MIMO RADARS AND THEIR CONVENTIONAL EQUIVALENTS – AN UPDATE

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Abstract: It had originally been shown in the literature that a MIMO full/thin array radar system (consisting of a full transmit linear array of N elements having $\lambda/2$ spacing and a collocated, parallel, linear thinned receive array having $N\lambda/2$ spacing) is equivalent to a full array of N^2 elements having $\lambda/2$ spacing and thus achieves N times the accuracy and resolution as a conventional full array of N elements, 10 times or 100 times or 1000 times better than a conventional array depending on N [1]. It has since been shown that a conventional array radar can do as well as a MIMO full/thin array radar [2]. Specifically, a conventional full/thin array radar was shown to provide the same resolution and accuracy as the MIMO array. The conventional full/thin array had some disadvantages relative to grating lobes that had to be dealt with but in some situations it could provide better energy search efficiency than its MIMO equivalent. Here a new conventional array is presented which has no grating lobes, the same resolution and about has the same accuracy as the MIMO full/thin array radar. Also it uses the same search time and about the same power-aperture product to do volume search as the MIMO radar. The new conventional array consists of the same full and thin arrays but with their roles reversed with the thin array transmitting and the full array receiving. The new conventional array is called a thin/full array to distinguish it from the former full/thin array. The properties of the full/thin and thin/full MIMO and conventional array radars are detailed relative to waveforms and matched filter signal processing loads. The matched filter processing load for MIMO full/thin and thin/full arrays are dependent on whether the transmit or receive beam forming is done first. It is pointed out that MIMO radar systems do not have any advantages relative to barrage jammer, hot clutter jammer or repeater jammer suppression. Finally it is shown how the conventional thin/full array can be used for GMTI so that it should provide the same minimum detectable velocity as does the MIMO thin/full array.

1. New Conventional Thin/Full Array

As in [2, 3] consider a MIMO full/thin radar consisting of collocated, parallel, linear transmit full array and thin receive arrays each N=10 elements with spacing $\lambda/2$ for the transmit elements and 5λ for the receive elements. Assume uniform weighting for receive and transmit. It has been shown that a MIMO full/thin 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 [4]. For N=10 the virtual array is a full array of 100 elements with $\lambda/2$ spacing. In [2, 3] it is shown how the full/thin MIMO array can be used as a conventional array to give the same accuracy and resolution as the 100 element virtual full array but with some grating lobes which can be dealt with. The grating lobes can be removed by using a transmit antenna with approximately a rectangular antenna pattern. This requires an increase in the size of the transmit array by a factor of two or so. Alternately we use transmissions which have low level grating lobes that we can live with. The latter approach reduces the search efficiency of the equivalent conventional full/thin array but for some situations its search efficiency will be better than that of the MIMO full/thin array radar. Here we present an equivalent conventional array radar to the MIMO full/thin array radar which does not have the grating lobes and is equivalent to the MIMO full/thin array. For the new equivalent array we use again the same full and thin arrays of the full/thin array except we reverse their roles with the thin array used for transmit and the full array for receive. We call this a thin/full array to distinguish it from the previous one which we called a full/thin array. We show that the thin/full conventional array is equivalent to the full/thin MIMO array radar for N=10 and its equivalent 100 element full array, having no grating lobes, the same resolution as the 100 element full array and about the same angle accuracy.

