COGNITIVE ADAPTIVE ARRAY PROCESSING (CAAP) – ITS TIME HAS COME

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Abstract: Cognitive Adaptive Array Processing (CAAP) is adaptive array jammer cancellation which makes use of information gathered about the jammer. With CAAP the jammer cancellation can be done with dramatically less processing, with orders of magnitude fewer training samples and with less degradation of the antenna sidelobes. With digital beam forming (DBF) now being more widely used CAAP becomes more feasible to implement. Its time has come. It should be looked at. The results are presented in tutorial form without heavy math. Instead physical explanations are given for these results. The CAAP technique 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 Knowledge Aided-STAP (KA-STAP) technique used by DARPA. In many cases no interference covariance matrix inversion is needed and when needed the matrix size is reduced by orders of magnitude and in turn the computation of its matrix inverse. This method reduces the 10 to 30 dB antenna sidelobe degradation usually resulting from using the SMI method. The advantages re the use of diagonal loading (DL) and the principal component (PC) techniques are also addressed. The CAAP technique lends itself well to conventional and MIMO array systems when digital beam forming is used which is the future trend.

1. Barrage Jammer

We first address the ability to cope with barrage jammers with the conventional monostatic radars consisting of a linear array of N elements having lambda over 2 spacing between elements [2, 3, 12]. It is important to first realize that cancelling the jammer is independent of the waveform used or the type of radar. This is true certainly if we first cancel the jammers before any signal processing. For our conventional monostatic radar we first form a stack of focused high gain receive beams that cover the FOV. Our goal is to make these beams jammer free. It is not necessary to form all the beams simultaneously in practice but for pedagogical reasons we will do that here. Detection of the targets follows jammer rejection. By proceeding this way we demonstrate that the rejection of the jammers is independent of the type of radar we have and the radar waveforms used. Cancelling the jammers is only dependent on the jammer properties. 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 larger 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 coming into 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 as the auxiliary jammer signal. We have thus achieved our goal except for beam m. We are left with the problem of main lobe jammer cancelling to remove the jammer from the mth port. This is a main lobe jamming problem which involves more sophisticated processing which we will not deal with here. It is a problem to be dealt with in another study. The simple technique for cancelling the jammer just described is Cognitive Adaptive Array Processing (CAAP). It is what I used to call Adaptive-Adaptive Array Processing (AAAP) [5-9]. It uses as the aux for cancelling out the jammers in the N-1 beans. The aux is a high gain beam formed from the same array used to detect the target. With the advent of DBF this becomes easy to implement.

For this case of a single jammer no matrix inversion is required and the number of training range samples needed to cancel the jammer is small, just a few range samples, i.e., the transient time is short, independent of the size N of the array. Specifically for the cancelation of one jammer only K=1 sample is needed to get to within 3 dB of the optimum SIR. To get to within 1 dB of optimum K=4 samples are needed. The physical explanation of these results is simple. For K=1 the accuracy of the weight estimate W_e is limited by the main beam channel thermal power noise level n. 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 power level of 2n in the main channel after cancellation so there is a 3 dB increase in the interference level after cancellation. If K=4 cells are used then the noise in the estimate of W_e is reduced by K=4 to n/K=n/4. But we still have a noise level n in the main channel cell we are looking for a target in so the noise in the main channel becomes effectively n(1+1/K)=1.25n for a 1 dB SIR degradation after cancellation when K=4. (This analysis assumes a constant amplitude jammer, a large jammer-to-noise ratio in the aux and that the weight estimate is given by the ratio of the main to aux channel voltage.) 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. With one sample one could be sampling when the jammer was at or near a null and we would not be getting a good estimate of the jammer signal. Even with constant amplitude noise one could be sampling when the thermal noise is peaking and again not have a good estimate of the aux jammer signal. Note that a rejection of the target signal in the main channel will not occur as long as the signal is not present in the training cells. This will be the case if the jammer is not in the main beam.

