MIMO VERSUS CONVENTIONAL RADAR PERFORMANCE AGAINST JAMMERS

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Abstract: It has been claimed that MIMO radars perform better than conventional radars against repeater and hot clutter jammers (jammer signals reflected from the ground into the radar). It is shown here that conventional radars can perform as well if not better than MIMO radars against these jammers as well as against barrage noise jammers. The results are presented in tutorial form without heavy math. Instead physical explanations are given for these results. Applied here to reject the barrage jammer and hot clutter is the Adaptive-Adaptive Array Processing (AAAP) technique which makes use of the information available as to where the jammers are rather than assuming there location is not known as done for the classical sample matrix inversion (SMI) method. This is reminiscent of the KA-STAP technique used by DARPA. It also could be called Cognitive Adaptive Array Processing (CAAP). The method reduces the transient time (the number of time samples needed to calculate the interference covariance matrix) by orders of magnitude. Also the interference covariance matrix size is reduced by orders of magnitude and in turn the computation of its matrix inverse. Finally this method reduces the sidelobe degradation usually resulting from using the SMI method. The AAAP technique lends itself well to both the MIMO and conventional array systems when digital beam forming is used.

1. Monostatic MIMO Array Radar

We first give our results for the monostatic MIMO array radar and its conventional equivalents. Fig. 1 shows a generic monostatic MIMO radar consisting of a linear full array of N elements having element spacings of $\lambda/2$. When this array is used in a conventional monostatic radar each element transmits the same waveform at the same frequency but with a different phase shift per element. The ith element would have a phase shift $i\alpha_k$ to generate a focused beam to an angle θ_k off-boresight. The angle at which the beam steers is determined by the phase shift α_k between elements [1]. For a 100 element array having $\lambda/2$ spacing between elements the beamwidth would be ~1° at boresight. In contrast when this linear array is used for a MIMO radar each element transmits a different waveform with these waveforms being orthogonal to each other [2, 3]. Because of this the antenna does not form a focused beam as done with a conventional array. Instead the MIMO array radiates over a beamwidth determined by the beamwidth of each element. Typically the 3 dB beamwidth of each element might be like 120° wide. Thus with the simultaneous transmission of the orthogonal waveforms from the N elements one is illuminating a 120° field-of-view [FOV]. These N orthogonal signals leaving the N transmit elements will go to the target and be reflected back. On receive each element will receive the N reflected orthogonal echo waveforms from the target. To process these signal each element needs N matched filters (MFs) for the N orthogonal echo signals as shown in the Fig.1. For the ith element the jth MF, MF_j, pulse compresses and passes the echo resulting from the waveform transmitted from element j and rejects all others. At the output of MF_j a weight W_{Tijk} is applied which consists of the amplitude weighting and phase shift $j\alpha_k$ we would have used on transmit for the jth transmit element if we had used the array as a conventional array with its beam focused to the direction θ_k. This is followed by a summer whose output is E_{ik} which is, to within a constant, the echo signal we would have gotten if the array was used as a conventional array on transmit. After this point the receive beam forming is done as we would have done for a conventional array. Specifically a received beam is formed from the echoes E_{ik} to generate a focused receive beam at the angle θ_k. This is done by summing the signals E_{ik} with weightings W_{Rik} consisting of the amplitude weighting and phase shift $j\alpha_k$ to form nominally a focused receive beam pointing at the angle θ_k. Thus the difference between the conventional and MIMO array radars is that for the conventional array the transmit beam forming is done on transmit while for the MIMO array the transmit beam forming is done in the receiver. It is important to point out that the reason we are transmitting orthogonal waveforms is to be able to do the beam forming in the receiver instead of the transmitter for the MIMO system. The use of orthogonal waveforms allows us to do this. It is a means for labeling the waveforms from the different transmit elements so that we can do the transmit beam forming in the receiver. This is a very nice feature of the MIMO array. It allows one to do adaptive transmit beamforming in the receiver. Hence if there was strong clutter and or scatterers in a given region of space the transmitter and receiver antenna weights could be adaptively adjusted to simultaneously put nulls in the transmit and receive beams where the clutter exists for optimum signal-to-interference as done in [4].