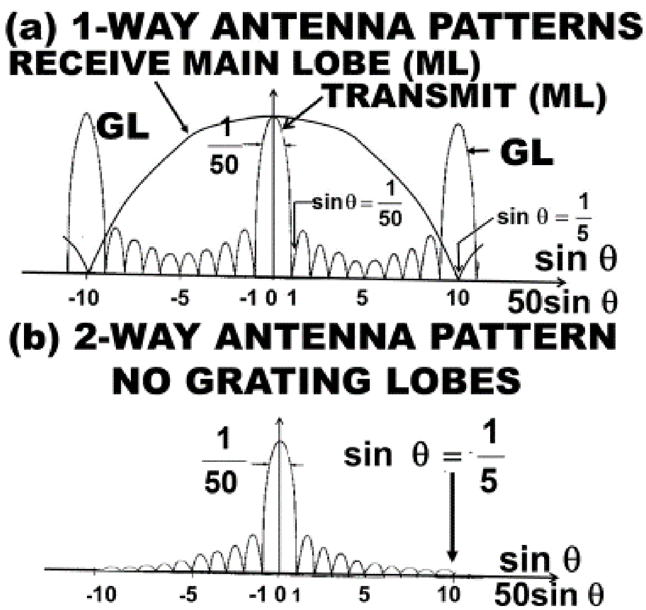

Figure 1. Thin/Full Array Used as Conventional Array. Note: GL=grating lobe.

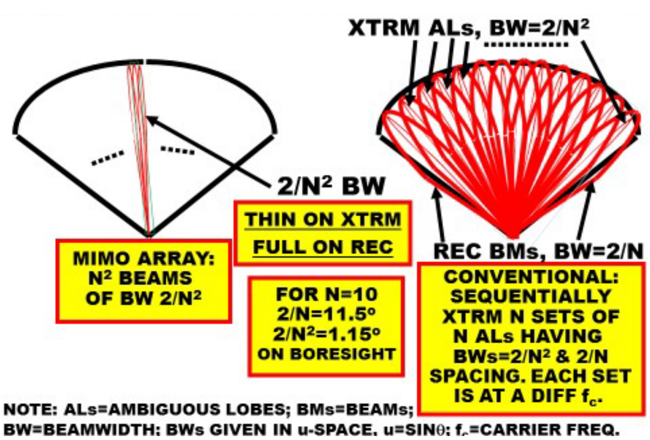

Figure 2. MIMO thin/full array & conventional equivalent; thin on transmit, full on receive; each N element linear array; volume search of 120°.

Fig. 1a shows the transmit beam pattern and receive antenna pattern obtained for the thin/full conventional array when both are pointing at boresight. Fig. 1b shows the resulting 2-way beam pattern. What is apparent is the resultant 2-way beam pattern for the conventional array has the same beamwidth as a full array consisting of 100 elements having a spacing of $\lambda/2$. Hence it has the same beamwidth and resolution as our N=10 MIMO full/thin array. Furthermore the conventional array does not have any grating lobes (GLs) 2-way in Fig, 1b, the GLs falling at the nulls of the receive array. Although only two GLs are shown in Fig. 1a there are actually N-1 GLs within the linear array antenna field-of-view (FOV) of ±90°. All the other N-3 GLs also fall on the nulls of the receive antenna pattern so that two-way there are no GLs for our conventional thin/full array. For the thinned transmit array of N elements with spacing 5λ there are N ambiguous lobes (AL) [5]. One of these is chosen to be the ML, the lobe we select to detect the target within. The other N-1 ALs form the GLs. The GLs we would like to get rid of. This was done above in Fig. 1a by placing the peak of a full array receive beam at the peak of the AL chosen to be the ML; see Fig. 1. In the receiver we do this simultaneously for each of the ALs to form N MLs; see Figs. 2 and 3. Specifically we simultaneously form in the receiver N receive beams with each having its peak a different one of the ALs so as to form N MLs. The N transmit antenna ALs are spread out uniformly over the ±90° field-of-view (FOV). More exactly the ALs are spread uniformly in u-space from -1 to +1, the FOV in u-space where $u=\sin\theta$ [5]. Comments relative to the FOV is needed. The FOVs of N element arrays of Figs. 2 and 3 is ±90° but because of the element pattern fall off a fraction of this FOV is used in practice, like ±60°, hence the smaller coverage shown in Fig. 2. In Fig. 3 the thinned array element pattern is not taken into account, it is assumed to be isotropic in effect.