The CAAP technique just described makes use of the fact that we can locate the jammer and use that information for canceling out the jammer by using a simple SLC instead of blindly using the classical SMI approach. There are several significant advantages gained by using CAAP over SMI. One major advantage of CAAP is that with classical SMI we have to invert an estimate of an NXN interference matrix M_N. For N=10,000 it is a 10,000X10,000 matrix which requires of the order of N^3 multiplies and divides which for N=10,000 is ~1,000 billion ≈ 10^{12}. With the CAAP for K=4 we only need K=4 complex divides and one complex multiply to cancel out the jammer independent of N. Another major advantage is that it does not need many training samples. For an N=10,000 element array K=5N=50.000 samples are needed with the classical SMI approach to get a SIR within 1 dB of optimum, based on Brennan's rule [11]. With CAAP only K=4 samples are needed independent of N as shown above.

CAAP also has the advantage of not degrading the adapted antenna sidelobes as done with SMI [5, 6]. This is because it does not do SLC using beams pointing where there are no jammers as elaborated on shortly. As a result there is only a small degradation of the adapted sidelobes. Specifically for the case of one jammer it only raises by a small amount, about 2 dB, the 2 sidelobes straddling the jammer null [5, 6]; see Fig. 1. A comparison of the adapted antenna patterns using CAAP versus conventional SMI method for the case of one jammer is shown in Fig. 2. On the left is the antenna pattern without adaption and on the right of it with SMI and CAAP. With SMI all the sidelobes except one are degraded 20 to 30 dB. Another very important advantage of CAAP is that for the single jammer case the jammer is suppressed to 6 dB below the thermal noise in the main beam no matter how strong the jammer is when K=4. If the jammer level is increased by X dB the cancelation is increased by X dB. This is true as long as the jammer is not at the null of the main beam sidelobes. In latter case no SLC is needed. If used with CAAP it would increase the noise level in the main beam by a small amount due to what is called aux channel carry over noise. To avoid this the determination can be made that the jammer is not present in a main beam by monitoring the noise level out of all the beams. This involves averaging the power out of each beam channel by averaging the power over a few range samples like 5 to 10. This is what CAAP does anyways to locate where the jammer is.

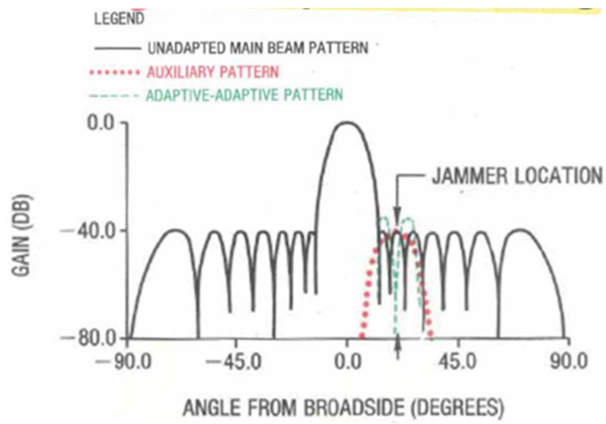

Figure 1. Illustration of small degradation of only two sidelobes straddling (shown in green) the adapted pattern null when using CAAP [5, 6]. Red dashed curve is beam pointing at jammer with its gain adjusted to equal to that of sidelobe in beam we are looking for a target in so as to form a null at the jammer angle in the adapted antenna pattern formed by subtracting the aux signal from the main beam signal.

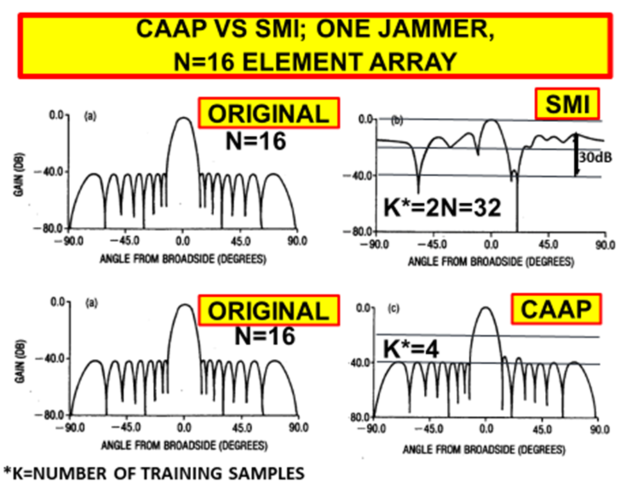

Figure 2. CAAP vs SMI for 1 jammer case; After [5, 6].