Although N MFs are shown per receive element in Fig. 1, typically FN MFs are needed per element to pulse compress the N orthogonal waveform echoes. This is because orthogonal waveforms which are typically noise like are Doppler intolerant. As a result to pulse compress one orthogonal signal echo received by one element a bank of F Doppler filters are needed to cover all doppler shifts of the echo. For simplicity in Figure 1 it is shown as if F=1.

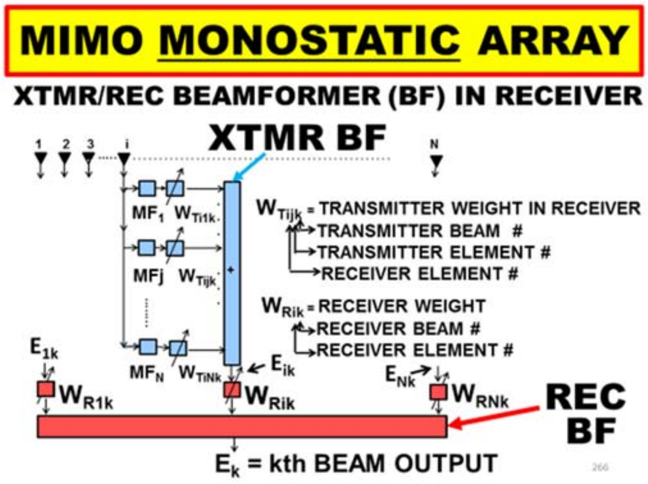

Figure 1. MIMO monostatic array receive architecture. Here the transmit beam forming is done first.

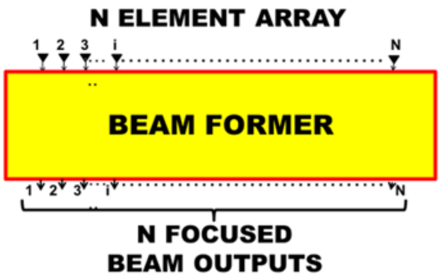

Figure 2. Receive beam forming of N focused beams before any signal processing or barrage jammer cancellation.

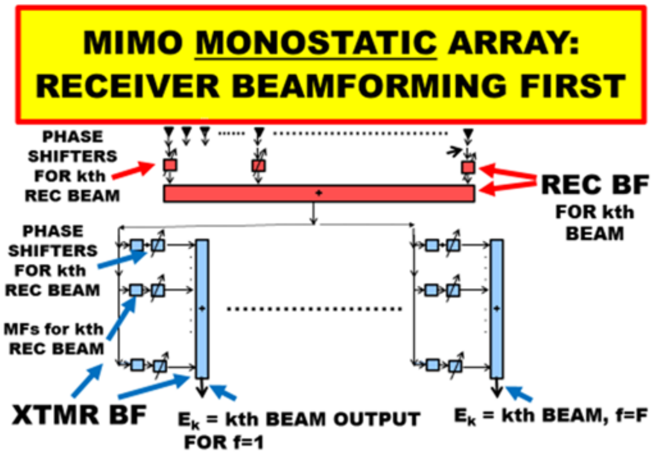

Figure 3. MIMO monostatic array receive architecture where the transmit beam forming is done after receive beamforming.

1.1 Barrage Jammer

It is important to first realize that cancelling the jammer is independent of the waveform used or the type of radar, conventional or MIMO. Thus what we should do first is cancel the jammer. To do that our goal would be to form for our MIMO and conventional monostatic radars a stack of beams that cover the FOV with these beam being jammer free. That is with the jammers having been cancelled from all the beams. After doing that we can process the return for detection of the targets. To achieve this goal the rejection of the jammers would be independent of the whether we had a MIMO or conventional array and independent of the radar waveforms used. Cancelling the jammers would be only dependent on the jammer properties. Toward this end let us first form a stack of N focused beams covering the FOV as shown in Fig. 2. For the MIMO array we would do the transmit beam forming after the receive beam forming instead of before as shown in Fig. 1. Thus the receiver beam forming would be done first as shown in Fig. 3. Having formed the N focused beams we have to do a jammer cancellation as shown in Fig. 4. Toward this end Adaptive-Adaptive Array Processing (AAAP) [5-9], or what could be called equivalently Cognitive Adaptive Array Processing (CAAP), will be used as to be now described. It is a very good match.