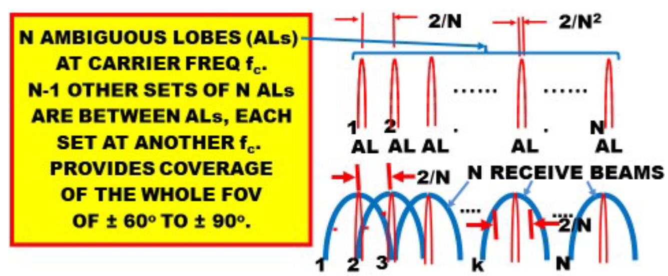

Figure 3. Conventional thin/full linear array; thin on transmit, full on receive; N elements each.

It helps to express the angles in degrees. For N=10, 2/N is 11.5° on boresight and $2/N^2$ is 1.15° on boresight. Note that we are covering only 1/Nth of the FOV. But, what we are showing in Figs. 1 to 3 are the beams formed from one pulse transmission. The waveform could be a simple conventional chirp pulse at a carrier frequency f_c and with a pulse width T_p. The transmit array being a conventional array, the same waveform is transmitted from all the transmit antenna elements at the same f_c. The phase shifts used for the transmit array on one pulse transmission form the N ALs at a specified angles in Figs. 2 and 3 with these ALs becoming N MLs at the outputs of the N receive beam channels. To cover the angle space not covered the one pulse we transmit immediately after the chirp pulse to form the beams shown in Figs. 1 to 3 a 2nd identical chirp pulse at another carrier frequency to form a second set of N ALs and in turn MLs the same as shown in Figs. 2 and 3 but all shifted to the right by $2/N^2$ to cover the adjacent angles to the first set of MLs. This is repeated another

N-2 times, for

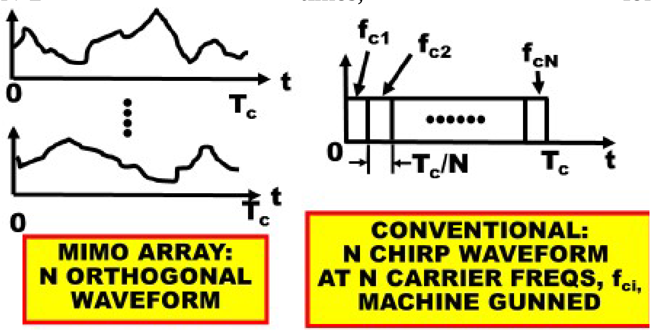

Figure 4. Waveforms for MIMO thin/full array & conventional equivalent.

a total of N times to cover all of the u-space, that is, the whole field-of-view (FOV) which in this case is ±1 in u-space or ±90° in angle space [5]. The N sets of carrier frequencies are chosen so that the N chirp signals are orthogonal to each other. The N chirp pulses are transmitted one after the other. This is called machine gunning [6, 7]. After all the N chirp pulses have been transmitted there is a listening time for the received echoes. The echoes from the N pulses can and are received simultaneously because they are orthogonal. To do this N receivers tuned to the N carrier frequencies are used. This can all be done digitally with no hardware being needed as discussed shortly.

Fig. 4 shows the waveforms for the MIMO array radar and its conventional thin/full equivalent. The MIMO array can be either a full/thin or thin/full array. In Fig. 4 the MIMO orthogonal waveform amplitude modulation is only shown. It also has phase modulation. If possible it would be desirable for these orthogonal waveforms to be realized using only phase modulation so that linear power amplifiers are not needed. As discussed above the N sets of transmit ambiguous lobes (ALs) and in turn MLs for the conventional thin transmit array are formed sequentially one after the other using chirp waveforms. These chirp waveforms have pulse widths and in turn coherence times T_p where $T_p=T_c/N$, where T_c is the coherence time of the MIMO equivalent array; see Fig. 4. Thus the conventional thin/full array has a coherence time 1/N times that of the MIMO equivalent array. Both the conventional and MIMO thin/full systems have the same total transmit and receive times. The receive listening time follows immediately after the transmit time for both. For the MIMO radar N orthogonal waveforms having a duration T_c are transmitted simultaneously whereas for the conventional radar N chirp waveforms each of duration T_c/N but different carrier frequencies are transmitted sequentially over the same total time T_c which in both cases is followed by the same listening time. As a result the volume search times are the same for both systems. Also both require about the same energy to search the same volume of space. To see why consider that on one transmission the conventional array has a gain N times that of the MIMO transmit array. As a result each transmit pulse requires 1/Nth the energy of the MIMO pulse. But N pulses are required to cover the whole FOV with the conventional array; see Fig. 2. As a result the target being searched will provide the same SNR for the conventional array if it is at the peak of one of the transmit ALs. If not at the peak of an AL during search there will be a transmit beam shape loss (BSL) for the conventional system. For a 2-dimensional azimuth-elevation (AX-EL) volume search with a pencil beam or horizon fence search with a pencil beam there would be about a 3 dB BSL for the conventional system [8]. The MIMO system has an advantage here because it can use a maximum likelihood estimate (MLE, [9]) to detect and locate the target with the result that the BSL is lower, of the order of 1.5 dB instead of 3 dB, so the conventional array has about a 1.5 dB higher BSL in this case. If the volume search is done with a fan beam as done for mechanical rotating antennas then we have a one dimensional search and the BSL for the conventional system is about half as much at ~1.5 dB [8] while for the MIMO system it is ~0.8 dB for a difference of ~0.7 dB in the MIMO radars favor. The BSL is not completely eliminated because of the increase in false alarm rate that result from generating many search beams when using MLE for detection [10].