One can use the methods of principal components (PC) or diagonal loading (DL) of the interference matrix to cancel the above single jammer to eliminate the sidelobe degradation of the SMI approach; see [11, Fig. 2.11] and [11, 16]. However the PC method requires the estimation of the NXN interference covariance matrix M_N followed by determination of its eigenvectors. This computation requires of the order of N^3 multiplies and divides which for N=10,000 is ~1,000

billion ≈ 10^{12}. The DL approach requires the calculation of the inverse of M_N which also requires of the order of N^3 computations. See Table 1. Also with the diagonal loading one sees a degradation of the rejection of weak jammers present [16] and also of strong jammers [11, 16].

	CAAP	SMI
TRAINING SAMPLES*	4	50,000
ANTENNA SIDELOBES DEGRADED	ONLY 2	MANY BY >10 DB
MATRIX INVERSE NEEDED	NO INVERSE NEEDED	10,000X 10,000 MATRIX

*TO BE WITHIN 1 DB OF OPTIMUM SIR

Table 1. CAAP vs SMI for case of one jammer.

Next assume J jammers. J beams now contain the jammers. The outputs of these J beams are used as auxiliary beams for cancelling out the jammers in the other N-J beams; see Fig. 3 [5-9], which gives CAAP for the case of J jammers. CAAP is now a standard SLC with J auxiliary beams pointing at the J jammers with the aux beams again formed from the same antenna as used to form the beam to detected the target; see Fig. 3. Now one has to invert the estimate of only a JXJ jammer interference covariance matrix M_A for the J jammer beams of the CAAP SLC, see Fig. 3, instead of the NXN interference matrix M_N. Using Brennan's rule [11, 17] for J=10 the number of range samples needed to estimate the interference matrix M_A is estimated to be K≈2J=20 to achieve a SIR within 3 dB of optimum and K≈5J=50 to be within 1 dB of optimum. In contrast if the SMI or SMI with diagonal loading method was used and N=10,000, then as for the case where J=1 a 10,000X10,000 matrix has to be inverted. Also for the SMI method K≈2N=20,000 samples would be needed to achieve a SIR within 3 dB of optimum and K≈5N=50,000 to be within 1 dB of optimum [5, 6]. Guerci [11] showed that for N=16 and 30 dB Chebyshev weighting and J=6 widely spaced jammers using K=2N=32 resulted for respectively the PC and DL methods an SIR within 0.8 and 0.9 dB of optimum instead of 3 dB. Slightly better performance than Brennan's ruler estimates here.

The small sidelobe degradation that applied for CAAP for a single jammer still applies for the case of J jammers. Again only the sidelobes adjacent to the jammers will have their sidelobes degraded and then only by about 2 dB at most. In contrast when using the SMI approach many sidelobes are degraded as illustrated dramatically in Figs. 3 and 4 for the case of 2 widely spaced jammers. Brennan's rule estimates

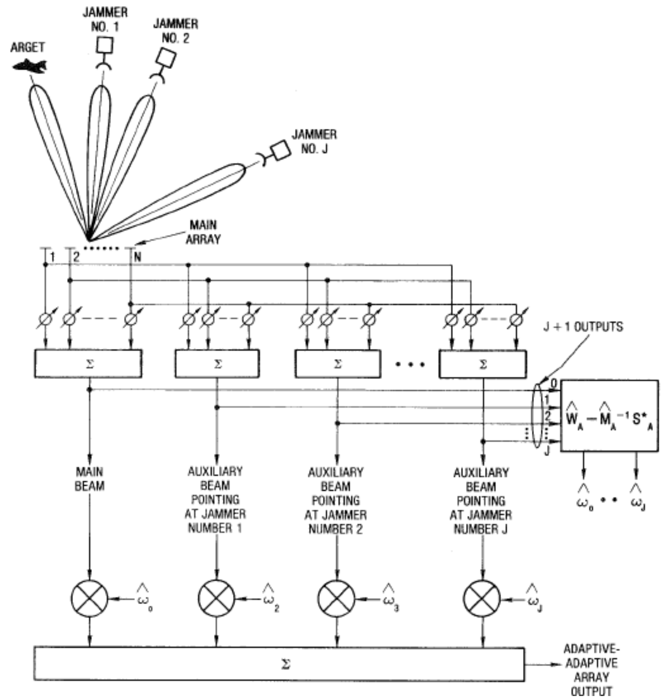

Figure 3. CAAP for J jammers [5-9].