For simplicity assume initially only one barrage jammer is present. Having formed the N focused beams we can easily locate this jammer by seeing which beam output port has a large noise output. Assume it is in the mth beam pointing at the angle θ_m. We can now use the output from this mth port to cancel the barrage jammer signals occurring in all the other N-1 beams through the sidelobes of these other beams. This just requires us to do simple sidelobe cancelling (SLC) for each of the other beams using the signal from the mth beam port. We are left with the problem of main lobe jammer cancelling to remove the jammer from the mth port. This is a

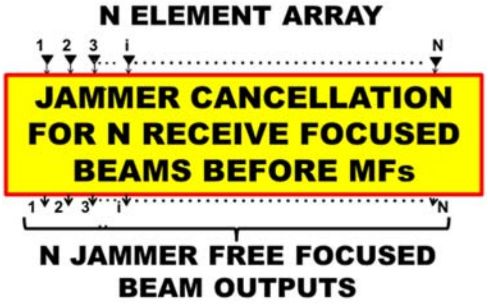

Figure 4. Have to do jammer cancellation for N focused beams independent of the type radar and its waveforms.

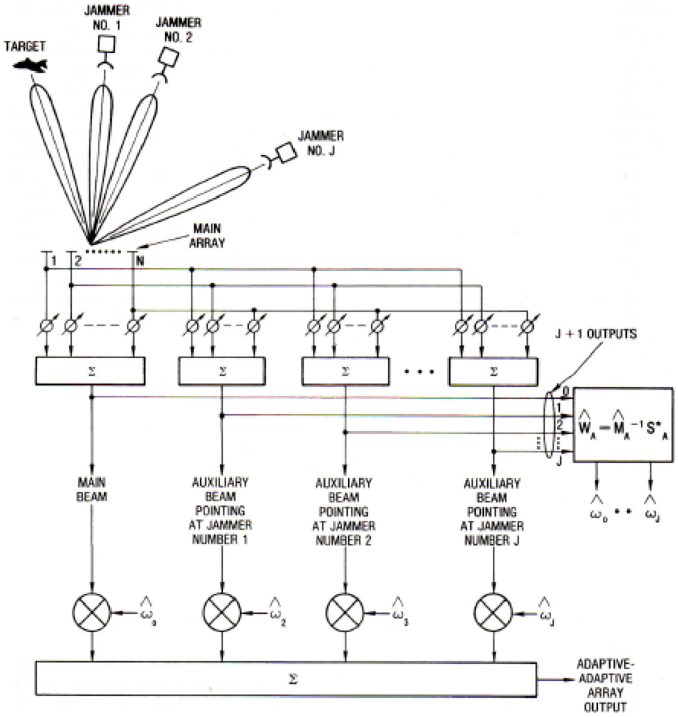

Fig. 5. Adaptive-Adaptive Array Processing (AAAP) [5-9].

main lobe jamming problem which involves more sophisticated processing which we will not deal with here. It is no different for the MIMO and conventional systems.