At first blush the thin/full conventional array appears to have the disadvantage of not being able to provide as good an estimate of the detected target angle location on search. This is because it has wide beams on receive, 11° wide instead of 1.1° wide. And it can cannot use the MLE with the narrow transmit beams as possible for the MIMO thin/full array radar. It gets around this problem by following the target detection with a conventional track dwell that uses sequential lobbing with the transmit beam. This is like a verify in a conventional radar but instead is used for target location and possibly track initiation. The dwell can be made long enough to provide a very high SNR and in turn very accurate angle estimate if desired. An alternate for getting target angle information during search with the conventional thin/full array is to use AL beams that are packed closer than at the 3 dB widths to search the volume of space, like spaced at half the 3 dB width apart for search but with beam having about half the energy that is used with a 3 dB spacing. In this case one would video integrate adjacent beams for detection, like beams 1&2, 2&3, 3&4, etc. On detecting a target the amplitudes of the echoes from adjacent beams would be used for target angle location estimation. This provides a coarse MLE for target detection and location based on the transmit beam locations. It is like doing sequential lobbing or conical scanning on search. The full/thin conventional array does not have this angle estimation issue. It uses on receive narrow ALs for MLE detection and angle estimation.

The conventional thin/full array system will require a wider bandwidth than its equivalent MIMO system. This is because N different carrier frequencies f_c are needed for the N subpulses of the conventional array; see Figs. 2 to 4. This wider bandwidth will not typically require more receiver hardware, just A/Ds with wider bandwidth. For example for search assume a narrow bandwidth of 100 KHz is used. Typically a narrow bandwidth is used for search to reduce the number of range cells needed for search which allows a larger false alarm probability per range cell and in turn more efficient search. For N=10 and a separation of 500 KHz between carrier frequencies the total bandwidth to be handled by each A/D is only 5MHz which is easy to handle with todays A/Ds. Having the thin array do the transmitting for the conventional array has the advantage of lower dispersion across the receive array since it is physically smaller, 1/N times smaller than the transmit array. This is an advantage when having to reject barrage jammers, a subject covered in Sect. 5.

It is worth noting that achieving good orthogonality for the waveforms of a MIMO system is not a trivial task [11-13]. For many applications it may not be possible to obtain waveforms with a satisfactory orthogonality. We will not address this problem here but assume that it is possible and examine other issues.

We now point out that the two-way conventional thin/full array pattern of Fig. 1b is actually identical to that of the MIMO thin/full virtual array. The conventional thin/full array two-way pattern given in Fig. 1b is the product of the thin transmit array pattern with the full receive array antenna pattern. From Fourier Analyses this is the pattern one obtains from an equivalent antenna obtained by convolving the weightings versus distance along the aperture functions for the conventional transmit and receive arrays. But this is just what the virtual MIMO array is; QED. It is important to point out that although the equivalent virtual antenna having N^2 elements has the same resolution as a full array of N^2 elements it does not have the PA (radiated power P times receive aperture area A product) or PAG (PA times transmit antenna gain G) of the full array antenna of N^2 elements. If we assume the same total power radiated by both then the virtual array's PA is a factor N lower and its PAG is a factor N^2 lower. For the same power per element for both the virtual array has a factor of N^2 lower PA and N^3 lower PAG.

