, Classification, Identification, Multiple-input Multiple-output (MIMO) Radar, Radar Waveform Design.

I. INTRODUCTION

Radar technology has been continuously developing over the last 70 years starting from the late 30s of the last century when radar was first invented for defence applications [1-3]. The desire for new more advanced radar technologies has been driven and is dictated by radar’s ubiquitous applicability ranging from micro-scale radars applied in biomedical engineering [4-5] to macro-scale radars used in radioastronomy [6]. To date, previous developments in radar were based on the idea that the signal can be processed coherently at the transmit and receive antenna arrays if the signal coherency is preserved.

The origin of radar cannot be attributed to any particular person or country in particular. The development of the technology was pushed by certain circumstances that lead to its appearance. The “discovery” was boosted by several factors and actors which contribution summed up to the materialization of the final product. However there are some milestones and historical moments that are worth mentioning since they added significant and relevant tools and inventions to the process.

The evolution of the radar system has progressed from a simple instrument for ship collision avoidance to the ubiquitous multifunction tool it is today. Multiple-input multiple-output (MIMO) radar is a more recent addition to this long and illustrious history. The MIMO radar concept, that of transmitting multiple, separable radar signals from distinct antenna elements, is not necessarily new [2, 3], with efforts to exploit the idea published as early as 1983. However, the topic has gained considerable attention in the past decade.

In the last decade, the development of a new radar paradigm that is best known under the title multiple-input multiple-output radar has become the focus of intensive research [3, 4, 7-9]. The essence of the MIMO radar concept is to employ multiple antennas for emitting several orthogonal waveforms and multiple antennas for receiving the echoes reflected by the target. The enabling concept for MIMO radar, e.g., the transmission of multiple orthogonal waveforms from different antennas, is usually referred to as the waveform diversity [3, 4]. Consequently, the waveform design and optimization has been the main focus of the research in MIMO radar [10, 11]. Beginning recently, two distinct applications of the MIMO concept have been studied extensively: the “statistical” MIMO radar or MIMO radar with widely separated antennas [3-15], and “coherent” MIMO radar or MIMO radar with collocated antennas [16-20].

Owing to the significant difference in system geometry and construction, these two forms of MIMO radar are quite dissimilar, though they both rely on the principle of using multiple, separable transmitters to improve radar system performance. The statistical MIMO radar aims to achieve.
transmitter diversity similar to that seen in communication systems literature. The wide separation of the transmitting elements is meant to counteract multipath fades, radar cross-section scintillations, and other impediments arising from the geometry of the radar system, target, and landscape. Many of the cited papers include references to other outstanding works on the topic of MIMO radar.

In conventional radar, target scintillations are regarded as a nuisance parameter that degrades radar performance. In order to relieve radar system from this performance degradation, MIMO radar system was proposed [1-7]. The novelty of MIMO radar is that it takes the opposite view, namely, it capitalizes on target scintillations to improve the radar’s performance.

The interesting topics on the MIMO radar with this type of antenna configuration include probing signal design and radar imaging. The other is the diverse antenna configuration, where the antennas are separated far away from each other to achieve spatial diversity gain. The MIMO radar with this type of antenna configuration is the so-called statistical MIMO radar [5, 10]. For the detection problem of targets with severe scintillations, this statistical MIMO radar system can achieve more processing gain at high signal to noise ratio than conventional radar system due to the use of waveform diversity and spatial (angular) diversity techniques.

Many approaches to MIMO radar have been developed that evolve around the main idea of exploiting the waveform diversity. Based on the array configurations used, MIMO radars can be classified into two main types. The first type uses widely separated transmit/receive antennas to capture the spatial diversity of the target’s radar cross-section [9]. This type assumes an extended target model and, therefore, takes advantage of the properties of the associated spatially distributed signal model. In this case, the waveform diversity is similar to the diversity concept in wireless communications over fading channels where signals or their simple modifications are transmitted over multiple fading links/channels and can be decoded reliably at the receiver due to the fact that it is unlikely that all links/channels undergo unfavorable fading conditions simultaneously [14, 15, 20]. The second MIMO radar type employs arrays of closely spaced transmit/receive antennas to cohere a beam towards a certain direction in space [9]. In this case, the target is usually assumed to be in the far field and, therefore, the point source signal model is commonly presumed. The waveform diversity, in this case, boils down to increasing the virtual aperture of the receiving array due to the fact that multiple independent waveforms are received by the same receiving array [8].