For the case of a single jammer assumed above no matrix inversion is required and the number of range samples needed to cancel the jammer is small, just a few range samples, i.e., the transient time is short. Specifically for the cancelation of one jammer only K=1 sample is needed to get to within 3 dB of the optimum signal-to-interference ratio (SIR). To get to within 1 dB of optimum K=4 samples are needed. For K=1 the accuracy of the weight estimate W_e is limited by the main beam channel thermal power noise level φ. When applied to cancel the jammer in another cell the thermal noise from that cell is added to the estimate so one has effectively twice the thermal noise level, of 2φ in the main channel so that there is a 3 dB increase in the interference level after cancellation above the optimum value of the thermal noise level of φ. If K=4 cells are used then the noise in the estimate of W_e reduced by K=4 to φ/K=φ/4 but we still have a noise level φ in the main channel cell we are looking for a target in so the noise in the main channel becomes effectively φ(1+1/K) =1.25φ for a 1 dB SIR degradation after cancellation when K=4. One would not in practice use 1 sample because if the jammer was a noise jammer with random amplitude instead of a noisy phase modulated waveform with constant amplitude then one could be sampling when the jammer was at or near a null. Even with constant amplitude noise one could be sampling when the thermal noise is peaking. Rejection of the target signal in the main channel will certainly not occur as long as the signal is not present in the training cells.

Assume now that J jammers are present. In this case J beam outputs will show that J jammers are present. Now we use the outputs from these J beams as jammer auxiliary beam outputs for use to cancel the J jammers present in the main beam, the beam pointing in the direction where we are looking for a target. We thus now have effectively a standard SLC with J auxiliary antennas. Now one has to invert a JXJ jammer interference covariance matrix M_A. The method just described for cancelling the J jammers is an implementation of the Adaptive-Adaptive Array Processing (AAAP) technique depicted in Fig. 5 [5-9]. Because for the MIMO system N beams are formed covering the FOV no extra computation is needed to form the auxiliary beams pointing at the J jammers when applying AAAP to the MIMO radar.

Here N=J for the SLC. From Brennan's rule [11] for J=10=N the number of range samples needed to estimate the interference matrix MA is K≈2N=20 to achieve a SIR within 3 dB of optimum and K≈5N=50 to be within 1 dB of optimum. In contrast if the SMI method was used and the array had N=1000, then K≈2N=2000 samples would be needed to achieve a SIR within 3 dB of optimum and K≈5N=5000 to be within 1 dB of optimum. Also if the classical SMI method is used for an N element array one has to invert a convariance matix that is NXN in size. To invert an NXN matrix requires N^3 operations (multiplies and divisions). So for N=1000 and J=10 we are talking about 1 billion using SMI versus 1000 for AAAP for the inverse computation. The classical SMI actually does just what AAAP processing does except that it is transparent to the user. This was shown amazingly in Sidney Applebaum's original "Adaptive Array" seminal paper and report [10]. In the case of the SMI the beams pointing in the direction of the jammers is done transparent to the user by eigenvectors of the interference covariance matrix. When such eigenvectors are used as the weights for the antenna they form beams pointing in the direction of a jammer. For J jammers there are ideally only J such eigenvectors and in turn eigenbeams used for SLC. This would be the case if one had a perfect estimate of the interference covariance matrix. However in practice one only has an estimate of the covariance matrix. It is corrupted by the radar thermal noise. As a result the SMI thinks there are jammers at N-J-1 other locations due to the thermal noise and points eigenbeams at these locations where there are no jammers. The result is a degradation of the adapted antenna sidelobe levels, see Fig. 6. The interference covariance matrix has N eigenbeams. J of these are pointing in the direction of the J jammers. The remaining N-J-1 beams point in the directions where there is no jammer. For a good discussion of this the reader is referred to [11].

AAAP has the advantage of not degrading the adapted antenna sidelobes as done with SMI in Fig. 6. This is because it does not do SLC using beams pointing where there are no jammers. As a result there is only a small degradation of the adapted sidelobes only raising the two sidelobes straddling the jammer null as illustrated in Fig. 7 for the case of one jammer. With the SMI method each jammer eigenvector beam has nulls in the direction of the other jammers. This could be done for the AAAP. However having beams with low sidelobes will often be good enough. AAAP will generally give optimum performance without the disadvantages of the classical SMI approach. After having removed the sidelobe barrage jammers from all the focused receive beams for the MIMO array using AAAP one proceeds to doing the transmit beam forming as indicated in Fig. 3.