We now show mathematically that the two-way pattern for the thin/full MIMO and its conventional exactly that of the N^2 element uniformly weighted virtual array. Let the antenna voltage patterns be given by $E_f(u)$, $E_t(u)$ and $E_{2w}(u)$ where $u=\sin\theta$, for respectively the full array of N elements of spacing $d=\lambda/2$, the thin of array of N elements having spacing $Nd=N\lambda/2$ and the thin/full array two-way pattern which is the product of the transmit and receive patterns. From [5] we get Eqs. 1 and 2 for $E_f(u)$ and $E_t(u)$, which yields their product Eq. 3, the 2-way pattern:

$$E_f(u) = \frac{\sin(N\pi du/\lambda)}{\sin(\pi du/\lambda)} \qquad (1)$$

$$E_t(u) = \frac{\sin(N^2\pi du/\lambda)}{\sin(\pi N du/\lambda)} \qquad (2)$$

$$E_{2w}(u) = \frac{\sin(N^2\pi du/\lambda)}{\sin(\pi du/\lambda)} \qquad (3)$$

But the above two-way pattern is the array voltage pattern for a full linear array of N^2 elements spaced $d=\lambda/2$, which is the MIMO virtual array. Again QED. Note that Eq. 3 has no grating lobes. Note that the voltage patterns given above are actually the linear array antenna patterns for the case where the elements radiate isotropically. This type of antenna pattern is called an antenna "array factor" [5]. Note also that this result applies when the arrays are uniformly weighted. It is because we have a uniform weighting for the full array that we have all the grating lobes of the thin array falling on the nulls of the full array. It does not matter whether we have a MIMO or conventional full/thin array. For this case the zeros of the Schelkunov polynomial form of the array factor are uniformly placed around the unit circle relative to the peak of the beam location [14]. If the full array was weighted the poles and in turn its array factor nulls would no longer be uniformly spaced so as to fall on the grating lobes of the thinned array. On the other hand applying weighting to the thinned array still keeps the grating lobes at the nulls of the full uniformly weighted array if we do not change the spacings between the elements of both arrays. It is desirable to apply weighting to the thin array because it lowers the close-in sidelobes of the thin/full array which with uniform weighting are only 13 dB down [5]; see Fig.1, too low for many applications. With a Dolph-Chebyshev 40 dB weighting applied to the thin array the close in sidelobes would be 40 dB down instead of 13 dB. One would in the process degrade the angle resolution of the full/thin array by 40% [5, 14]. This could be made up for by increasing the length of the thin array by 40%. Weighting the full array also is still an option. If this is done one would then want the first grating lobe to be at the first null of the weighted full array, or close to it. Now the higher order grating lobes do not fall at the nulls of the full array. However, if a Dolph-Chebyshev 40 dB weighting is used for the full array the higher grating lobes, although not at the nulls of the full array, are 40 dB or more down.

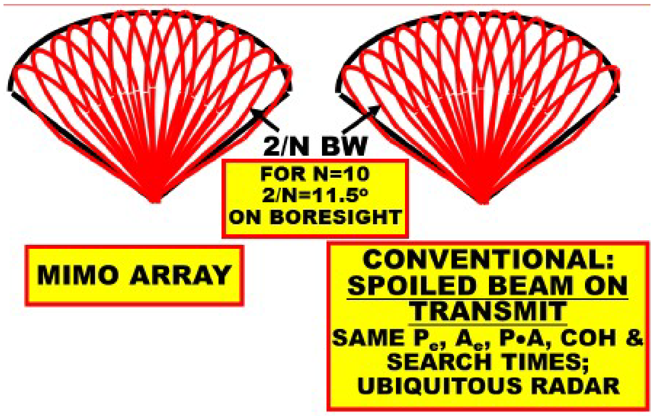

Figure 5 MIMO monostatic linear full array of N elements and its conventional equivalent using spoiled beam on transmit, Ubiquitous radar; volume FOV search of 120°.