Most radar systems operate by radiating a specific electromagnetic signal into a region and detecting the echo returned from the reflecting targets. The nature of the echo signal provides information about the target, such as range, radial velocity, angular direction, size, shape and so on [1]. This signal is usually referred to as the radar waveform, and plays a key role in the accuracy, resolution, and ambiguity for radar in performing the above mentioned tasks [2]. The design of radar waveforms has been under long and intensive study to optimize a radar’s performance in target detection and information extraction.

A key facet of MIMO radar design is the manner in which these additional independent virtual elements are generated. Ideal MIMO radar waveforms, those which inhabit the same time and frequency space with desirable auto-correlation functions and vanishingly small cross-correlation functions, do not exist [21], and approaches that do not rely on minuscule cross-correlation functions must be applied to ensure the independence and separability of the transmitted sequences. Techniques for achieving waveform independence impact other facets of radar system performance, reinforcing that the decision to include MIMO technology for radar is one which must be made at the system level.

This study aims to provide an introduction to coherent MIMO radar technology, lend insight into its benefits and disadvantages, and present practical MIMO radar system design information for successful implementation. Due to its potential to improve target detection and discrimination capability, MIMO radar has generated significant attention and widespread interest in academia, industry, government labs, and funding agencies. This important new work fills the need for a comprehensive treatment of this emerging field.

II. MIMO RADAR FUNDAMENTALS

Different from the statistical MIMO paradigm, the coherent MIMO radar approach seeks to improve radar system performance via creating additional independent spatial channels by transmitting separable waveforms from distinct radiating elements. Specifically, MIMO radar literature has demonstrated the technology’s ability to generate an array of $M \times N$ virtual elements from $M + N$ real elements for a radar system with $N$ receivers and $M$ transmitters when the transmitted waveforms are independent [17]. The additional virtual elements provided by a MIMO array improve the radar system’s ability to, for instance, precisely localize targets in angle, or detect targets in clutter. Therefore, realizing these additional virtual array elements via MIMO technology grants the radar system designer options in aperture, weight, size, power, and cost constrained applications [21]. This capability is at the heart of the performance enhancements offered by MIMO radar, and proper understanding of this principle and the benefits afforded by it is paramount when evaluating MIMO approaches for a radar system.

The developments that follow rely on three assumptions commonly used in radar signal processing:

- The first is the narrowband assumption, which deals with the bandwidth of the radar signal with respect to the receiver array size and the speed of propagation in
The radar system targets high resolution performance with low power consumption in order to integrate a full MIMO (multiple-input multiple-output) radar transceiver with digital processor and antennas in a compact package featuring a size of 1 cm\(^2\). Achieving such a system requires the exploitation of a highly demanding digital architecture with signal processing gain and high range, speed and angle resolutions. The improved resolution and detection capabilities will be achieved by performing signal processing algorithms on the reflected waveform.

**A. Techniques of MIMO**

MIMO is an antenna technology for wireless communications in which multiple antennas are used at both the source (transmitter) and the destination (receiver). The antennas at each end of the communications circuit are combined to minimize errors and optimize data speed. MIMO is one of several forms of smart antenna technology, the others being MISO (multiple-input single-output) and SIMO (single-input multiple-output).

Systems with multiple antennas at the transmitter and receiver, also referred to as multiple-input multiple-output (MIMO) systems offer superior data rates, range and reliability without requiring additional bandwidth or transmit power. By using several antennas at both the transmitter and receiver, MIMO systems create multiple independent channels for sending multiple data streams. The number of independent channels and associated data streams that can be supported over a MIMO channel is equivalent to the minimum number of antennas at the transmitter or receiver.