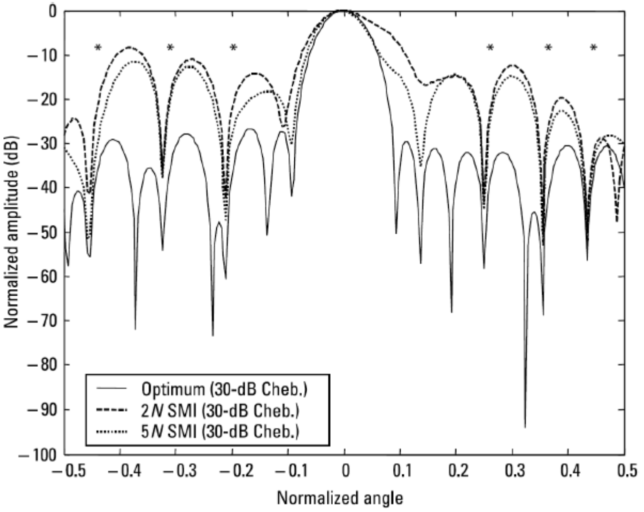

Figure 6. Degradation of the adapted SMI antenna pattern for an N=16 element linear array having 30 dB Chebyshev weighting. There are six jammers present at the angles indicated by the *. The SNR at each element is 0 dB. The JNR at each element is 50 dB for each jammer. (Figure from J. R. Guerci, "Space-Time Adaptive Processing for Radar", Artech House, 2^{nd} Ed. 2015 [11]).

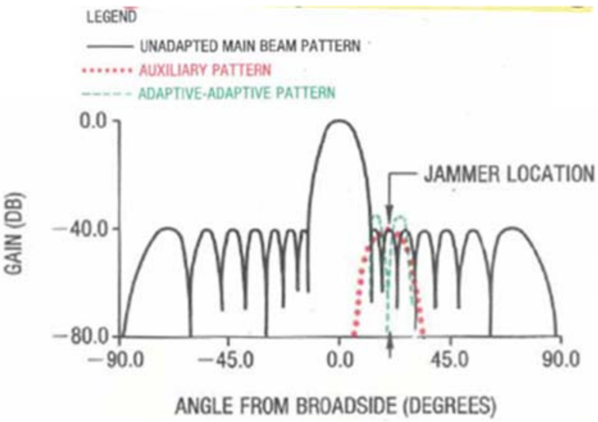

Figure 7. Illustration of small degradation of only two sidelobes straddling (shown in green) the adapted pattern null when using AAAP [5, 6]. Red dashed curve is beam pointing at jammer with its gain adjusted to equal to that of sidelobe in beam we are looking for a target in.

We now come to the conventional equivalent to the MIMO monostatic array. Two types of conventional equivalent have been proposed. One is the ubiquitous array equivalent and the other the machine gunning equivalent [12]. The ubiquitous equivalent consists of the uniform linear array used as a conventional array with the beam spoiled on transmit to cover the whole field of view (FOV). On receive N or so focused beams are simultaneously formed in the receiver to cover the whole FOV. For the conventional ubiquitous array AAAP is applied to the outputs of the focused receive beams as done for the MIMO system as described above. The barrage jammers will be suppressed to the same level as for the MIMO system in both cases because the jammer cancellation is just dependent on the jammers and not on the signals. So MIMO does not do any better at rejecting the sidelobe barrage jammers than does the ubiquitous conventional equivalent. The jammer cancellation: performance, processing load and the transient times are the same for both.

