URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Optimized Virtual Antenna Array of Wideband Narrow Beam MIMO System for Overlapped Virtual Elements

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Abstract

This paper presents a novel process of creating an optimized virtual array for a Multi-Input, Multi-Output (MIMO) antenna array. It has been shown that MIMO radars yield increased range and angular resolution as compared to non-MIMO phased array radars. This is due, in part, to the increased aperture size created from the MIMO virtual array. It is known that for certain linear phased array antenna geometries/layouts that antenna elements can become overrepresented in the resultant MIMO virtual array. Current literature pertaining to the generation of an optimized MIMO antenna virtual array has not been presented for overrepresented antenna configurations. This paper presents the general concept of MIMO radar, overrepresented MIMO array configurations and the processing problems that result. The proposed solution for this result is discussed.

Keywords—*MIMO; Virtual Array; radar; antenna*

1 MIMO RADAR AND VIRTUAL ARRAY

The creation of a MIMO virtual array is well defined [1, 2, 3] and its creation is one of the first steps in the MIMO radar signal processing. The virtual array is the effective or apparent aperture for a MIMO radar system. This comes from the convolution of the receive and transmit antenna phase centers used for the MIMO system [1]. For a traditional phased array, the angular resolution is limited due to the physical size of the array. MIMO antennas utilize the spatial diversity of the transmit phase centers to realize the angular resolution of a larger antenna. The increase in angular resolution from a larger virtual array is due to the inverse relationship between bandwidth and the size, or length, of the antenna aperture. The larger aperture is achieved through the concept of the MIMO virtual array. For this paper, we will consider linear array with equal spacing. For simplicity, each element is assumed to be an isotropic radiator.

The return, or channel data, is represented, in (1), as measurements of the sample corresponding to the convolution of the transmit and receive phase centers [1,4]. It is also this convolution that is the basis for the concept of a MIMO virtual array.

$$Z = \sum_{range\ cell}(H \cdot S + N) \tag{1}$$

where S is the transmitted signal, N is noise, while H is the channel matrix. The channel matrix defines the phase of the return at a given location within the antenna. The channel matrix can be generalized as the convolution of the phase center location of the transmitting and receiving elements, as shown in [5], and is given below.

$$H=exp(ik \cdot rx \otimes tx) \tag{2}$$

Note that k is the wave number, rx is the array of receiver locations, and tx is the array of transmitter location. Both rx and tx are normalized about the center point of the linear array.

2 VIRTUAL ARRAY OVERPRERESNETATION AND BEAM STEERING

2.1 Virtual Array Overrepresnetation

As can be seen in (2) there are several geometries that can result in a channel matrix that does not contain all unique phases. When not all phases within the channel matrix are unique this is referred to as a virtual array with overrepresented elements. Overrepresentation can occur, for example, when a uniformly spaced linear antenna array consists of elements that are both transmitter and receiver.

It may not appear, at first glance, that an overrepresented virtual array will cause processing issues. In fact, the higher number of contributions results in more effective energy from the targets. It is not until the signals, as received by the virtual array, are processed that a problem becomes apparent. The received signals for an overrepresented virtual array element are, by definition, not correlated. Even after basebanding the signals to allow for coherent processing the virtual array contains elements with different signal magnitudes. For an idealized MIMO array it is assumed that each transmit element transmits/radiates with equal magnitude. The resultant received signals from a given target is then limited to the small variation in the signal magnitude across the virtual array due to path differences. The received signal can then be thought of as a nominal magnitude of 0dB for a virtual element contribution of one. It is simple to see that as the number of contributions increases so does the received signal magnitude. A contribution of four, for example, would yield 6dB higher magnitude as compared to the baseline of 0dB.

An overrepresented MIMO virtual array also causes a problem in the case when the MIMO system is wideband and narrow beams are required. In this case the MIMO return data must be corrected using a Keystone process to eliminate range walk as a function of frequency within the bandwidth. Failure to correct this walk across the bandwidth results in poor coherent combining of the energy falling on a given virtual array phase center location.

2.2 Keystone Processing

A benefit of utilizing a phased array radar system is the ability to electronically steer a beam without the need to physically maneuver the antenna. The process of beam steering, or beam forming, is well known [6,7]. When considering a wideband antenna the result is wideband beam steering. The rule of thumb for beam steering using phase only is that the bandwidth, in percentage as a ratio between the bandwidth and carrier frequency, should remain less than the beamwidth in degrees [6]. For a wideband antenna system, it is often desired to form narrow beams that will violate the rule of thumb to support the application. This causes some concern as the beamwidth is very small but over a large band which results in the formed beam having peak directionality that varies as a function of frequency within the bandwidth.

The frequency dependence of beam steering can be corrected with the concept of Array Keystone processing [8]. The Keystone process performs an interpolation of the data across the array for frequencies within the bandwidth about the center/carrier frequency. Due to overrepresentation within the virtual array the magnitudes are no longer uniform over the virtual array. This nonuniformity in the magnitudes introduces error into the interpolation function of the Keystone process. An example for a linearly spaced seven element virtual array with a 50dB average signal magnitude is shown in Figure 1. The x-axis is the set of initial values to a Monte Carlo simulation representing the offset from the input signal (50dB). The error is computed for the channel (per element) and for the entire array. The error associated with Keystone processing can be corrected by eliminating elements from the virtual array that spatially overlap. This forces the virtual array to have signal magnitudes that are uniform but there is a net loss in SNR due to the omission of elements from the channel matrix.