In conventional wireless communications, a single antenna is used at the source, and another single antenna is used at the destination. In some cases, this gives rise to problems with multipath effects. When an electromagnetic field is met with obstructions such as hills, canyons, buildings, and utility wires, the wavefronts are scattered, and thus they take many paths to reach the destination. The late arrival of scattered portions of the signal causes problems such as fading, cut out (cliff effect), and intermittent reception (picket fencing). In digital communications systems such as wireless internet, it can cause a reduction in data speed and an increase in the number of errors. The use of two or more antennas, along with the transmission of multiple signals (one for each antenna) at the source and the destination, eliminates the trouble caused by multipath wave propagation, and can even take advantage of this effect.

Radar, instead of sound waves, uses electromagnetic waves. Radar can be defined as an electromagnetic sensing device for locating and deriving further information regarding the detected object, through processing and analysis of the information contained in the signals coming back from the reflecting objects. The summarized radar operation, shown in Fig. 1, is outlined as follows:

- Initially the radar transmitter, by means of an antenna, radiates energy in space, in the shape of electromagnetic waves.
- Through space, electromagnetic waves might come across with an object, called target. Depending on the reflectivity of the target, a portion of the energy will be reflected back.
- The electromagnetic energy hitting the target, is reflected in multiple directions. One of the directions comes to be the same direction of the initially radiated electromagnetic wave. This energy is received by the radar receiver antenna.
- After an amplification and with the assistance of convenient signal processing a decision has to be made in whether there is a detection or not in the signal received.
- After the decision is made, other information about the target can be extracted for further analysis and processing.

![Fig.1 Radar basic Operation Principle](image-url)
It is one of the main features of a radar and describes its ability to determine the distance from a target. As mentioned before, this is done by measuring the time that the electromagnetic wave reflected back to the receiver takes from the moment it has left the transmitter. Depending on the distance at which the target is located and other parameters (such as the pulse duration), the precision of the range can be as good as few centimeters.

Radar can also be used to obtain the information concerning the speed of a moving target. This information can be gathered from the distance variation over certain duration of time. Another used method is by means of the changes in the measurement of the Doppler frequency. The Doppler frequency accuracy will vary depending on the time of observation; meaning that an accurate frequency Doppler measurement will require long integration time.

Fig. 2 Illustration of Doppler Shift Phenomenon [22]

Fig. 2 illustrates the Doppler shift phenomenon, where a target moving radially toward the radar system causes an increase of the carrier frequency of the reflected signal by $f_d = 2uf_c/c$ (where $f_c$ center frequency of the radar system, $f_d$ denotes the Doppler frequency shift, and $u$ represents the magnitude of the target’s radial velocity). The frequency of a reflected signal increases with an inbound target, and decreases with an outbound target.

Another relevant parameter that will be used to improve the characteristics of the presented radar system is the angle. Using the angle information embedded in the reflected waves will allow us to determine the direction to a target by doing a sweep along the sight of the antenna.

The advantages of the new radar technique, that is naturally called phased MIMO radar, over the phased array and MIMO radars are analyzed in terms of the corresponding beam pattern and signal to noise plus interference ratios expressions. Particularly, the new radar technique [23]:

- enjoys all the advantages of the MIMO radar, i.e., it enables improving angular resolution, detecting a higher number of targets, improving parameter identifiability, and extending the array aperture,
- enables the use of existing beamforming techniques at both the transmitting and the receiving ends,
- provides the means for designing the overall beampattern of the virtual array,
- offers a tradeoff between resolution and robustness against beam shape loss,
- offers improved robustness against strong interference.

Spatial multiplexing requires MIMO antenna configuration. In spatial multiplexing, a high rate signal is split into multiple lower rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures and the receiver has accurate channel state information (CSI), it can separate these streams into (almost) parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher signal to noise ratios (SNR). The maximum number of spatial streams is limited by the lesser of the number of antennas at the transmitter or receiver. Spatial multiplexing can be used without CSI at the transmitter, but can be combined with precoding if CSI is available. Spatial multiplexing can also be used for simultaneous transmission to multiple receivers, known as space division multiple access or multi user MIMO, in which case CSI is required at the transmitter. The scheduling of receivers with different spatial signatures allows good separability [22, 24].