The second machine gunning equivalent conventional array is where again the same array of N elements is used except that one covers the transmit FOV by sequentially transmitting on the order of N focused beams [12]. These beams are formed by transmitting N pulses one after the other in what is called machine gunning. Because the array is used as a conventional array here it has a gain of N times that for when the array is used for the MIMO radar or ubiquitous radar. Hence each of the N pulses will need a pulse width 1/Nth that of the MIMO or ubiquitous array, that is a pulse width T_c /N where T_c is the pulse width needed for the MIMO radar and ubiquitous radar. Thus the total transmit time is the same for the macnine-gun conventional array radar and the MIMO and ubiquitous conventional array radar. The listening time occurs immediately after the transmit time and is the same for all three and hence they have the same total search time. For some applications the frequencies of the machine gunning pulses can be the same whereas for some it would be desirable to have some of the pulses have a different frequency in order to unambiguously identify the echoes received by the different beams. If all the beams have the same frequency the AAAP processing load will be the same as for the MIMO radar. If some of the beams have different carrier frequencies then the AAAP processing load will increase because auxiliary reference jammer noise signals have to be generated for each of the additional frequencies. This involves just digital IF bandpass filters to generate the additional barrage noise jammer reference signals. The bottom line is that barrage jamming can be handled as well for the two conventional monostatic radars as for the monostatic MIMO radar.

1.2 Hot Clutter Jammer

First what is hot clutter? It is a jammer signal that enters the radar sidelobes or main lobe after reflecting off the ground as shown in Fig. 8. In Fig. 8 we illustrating a case where we have the mainbeam of the radar looking for a target with the mainbeam of the radar pointing at the same time at the reflection point of the jammer signal. For this case we have mainbeam jamming by hot clutter, a worst case situation. It has been claimed that the MIMO array can reject hot clutter for this main lobe jamming without suppressing the target return whereas a conventional array cannot do this [13, 14]. We show that this is not true. We show that a conventional array can suppress maimlobe hot clutter jamming just as well as a MIMO array can. To cancel the scattered jammer and direct jammer signals we apply here again the AAAP technique described above. Specifically we generate two focused beams, one in the direction of the jammer and the other in the direction of the hot clutter jammer signal reflection point and which contains the target echo as well; see Fig. 8. To cancel the scattered jammer signal we use the jammer signal coming from the beam pointing in the direction of the jammer. This becomes our aux beam used to cancel out the hot clutter main lobe jamming signal. This aux signal will not cancel out the target echo signal as done for a main lobe canceller in general. This is because the signal is very weak in the aux beam, it coming in through the sidelobes of the aux beam. The hot clutter jammer signal coming into the main lobe of the beam pointing in the direction of the target will be canceled though. If the hot clutter is dispersed then a tapped delay filter needs to be used for the aux reference signal. This cancellation is independent of the transmit waveform and of whether we are doing MIMO or conventional array processing. So we have shown that conventional radars can handle main beam hot clutter just as well as MIMO radars.

1.3 Repeater Jammer

We now consider the ability of monostatic MIMO of Fig. 1 and its conventional equivalents to handle repeater jammers. For both types of systems standard sidelobe blankers (SLBs) can be used to locate and gate out the repeater signals coming through the sidelobes of a focused receive main beam. Specifically an omni receive beam can be used whose gain is larger than the gain of the receiver main beam sidelobes. If an echo detected in the main beam has an amplitude less than that of the omni echo at the same range it is declared to be a repeater signal, otherwise a target. Better yet here the stack receive focused beams can be used in place of the omni beam. This type of SLB can be used equally effectively for the monostatic MIMO of Fig. 1 and its conventional equivalents. The conventional equivalent of Fig. 1 that uses machine gunning has the advantage over its MIMO and ubiquitous equivalent radars in that it can use open loop nulling and spoofing to defeat repeater jammers. Specifically, for the conventional machine gunning system for the beam pointing in the direction where a target is to be detected open loops nulls can be placed in its sidelobes on transmit in the direction of the repeaters. This would reduce the sensitivity of the repeater to the transmit signals. Furthermore, it helps with spoofing of the repeater. Spoofing is achieved by forming a transmitter beam in the direction of the repeater jammer which transmits a spoofing signal (also called a cover pulse) at another frequency at a level somewhat larger than from the sidelobe of the beam used to detect the target. This will spoof the repeater. Using spoofing for the monostatic MIMO radar and its ubiquitous equivalent is more difficult. It requires first applying nulls in the transmit beam in the directions of the repeaters. If MIMO is done at the element level this is not possible if different waveforms are transmitted from each element. If MIMO subarraying is used it is possible but has issues. When the jammer is in the main lobe of a subarray pattern it will results in loss of coverage over an angle around the null which will be wide. Repeater jammers are somewhat equivalent to strong clutter interferers. The use of MIMO radar to reject strong clutter interference and as indicated earlier is covered in reference [4].