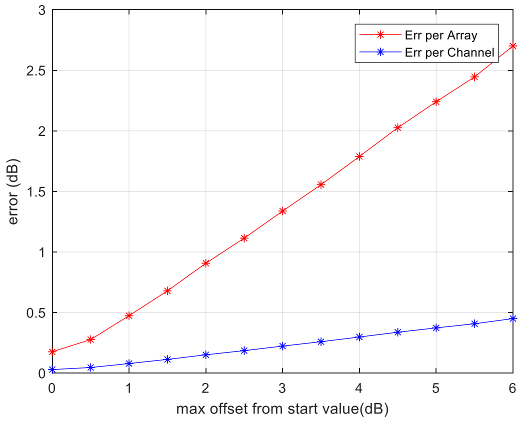

Figure 1: Interpolation error within Keystone processing for array within non-uniform magnitudes

3 FULL VIRTUALIZATION

Depending on the geometry of a MIMO array the resultant virtual array has the potential to contain overrepresented elements. If the virtual array is created in a traditional way of including all contributions (total number of elements that contributed information/data/power to a given virtual array element location) for a given receive phase center the resultant array will not produce a uniform magnitude across the elements. If the transmitting and receiving elements are co-located and all elements are considered transmit/receive pairs then the virtual array is guaranteed to have a contribution of one at the end virtual elements while the middle element can be seen to have up to N times the contribution, where N is the number of transmitting phase centers. To maximize the resultant SNR of the MIMO system an algorithmic method for creating a virtual array has been devised such that all contributions are utilized.

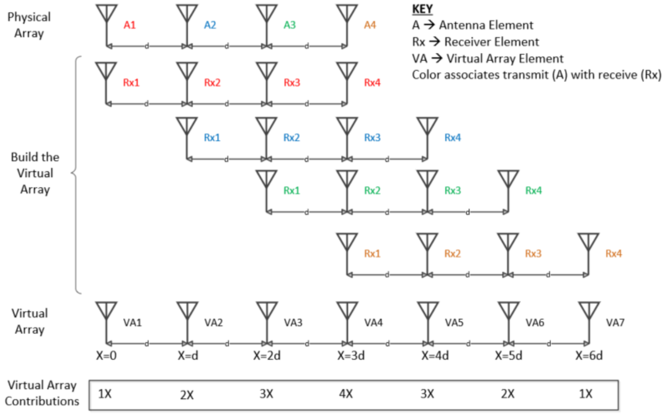

Figure 2: Four element uniformly spaced linear array, virtual array, and contributions

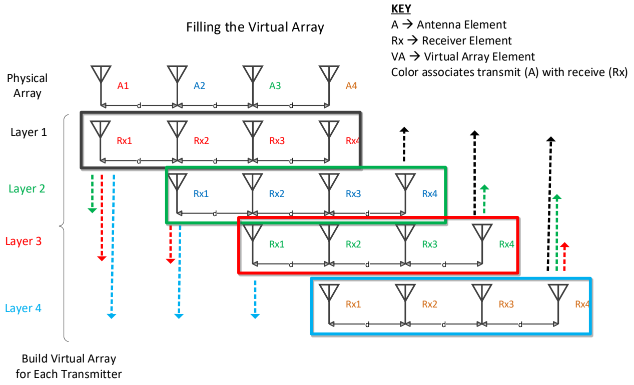

Figure 3: Full virtualization layer creation of a four element uniformly spaced linear array

This, in general, is performed by creating K virtual arrays or layers. The value of K is defined as the maximum number of contributions across the entire virtual array. An example is shown in Figure 2 for a uniformly space 4 element linear array where all elements are transmit/receive pairs. This geometry results in a seven element virtual array where the center element of the virtual array contains the maximum number of contributions, four. This indicates that four layers are needed to remove the overrepresentation in the virtual array. Figure 3 shows one possible result from the algorithmic creation of the K=4 virtual arrays (four layers). Note that the creation of the K=4 layers utilizing all 16 elements of the H matrix has many solutions in this example geometry. It is assumed that all antenna elements are identical and therefore any solution resulting in the use of all 16 elements of the H matrix would result in the same performance improvement.

The formulation of the virtual array in this way allows for the Keystone processing to be performed independently on K virtual arrays. This forces each Keystone process to be performed on an array that is uniform and thus minimizes the potential for error. The process also guarantees that all energy from the return data be utilized. The output of the K Keystone processes can simply be summed in the array dimension without the need to worry about poor coherent combining across the bandwidth. The result is an SNR that maximizes the diversity of the system and therefore is maximized for the system.

For a system with N receive elements and M transmit elements, where the ending receive elements are transmit/receive pairs, the increase in SNR due to utilizing the method over the traditional method is shown below.

$$10log_{10}(\frac{NM}{2N-1}) \tag{3}$$

4 CONCLUSION

The MIMO virtual array is the first step used to process the return data from a MIMO radar system and is based on the channel matrix. The channel matrix defines all phases based on the convolution of the transmit and receive elements of the system. For a wide bandwidth system where narrow beams are desired the Keystone process must be used to correct frequency dependence of the beam steering. The Keystone process corrupts the data when all elements in the channel matrix are not unique. By generating multiple virtual arrays and performing the Keystone process for each array the output SNR for the system can be maximized.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Qualcomm as this research was performed by Tanski prior to joining Qualcomm.

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