that only K=5J=10 training samples are needed to be within 1 dB of optimum for CAAP. For Fig. 3 the SMI method is using K=15 training samples which Is 1.5 times the K=10 estimated to be needed with the CAAP method for 2 jammers and we see the main lobe is destroyed and the sidelobes are at the same level as the main lobe. In Fig. 5 the SMI method is using 3,000 training samples, 300 times the 10 needed with CAAP and we still are getting over 30 dB degradation of some sidelobes. These results are in agreement with Kelly's [19, see also 16] estimate that for an expected power sidelobe level of SLL we need K to be given by SLL=1/(K+1), which for K=3,000 gives us SLL= ~35 dB down SLs, close to the SLL of Fig. 5. Once the J beams with the jammers are located and the SLC weights needed by each beam to do the SLC found, it is possible to replace the J jammer beams and one main beam with one beam, the main beam in which the jammers are cancelled out. Doing so reduces the computation, only one beam being formed instead of J+1. This may be desirable for some implementations.

To estimate the number and location of the jammers modern estimation and super resolution methods could be used [8, 9]. An interesting case to consider is where there are two jammers of nearly equal strength in one sidelobe. Here we need for the CAAP two closely spaced beams to best cancel out the 2 jammers. Gabriel showed that for this case 2 eigenbeams are needed, one being a sum beam and the second a difference beam [9, p. 185]. Probably having 2 squinted sum beams for the aux would do just as well. If one wanted to allow for the cancelation was achieved using 2 sum beam closer than a beamwidth apart.

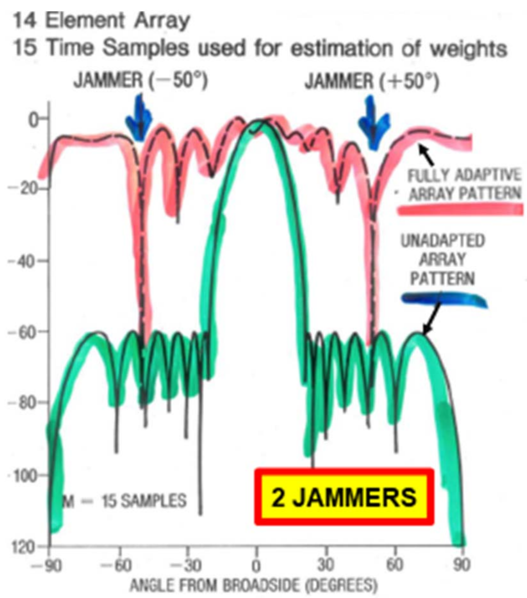

Figure 4. Here J=2 and N=14. SMI processing used showing destruction of main lobe and practically all the sidelobes at near the same level as the main lobe when using 1.5 times as many training samples K as needed with CAAP to be within 1 dB of optimum, i.e. K=15 instead of the 10 needed with CAAP for the N=14 element array [5].

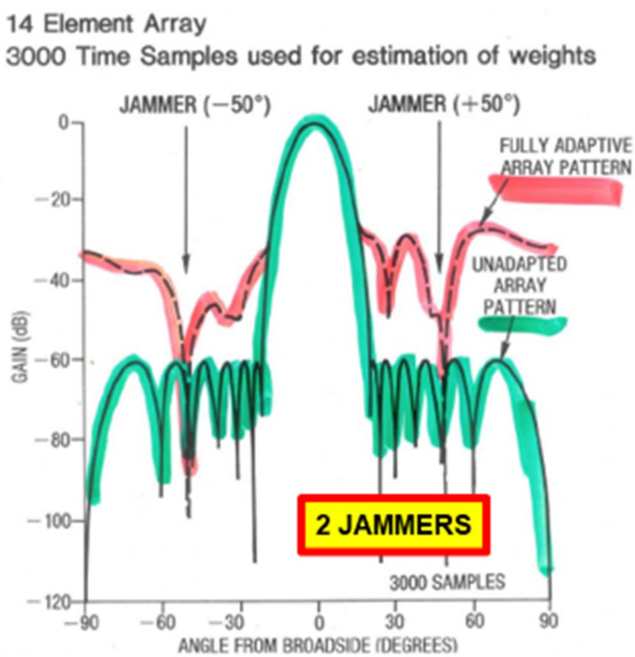

Figure 5. SMI processing showing poor sidelobes when using a large number of training samples of K=3,000≈200N, 300 times that needed with CAAP. Again J=2, N=14 [5].