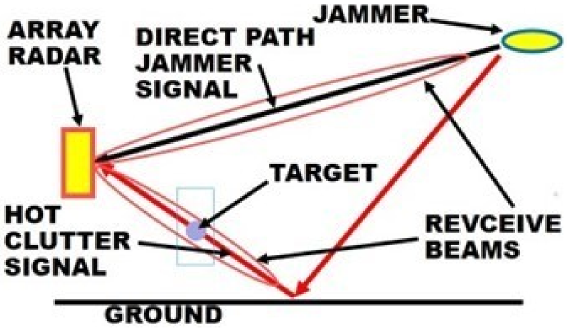

Figure 8. Hot clutter geometry.

2. Thin/Full and Full/Thin MIMO Array Radars

A MIMO thin/ full array radar here consists of two collocated parallel linear arrays of N elements each [2, 3, 12]. One of these arrays is a thin array used for transmit and the other a full array used for receive. Both arrays have N elements. For the thin array the element spacing is $N\lambda/2=5\lambda$ for N=10. The full array has spacing $\lambda/2$. Assume uniform weighting for receive and transmit. It has been shown that a MIMO thin/full array for which orthogonal waveform are transmitted from the N elements is equivalent to a virtual array consisting N^2 elements having $\lambda/2$ spacing [2, 3, 12]. For N=10 the virtual array is a full array of 100 elements with $\lambda/2$ spacing. The advantage of the MIMO thin/full array is that one has the performance of a full array of 100 elements when using only 2N=20 elements. That gives us a factor of N=10 better resolution and accuracy with the MIMO thin/full array using only 2N=20 elements than with a conventional full array of N=10 elements. An order of magnitude better resolution and accuracy. For N=100 we are 100 times better with the MIMO thin/full array and for N=1000 we are 1000 times better. A full/thin MIMO array radar is the same as a thin/full MIMO array radar except that the thin array is used for receive and the full array for transmit. The full/thin array radar is also equivalent to a full array of N^2 elements. Hence it has the same advantages with respect to resolution and accuracy. In [2, 3, 12] it is shown how the MIMO thin/full and full/thin array radars can be used as conventional array radars to give the same order of magnitude resolution and accuracy performance as achieved with the MIMO thin/full array.

The AAAP can be applied as well to the thin/full and full/thin MIMO array radars and their conventional equivalents to show that their performance against barrage noise jammers and hot clutter are equivalent. The thin/full MIMO radar and its conventional equivalents have the disadvantage of a wide receive main lobe of width 2/N (11.5° on boresight for N=10) vs $2/N^2$ (1.15°) for the full array of length N^2. The full/thin array has narrow ambiguous lobes (ALs) of width $2/N^2$ (1.15°) but there are N of them so the total angle main beam jammed is still 2/N (11.5°). To cope with this issue for both the MIMO and conventional array radars it would be desirable to be able to switch between a full/thin and thin/full array depending are where the jammers are for a given situation. This could be achieved by using T/R modules at all the elements of the transmit and receive array. The conventional array equivalents can be better against repeater jammers for the reasons given above for the monostatic MIMO system.

8. Future Work

The study by simulation of use of AAAP (CAAP) for coping with different sidelobe and mainlobe jammer combinations would be very fruitful. This is now made easy with programs like the MathWorks MATLAB. A lot can be learned by such simulations as shown by Gabriel's work which is summarized in [9, Chap. 4]. His work showed that if there are two nearly equal strength jammers closer than a beam width apart the two eigenbeams needed are a sum and difference beam. Two squinted sum beams would probably do just as well.

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