Diversity coding techniques are used when there is no channel knowledge at the transmitter. In diversity methods, a single stream (unlike multiple streams in spatial multiplexing) is transmitted, but the signal is coded using techniques called space time coding. The signal is emitted from each of the transmit antennas with full or near orthogonal coding. Diversity coding exploits the independent fading in the multiple antenna links to enhance signal diversity. Because there is no channel knowledge, there is no beamforming or array gain from diversity coding. Diversity coding can be combined with spatial multiplexing when some channel knowledge is available at the transmitter.

All these techniques, whether utilized individually or in some combination, provide benefit which can be measured in terms of lower required transmit power, greater range, more noise immunity or higher throughputs.

B. MIMO RADAR TRANSMIT/RECEIVE BEAMFORMING

In general, however, the radar antenna can consist of an array of identical elements, rather than one larger antenna. If the array of elements spans the same aperture as the larger antenna, then the array and the larger antenna will have similar angular resolution capabilities. The spacing between elements in the array controls the unambiguous angular sector which can be monitored by the radar system.

One benefit of replacing a directional antenna (such as the one in Fig. 1) with an array of nondirectional or isotropic antennas is that the array can be electrically steered to various angular sectors. These arrays, referred to as phased arrays, are commonly used in modern radar systems [1]. The phased array focuses the energy radiated from its elements by
delaying or phase shifting the signal to be emitted from each of the transmitters. Specific patterns of phase shifts across the array magnify the array output in specific directions. In the receiving case, the signals induced on the elements can be combined or summed after applying specific phase shifts across the array to enhance signals arriving from a particular angle.

Precoding is multistream beamforming, in the narrowest definition. In more general terms, it is considered to be all spatial processing that occurs at the transmitter. In (single stream) beamforming, the same signal is emitted from each of the transmit antennas with appropriate phase and gain weighting such that the signal power is maximized at the receiver input. The benefits of beamforming are to increase the received signal gain by making signals emitted from different antennas add up constructively and to reduce the multipath fading effect. In line of sight propagation, beamforming results in a well defined directional pattern. However, conventional beams are not a good analogy in cellular networks, which are mainly characterized by multipath propagation. When the receiver has multiple antennas, the transmit beamforming cannot simultaneously maximize the signal level at all of the receive antennas, and precoding with multiple streams is often beneficial. Note that precoding requires knowledge of CSI at the transmitter and the receiver [22].

Several properties of the electromagnetic waves radiated by the radar system are of interest, including the modulation (if any) of the signal, the range of frequencies the signal spans, and the power of signal. The earliest developed radar systems used short “bursts” of a high frequency electromagnetic wave as their radar signal or probing waveform. The range of frequencies spanned by these signals, or their bandwidth, is inversely proportional to the duration of the burst. A short, high bandwidth pulse is capable of more precise range measurements than a longer burst with lesser bandwidth. The ability of a radar system to resolve, or distinguish, between two identical targets separated in range is called the system’s range resolution.

The key concept in MIMO radar is that of using multiple, separable signals on transmission that yield additional independent spatial channels on reception. Fig. 3 depicts the simplest case of a radar where the MIMO paradigm is useful. As depicted in both images, the radar consists of an array of radiating elements that in general may be used for transmission or reception of electromagnetic signals. In the developments that follow, the number of receiving elements in a system will be denoted \( N \), while the number of transmitting elements in a system is given by \( M \). Because each antenna element in Fig. 3, and Fig. 4 is capable of transmitting and receiving, the system has \( N = M = 4 \) receiving and transmitting elements.
Conversely, the illustration in Fig. 4 displays a radar operating according to the MIMO principle. Here, each of the elements in the array is used for transmitting a different signal. Thus, the “multiple-input” terminology here refers to the fact that this array has M distinct transmit phase centers, each corresponding to the location of the individual transmission elements. If these signals are separable or orthogonal when received, knowledge of which signal was radiated from which transmitter may be used to improve aspects of the radar system’s performance.