possibility that there was 2 jammers in a beam without using super-resolution one could with CAAP simply see if better

The classical SMI actually does just what CAAP processing does. This was shown amazingly in Sidney Applebaum's original "Adaptive Array" seminal paper and report [10]. With SMI he showed beams are formed pointing in the direction of the jammers transparent to the user. These beams are formed by eigenvectors of the NXN interference covariance matrix M_N. When such eigenvectors are used as the weights for the antenna they form beams called eigenbeams. If there are J jammers J eigenbeams are formed pointing in the direction of the J jammers just like for CAAP. Furthermore with SMI the J beams are used to do SLC of the J jammers just like with CAAP. Unfortunately the SMI method forms from M_N N eigenvectors and eigenbeams. The other N-J beams are due to the thermal noise present. The remaining N-J beams point in the directions where there is no jammer just thermal noise. If we do not have a perfect estimate of M_N these noise beams attempt to cancel out jammers in the direction where there is no jammer just thermal noise. As a result they degrade the adapted beam sidelobes as shown in Fig. 2 for the case of one jammer, in Figs. 4 and 5 for two jammers and Fig. 2.9 of [11] for 6 jammers. If one has a perfect estimate of M_M then the noise eigenbeams are not used to put nulls in the direction of the thermal noise and as a result do not degrade the adapted beam sidelobe level [11]. With CAAP there are no such thermal noise beams being used to put nulls in the direction of the noise beams. As a result with CAAP there is only typically a sidelobe degradation of about 2 dB of the two sidelobes next to the null. The same is true when using the method of PC, the noise eigenbeams being set effectively to zero [11]. With DL the noise eigenbeams are reduced in strength. The larger the diagonal loading the smaller the subtracted noise eigenbeams and hence the smaller the degradation of the adapted sidelobe levels. DL has the disadvantage of modifying slightly the jammer eigenbeam level so as to spoil the null at the location where the jammers are [11]. The larger the diagonal loading the greater the degradation of the jammer nulling. DL is an approximation of the PC method. As a result in general it will have greater sidelobe degradation and poorer nulling than achieved with the PC and CAAP methods.

With the SMI method each jammer eigenvector beam has nulls in the direction of the other jammers. This could be done for CAAP by appropriately selecting the zeros of the polynomial Schelkunov form for the arrays factor of the jammer beams [20]. But having beams with low sidelobes will often be good enough. CAAP will generally give near optimum performance without the disadvantages of the SMI, DL and PC methods.

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. Here we consider the case of an elevated radar having to look down for the target with its main beam pointing at the reflection point of the jammer signal. For this case we have main beam jamming by hot clutter, a worst case [13, 14]. We show how with CAAP a conventional array can suppress main lobe hot clutter jammer signal without suppressing the main lobe signal. To do this we generate from the array a second focused beam pointing at the jammer. We use this second beam as an aux beam to cancel the hot clutter in the main beam. This aux signal will not cancel out the target echo signal as done for a normal main lobe canceller. 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 will be canceled though. If the hot clutter is dispersed in time then a tapped delay filter needs to be used for the aux signal. This cancellation is independent of the transmit waveform and type of radar. So we have shown how a radars can easily handle main beam hot clutter using CAAP.

3. Repeater Jammer

We now consider the ability of the monostatic array radar to handle repeater jammers. For such 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 a stack of receive focused beams can be used in place of the omni beam. Each of these beams is set to have a gain larger than that of the sidelobe at that angle in the main beam being jammed. Doing this customizes the SLB operation and gives better performance. It represents CAAP SLB. We can go another step forward with CAAP. The monostatic array radar can use open loop nulling and spoofing to defeat repeater jammers. Specifically, 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 reduces the level of the sidelobe signal seen by the repeater. This 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 or in effect jam the repeater. Having nulls in the sidelobes of the main beam in the direction of the jammer can reduce the power needed by the spoofer by 10's of dB.