It is important to note that viewing the thin/full MIMO and its conventional equivalent in the antenna pattern angle, or equivalently u-space domain, instead of the array weighting domain (of weighting versus distance along the array with its convolution to get the virtual array) gives us physical insight as to what is going on. When viewing from the angle or u-space domain we see right away that it is not necessary to have the number of elements N for the thin and full arrays be the same. Also the spacing of the elements of the thin array does not have to be equal to width of the full array. What is desired is that the first grating lobe be at or near the first null of the full array when heavy weighting is used for the full array. Also we see that we can have weighting for the thin and/or full array. Also the phase centers of the full and thin array do not have to coincide. This viewpoint also gives us right away a feel for the effects of errors on the MIMO array based on what we know already for conventional arrays as given in [5]. It is also very important to realize that the MIMO system is the same as the conventional array except that the transmit beam is formed in the receiver instead of in the transmitter. Their one-way transmit and receive patterns are the same when the same weightings are used. Also their two-way patterns are the same. Although the results given in this paragraph and the three before it were given for a thin/full MIMO and its conventional equivalents they apply as well to the full/thin described in [2, 3, 15].

2. Conventional Full/Thin Array

The full/thin MIMO and conventional array search waveforms are presented in [3]. If for the conventional full/thin array one chooses to receive only 4 narrow receive beams instead of 10 on each transmission, to keep the GL amplitude down as indicated in [3] then for N=10, 25 pulses and beams of width 2/N have to be transmitted instead of 10; (10N/4=2.5N=25). The search time then is 2.5 times that for its MIMO equivalent for a 4 dB search energy loss and a 2.5 times longer search time. But if the ideality factor n=1.5 the search power needed for the MIMO array would be 5.2 dB higher than for the conventional array [2, 3, 15] if we did not suffer the above factor of 2.5 (4dB) in the number of transmit beams. This leaves us with about 1 dB (5.2-4 dB≈1 dB) less search power needed for the conventional full/thin array than for the its MIMO equivalent [3]. The antenna one-way imbedded element power pattern is in terms of n is $\cos^n(\theta)$.

3. Comparison of Monostatic MIMO and Conventional Full Array Radars

Figs. 5 shows the volume search for the monostatic MIMO linear array and its conventional equivalent for the case where the latter uses a spoiled beam on transmit with focused beams on receive. The latter is called the ubiquitous radar by Merrill Skolnik. This conventional array radar equivalent has the same performance as the MIMO radar with respect to power and time needed to search the FOV. The MIMO system provides a $\sqrt{2}$ better angle estimate during search [2, 6, 16, 17]. But the MIMO requires a much larger signal processing throughput; see [2, 3]. A better conventional array is to use focused beams on transmit and machine gunning as done in Fig. 3. Doing this allows us to vary the transmit energy needed according to the off-boresignt loss and thus achieve higher search efficiency. As a result to search a 120° horizon fence for an ideality factor of n=1 we need 3.7 dB less energy for the monostatic conventional array than for the MIMO array, for n=1.5, 5.2 dB less energy, the same 5.2 dB as given above for the full/thin array in the paragraph above Fig. 5 [2].

4. Computation Complexity of MIMO Radar

It was indicated in [2,3 15] that a monostatic MIMO radar consisting of a linear array of N elements requires FN^2 matched filters (MFs) where F is the number of doppler matched filters per orthogonal waveform needed to handle the doppler intolerance of each orthogonal waveform. Thus for N=100 and F=30, 300,000 MFs are required for MIMO radar vs N=100 MFs for a conventional array radar which can use a chirp waveform that is doppler tolerant, 3,000 fewer MFs. This result is independent of whether the receive or transmit beamforming is done first. Thus the MIMO MF computation load can be orders of magnitude more than for a conventional radar. The MIMO full/thin array also requires FN^2 MFs. This result as well is independent of whether the transmit or the receive beamforming is done first. For the MIMO thin/full array radar again FN^2 MFs are needed if the transmit beamforming is done first. If the receive beaming is done first then number of MFs needed is FN^3. For the above conventional thin/full array radar the number of MFs needed is N^2. There are applications where doppler intolerant waveforms can be can used for the MIMO radar like for HF Over the Horizon (OTH) Radars which can use time or frequency separation for orthogonality [18]. Also when coherently combining radars [2, 3, 15].