The difference between SIMO and MIMO radar transmissions gives rise to received signals with distinct qualities. As depicted in Fig. 3 for the SIMO case, the signal reflected from the target is simply a scaled and delayed version of the single emitted signal. If the target resides in a single resolution cell, the signals will combine coherently at the target position and effect a signal power gain proportional to the square of the number of transmitters, M². This is the means by which the additional phase centers are generated by a MIMO radar. It is important to note that the orthogonal signals radiated by the MIMO system, in general, do not experience any signal power gain on transmission from the array.

The virtual array of the MIMO radar can be seen below the physical aperture in Fig. 4, and is illustrated using circles of various colors to differentiate which transmitting elements are associated with which virtual receiver elements. Comparing the virtual array of the SIMO radar with that of the MIMO radar, it is apparent that the space spanned by the MIMO system’s virtual array is nearly twice that of the SIMO system’s. The virtual array depicted in Fig. 4 contains many redundant elements. That is, several locations in the virtual array are realized by multiple transmitter/receiver pairs. This is a consequence of the geometry of the example system, and is not necessarily the case for all MIMO systems.

While each of these benefits may seem different from one another, they are all a direct consequence of the additional virtual elements afforded by a MIMO radar architecture.

MIMO radar technology can also reduce the cost, size, and weight of a given system by reducing the number of elements required to synthesize a given array [21]. Another benefit of MIMO radar technology is additional flexibility (with regards to a SIMO system) in designing transmit beampatterns [18, 25]. Fig. 5 displays an image of a “critically sampled” MIMO array, where the receiving elements are separated by a half wavelength, and the transmitting elements are spaced by N λ/2. Different from the configuration in Fig. 4, the virtual array generated by this construction has no redundant elements, which maximizes the number of useful additional phase centers. The decision to space the receivers in a critical fashion rather than the transmitters does not impact the resulting virtual array. However, choosing one or the other can have implications in terms of the MIMO transmission scheme to be applied.

C. How Do It Make Incredible Jumps In Speed?

Increasing speed is a tricky business in the theoretical world. The biggest factor limiting speed is bandwidth. Each phone tower has a given total width of frequencies it can transmit on, with each person that connects being allocated a small channel of a certain width. This means that each tower has a limited number of customers it can service before becoming congested. So the most obvious way to increase speed would be to give each customer a wider range of frequencies to transmit on, but this means less people per phone tower, which means building more phone towers, which is expensive.

The fundamentals of radar can be seen as an analogy to the reflection caused by a sound wave (Fig. 6). When a shout is generated a series of echoes can be received back as a result of reflections from objects surrounding the origin. Moreover, the distance of the reflecting object can be easily computed, by knowing the speed of the sound and the coefficient of the medium through which the sound is being propagated [26].

Once we have squeezed out all the performance we can from antenna to antenna transmission we have to approach the problem differently. This is where MIMO comes in to play, if we are unable to improve air transmission, why not increase the number of antennas?
Eigen beamforming can be done at both the transmit side of a link and the receive side. Classical beamforming is like using a high gain antenna, but one that need not be reoriented to point in different directions. Eigen beamforming achieves the same gain but is insensitive to antenna orientation or scattering elements in the vicinity of the antenna. Many people think of systems like phased array radar when the idea of beamforming is introduced, and indeed phased array is a method of using multiple antenna elements to steer the directivity of the antenna cluster in different directions, forming a transmit or receive antenna beam.

In particular MIMO systems can utilize a type of beamforming known as eigen beamforming. Eigen beamforming is not limited to forming a simple beam in three dimensional space. It is not adversely affected by scattering objects or multipath reflections. An eigen beamformer receiving a signal in a non line of sight situation with multiple reflections may form an effective antenna pattern that increases gain in multiple directions corresponding to the individual reflections. Using digital signal processing, MIMO systems have the ability to adapt these patterns on a packet by packet basis.

Despite phased array having a seemingly advanced air to it due to its use in extremely expensive military systems, it is actually a simpler form of beamforming than can be done with a modern MIMO system. Phased array systems perform their beamforming using limited capability of phase shifting and combining of signals in the analog domain, which has some significant drawbacks including the fact that the performance benefit degrades as the channel bandwidth is increased and that it generally works only in pure line of sight situations in the absence of any scatterers or multipath which cause significant degradation. MIMO eigen beamforming on the other hand converts the signals from all of the antennas into the digital domain where sophisticated digital signal processing can be used [26, 27].