4. MIMO

With conventional phased arrays we form the transmit beam in the transmitter [1]. For a MIMO (Multiple Input and

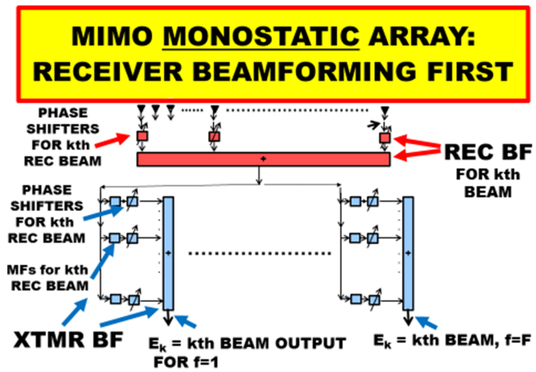

Figure 6. MIMO monostatic array receive architecture with transmit beam forming done after receive beamforming.

Multiple Output) array radar the transmit beam is formed in the receiver [2, 3]. The latter is achieved by transmitting a different orthogonal waveforms from each element of the array. 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 SIR as done in [4].

We now compare the ability of a MIMO radar to cancel barrage jammer vs a conventional radar [2, 3]. Usually for a MIMO phased array radar the transmit beam forming is done first followed by receive beam forming [3]. However if the receive beam forming is done first as shown in Fig. 6 with the transmit beam being done after we have the same situation re cancelling a barrage jammer as we had for the conventional array above. Specifically we want to first form receive focused beams that are free of the jammers. Doing this is not dependent on whether we have a conventional array radar or a MIMO array radar. Consequently the ability to reject barrage jammers is independent of whither we have a MIMO or conventional array radar. Hence the MIMO and conventional phased array have the same performance re cancelling a barrage jammer. This result holds whether we have a MIMO full array or a MIMO full/thin or thin/full array [3, 12]. It could monostatic or bistatic.

Let us now apply CAAP to MIMO radar for a repeater jammer. The MIMO radar can apply nulls in the direction of the repeater jammer in the receive beam and transmit beams once it detects and locates the jammer just as well as a conventional array radar can. Only for the MIMO system the transmit beam nulling is done in the receiver. Thus when it comes to spoofing the repeater jammer and preventing him from detecting the radar sidelobe signal the MIMO system is at a disadvantage. First re detecting the sidelobe signal from the MIMO radar. It is easier for the repeater to do this for the MIMO radar because the MIMO radar cannot put a null in the transmit sidelobes in the direction of the repeater because he is radiating a broad beam on transmit, not a focused beam. He does not have sidelobes just a broad beam. As a result the repeater will see a signal from the MIMO radar that could be 30 to 50 dB stronger than for the conventional radar. So it is much more difficult for him to detect the conventional radar signal than the MIMO radar signal. For the MIMO radar the repeater also has the additional advantage that he does not need as much gain in his repeater to generate a false echo in the MIMO radar. Also because the MIMO radar cannot put nulls in the radiated beam it is more difficult to jam of spoof the repeater. So the conclusion is that the MIMO array radar is at a disadvantage re the conventional radar when it comes to coping with a repeater jammer even with CAAP.

5. Future Work

CAAP represents a very fruitful area for future study. One area for study is how to cope with different jammer combinations in the sidelobes and main lobe. The advantages that may be gained if the J jammers are separated from each other by more than a beamwidth should be explored. Same for closely spaced jammers and main lobe jammers. The use of multiple aux beams for beams which show a jammer is present should be explored further by simulation. A lot can be learned for CAAP by doing simulations for different cases. Now with MATLAB it is easy. In the future when eigenbeam decomposition becomes inexpensive PC can be used to find the jammer eigenbeams. These can then be used as the beams pointing in the direction of the jammers. In this case CAAP becomes closer to the PC method. CAAP as described here does not handle jammers coming through the antenna backlobe. This is problem not unique to CAAP. To handle these jammers with CAAP one or two receive only arrays pointing to the rear of the main array could be used. Whether Brannan/s rule applies for the CAAP interference matrix M_A of Fig. 3 needs to be verified by analysis and or simulation. A simulation is being planned.

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