Space time coding is a mechanism which can be utilized to transmit over multiple antennas and achieve similar gains as can be achieved using multiple antenna diversity reception. Space time coding means taking the data which would ordinarily be transmitted from a single antenna and applying a signal processing coding technique in order to transmit a mathematically altered version of the same information content on additional antennas in a way that enhances the ability of the receiver to separate the data from the background noise. Space time coding can be a natural match to receive beamforming or diversity reception. Take a situation for example where a vehicle mounted radio can easily have four antennas whereas a small handheld unit might be limited to two or even one antenna [28]. If the handheld is transmitting on a single antenna, the vehicle unit can use receiver diversity or beamforming to improve the reception. Space time coding give the vehicle a way to transmit on all four antennas and achieve a similar gain when the handheld is limited to a single receive antenna, thus making the link symmetrical and much more useful for bidirectional communication.

The MIMO made use of the virtual array technique in order to create virtual antennas that contain more information, making possible to determine the direction of arrival with more precision. The different antennas used to transmit the signal need to propagate orthogonal waveforms so that the system was able to differentiate between the waveform belonging to each transmitter antenna in the receiver [18]. The proposed outer code method consisted in using just one sequence for all the antennas, instead of different codes for each of the transmitting antennas.

III. THE EXAMPLES OF MIMO RADAR SYSTEM

The development of the radar technology was guided by the war defense’s needs, while currently military applications are still the main market and reason for development, the use of radar has been widely extended to a number of varied civilian applications. The most known might be the traffic radars, used to measure the speed of cars, or the meteorological radars with which the weather forecasts are shown in TV news. Another radar very important for nowadays functioning of the transport is the air traffic control radar, used to control the aircraft traffic over the congested air space.

The MIMO simulations presented a chance to compare the outcomes difference between a SISO radar system and the extra capabilities of a MIMO configuration. The combination of the MIMO configuration with the rough beamforming provides the phase difference information under the selected angles, which allow a rough estimation of the angle of arrival and an extra processing gain. Different combinations of the number of transmitting and receiving antennas were simulated with varying targets’ scenarios.

Spatial multiplexing is often the technique that people find difficult to believe if not grasp. This MIMO technique actually transmits multiple unique information “streams” from different antennas, each operating at an identical center frequency. A receiver using at least as many antennas as the number of streams transmitted can decode these individually and thus increase the amount of data flowing through a fixed channel bandwidth. A 4 x 4 MIMO system can achieve four streams under optimal conditions and thus transmit four times as much data as a SISO system over the same channel bandwidth. If we have a transmitter that is transmitting four streams (A, B, C and D) these streams merge in the air and a garbled combination of wA + xB + yC + zD arrives at each of the four receive antennas, where w, x, y and z represent the channel distortions caused by a multipath rich channel that vary at each antenna. It is through very sophisticated MIMO digital signal processing that the receiver characterizes all these w, x, y, z channel effects in order to recover the original A, B, C and D streams by doing what amounts to solving four equations with four unknowns that many may remember from
linear algebra classes.

While SISO and SIMO radar systems are much more commonly produced and used, several examples of MIMO radar systems exist which serve as good test cases. Two systems are briefly introduced and discussed here, with a focus on the benefits provided by a MIMO array, and the tradeoffs required for successful operation.

1. SIRE (Synchronous Impulse Reconstruction)

The radar is a forward looking ground penetrating radar forward looking ground penetrating radar (FLGPR) system, which uses ultra wideband (UWB) impulse signals as its probing waveform. The radar operates from a ground based mobile platform, typically a sports utility vehicle. Similar to the simple example illustrated in Fig. 5, the SIRE radar consists of a filled receive array of sixteen antennas spanning 2 m, with two transmitters located at the extreme ends of the array.

An interesting aspect of the SIRE system’s operation is the use of synthetic aperture techniques to improve its detection ability. The SIRE radar operates in forward looking mode by transmitting its UWB pulses and receiving the backscattered signals from different locations as it moves forward. The data received from these various locations are then used to differentiate returns from different depths at a given offset from the platform [29].

At each location during a coherent processing interval the SIRE radar collects data using the first transmitter, then the second transmitter. The uniform time division multiple access (TDMA) approach is an excellent transmission scheme for the SIRE radar, as the objects to be detected are stationary and the radar platform is not fast moving. Therefore, the loss of unambiguous Doppler spectrum has no impact on system performance. Because of the geometry of the array, the SIRE radar has a cross-range, or angular resolution, of a system spanning 4 m, nearly twice that of its physical extent. This improved angular resolution is crucial for an FLGPR, by reducing the size of a resolution cell, the SIRE radar has dramatically improved the resulting signal to clutter ratio. The primary impediments to detecting buried objects are the signal reflections from the surface, which are termed clutter in this application. The power of the clutter return is proportional to the area of a cross-range resolution cell, whereas the signal power returned (from a target of interest), in general, is not. Thus, by improving the angular resolution capability of the system, the clutter power with which a signal return must compete is reduced, improving the detection performance of the radar.

2. MIRA-CLE (MIMO Radar Configurable) in Ka band

The MIMO radar configurable in Ka band is a 16 × 16 MIMO radar system designed and built by the Fraunhofer Institute for High Frequency Physics and Radar Techniques in Germany [30]. Whereas the SIRE system applied MIMO technology to enhance its cross-range resolution by a factor of two, the MIRA-CLE in Ka band system uses MIMO concepts to synthesize a larger virtual array of 256 elements using only 32 total physical transmitters and receivers. This reduction in physical elements dramatically reduces the cost and power consumption of the resulting design.

The MIRA-CLE in Ka band array consists of 2 sets of 8 critically spaced transmitting elements located on the extremes of the radar system, with 16 widely spaced receiving elements between them. This configuration yields a physical aperture of approximately 0.5 m with a virtual array of nearly 1 m.

The system’s high carrier frequency gives it access to wide bandwidths, granting fine range resolution. Further, the system is capable of fine cross-range or angle resolution due to its large virtual aperture. Finally, the small carrier wavelength makes the system quite sensitive to target movement, with movements as small as 2 mm reported as easily detectable [22]. Note that this the diagonal loading is used not only for the MIMO radar but also for the other two radar techniques tested for the reason of fair comparison. In all examples, output signal to noise plus interference ratios are computed based on 100 independent simulation runs for all methods tested [23].

Non-Adaptive Transmit/Receive Beamforming:
- Non-adaptive transmit/receive beampattern without spatial transmit aliasing
- Non-adaptive transmit/receive beampattern with spatial transmit aliasing
- Non-adaptive output signal to noise ratio
- Non-adaptive output signal to noise ratio in the presence of spatially distributed interference

Adaptive Transmit/Receive Beamforming:
- minimum variance distortionless response beamforming employing multiple transmit multiple receive antennas
- minimum variance distortionless response beamforming employing multiple transmit single receive antennas

Particularly, the new radar technique:
(i) enjoys all the advantages of the MIMO radar, i.e., it enables improving angular resolution, detecting a higher number of targets, improving parameter identifiability, and extending the array aperture;
(ii) enables the use of existing beamforming techniques at both the transmitting and the receiving ends;
(iii) provides the means for designing the overall beampattern of the virtual array;
(iv) offers a tradeoff between resolution and robustness against beam shape loss;
(v) offers improved robustness against strong interference [31-35].

IV. Result and Analysis

In this paper, we carefully discriminate these meanings. We
use “selectivity” to refer to channel features, which are determined by the environment (e.g., propagation and user mobility) and by basic system parameters (e.g., bandwidth and antenna spacing). In turn, the term “diversity” is reserved for performance metrics and for specific transmit/receive techniques, both of which have to do with the signal. Note that channel selectivity is a necessary condition for diversity strategies to yield an improvement in some diversity metric.

To solve the missed detections for low RCS targets in some far ranges, a bigger SNR is needed. The gain can be increased by expanding the number of used antennas or increasing the number of accumulations, but also by increasing the number of the radar systems working synchronized. In order to improve the range resolution, more bandwidth could be allocated or there could be investigated novel waveform shapes. The increase of angular resolution has been demonstrated to be effectively tackled by increasing the number of antennas while performing MIMO processing. Other possibility is the implementation of super resolution beamforming methods. The general information that is displayed after each radar system simulation is going to be introduced for a better understanding of the results that will be further shown [34].

Nevertheless, the drawback of all the system improvements is the increase of the computational complexity and thus the required energy; which translates in the variation of other hardware parameters, etc. The operations that digital front end of the radar system performs are actually very simple (correlations, accumulations, etc.), but they need to be done in large number and in parallel.

In order to find a middle point between getting excellent performance capabilities and work with an acceptable computing complexity, future improvements can be introduced. This future work can include the implementation of several radar modes depending on the perceived scenario: a detection mode and a tracking mode. The detection mode would require lower range gate, velocity and angular resolutions since the main goal is to broadly detect. Once there is detection and using the available information, the tracking mode of the radar would be triggered and the high resolution capabilities would be activated for a proper identification of the target. Once the tracking mode is active, less range gates would be needed since the target has been already localized; just the range gates surrounding the target would be activated. The implementation of these techniques would save many operations and the complexity would be considerably reduced. Ultimately, the interesting future topics are related with the radar system optimization and efficiency [36].

Regarding the bigger picture of automotive radar; the systems head towards the sensor fusion where complementary technologies (such as radar and imaging), would work together to sense the surrounding with very high detail. This could be done by also combining information from other sources such as weather, traffic density or car to car information exchange. In order to be able to afford such a computational complexity in a small surface, faster silicon would be needed.

V. Conclusion

Since the 1970’s, antenna diversity had been a preferred weapon used by mobile wireless systems against the deleterious effect of fading. While narrowband channelizations and non adaptive links were the norm, antenna diversity was highly effective. In modern systems, however, this is no longer the case. Link adaptivity and scheduling have rendered transmit diversity undesirable for low velocity users whereas abundant time and frequency selectivity has rendered transmit diversity superfluous for high velocity users. Moreover, the prevalence of MIMO has opened the door for a much more effective use of antennas: spatial multiplexing.

Indeed, the spatial degrees of freedom created by MIMO should be regarded as additional bandwidth and, for the same reason that schemes based on time/frequency repetition waste bandwidth, rate sacrificing transmit diversity techniques waste bandwidth. This conclusion is established on the basis of a suboptimal multiplexing technique, and it is only strengthened with optimal multiplexing. There are a number of different arguments that lead to this conclusion, and which will be elaborated upon:

- Modern systems use link adaptation to maintain a target error probability and there is essentially no benefit in operating below this target. This makes diversity metrics, which quantify the speed at which error probability is driven to zero with the signal to noise ratio, beside the point.
- Wireless channels in modern systems generally exhibit a notable amount of time and frequency selectivity, which is naturally converted into diversity benefits through coding and interleaving. This renders additional transmit diversity superfluous.
- Block error probability is the relevant measure of reliability. Since the channel codes featured in contemporary systems allow for operation close to information theoretic limits, such block error probability is well approximated by the mutual information outages. Although uncoded error probability is often quantified, this is only an indirect performance measure and incorrect conclusions can be reached by considering only uncoded performance.

At the same time, exceptions to the foregoing conclusion do exist. These include, for example, control channels that convey short messages. Transmit diversity is fitting for these channels, which do benefit from a lower error probability but lack significant time/frequency selectivity. Other exceptions may be found in applications such as sensor networks or others where the medium access control is non-existent or
does not have link adaptation and retransmission mechanisms.

It is also imperative to recognize that the notion of diversity is indelibly associated with channel uncertainty. If the transmitter has instantaneous CSI, then it can match the rate to the channel rendering the error probability dependent only on the noise. Diversity techniques, which aim precisely at mitigating the effects of channel uncertainty, are then beside the point. Although perhaps evident, this point is often neglected. In some models traditionally used to evaluate diversity techniques, for instance, the channel fades very slowly yet there is no transmitter adaptation. As we shall see, these models do not reflect the operating conditions of most current systems.

REFERENCES