5. Jammer and Clutter Suppression

It has been shown that conventional equivalents to MIMO radar systems can do just as well as MIMO systems in rejecting barrage noise jammers in spite of the larger number of degrees of freedom for the MIMO system; see [3, 19]. This becomes obvious when one realizes that the jammer rejection can be done first in the receiver without effecting the optimality of signal detection when the jammer is not within a beamwidth of the signal. When doing this the ability to reject the jammer or jammers is not dependent on the waveforms transmitted, and in turn whether it is a MIMO or conventional system. For a receive array of N elements the receiver architecture would consist of the formation of N, or more, focused beams for the detection of the targets in these focused beams over the FOV. This would be done independent of whether the system is a MIMO system or conventional array. For the MIMO system this would be the equivalent of doing the receive beam forming first, before the transmit beamforming with its MFs. The jammers present in each of the focused beams is next rejected using sidelobe cancellers (SLC) for each focused beam output. The auxiliary signals for the SLCs for a given beam are obtained from the outputs of the focused beams pointed in the directions of the jammers. The location of the beams pointed at the jammers can be easily determined by noting the strength of the outputs of the focused beams. This receiver architecture is an application of adaptive-adaptive beam forming for the jammer suppression; see [20-24]. The focused beams are approximations of eigenbeams [25]. Ideally they should have nulls or low sidelobes in the direction of the jammers. For a MIMO system next the outputs of each of the jammer suppressed N focused beams is followed by the formation of transmit focused beams which consists first of a bank of FN matched filters followed by the transmit beamforming. This architecture avoids doing the jammer suppression after the jammer signals go through the orthogonal matched filters where the jammer signal from the auxiliary may not be correlated with that from the signal channel. If the jammer is within a beamwidth of the signal then we have a mainlobe cancelling situation and the usual loss of signal strength. To detect such targets would require mainlobe cancelling techniques for both the MIMO and conventional systems and they should be equally effective in rejecting jammer.

It has been claimed that MIMO can handle hot clutter (which is barrage noise jammer signals received after reflection from the ground) whereas conventional arrays cannot [26, 27]. This is not true, conventional arrays can handle hot clutter just as well as MIMO arrays can [3]. Conventional radars can reject hot clutter coming into the mainlobe of the target beam without rejecting the signal return equally as well as MIMO radars; see Fig. 4 in [3].

Let us consider the ability of monostatic MIMO and its conventional equivalent of Fig. 5 to handle repeater jammers. For both types of systems standard sidelobe blankers (SLBs) can be used to gate out the repeater signals coming through the receive sidelobes of a focused receive beam pointing in the direction of a target to be detected. The location of repeater jammers can be determined for the monostatic MIMO and its conventional equivalent by noting the direction of the beams having many targets at several ranges coming from the same angle. The auxiliaries for the SLBs would be the beams in which the repeaters are located with their gains set to be slightly higher than the gains of the sidelobes in the direction of the jammer for the beam pointing in the direction of the target to be detected. This type SLB can be used equally effectively for the monostatic MIMO and conventional equivalents of Fig. 5. The conventional equivalent of Fig. 5 that uses machine gunning has the advantage over its MIMO equivalent radar in that it can use open loop nulling and spoofing to better cope with the repeater jammers. Specifically, for the conventional system nulls can be placed in the sidelobes in the direction of the repeaters for a transmit beam pointing in the direction of the target to be detected. This would reduce the sensitivity of the repeater to the transmit signals. Furthermore, it helps with spoofing of the repeater. Spooofing 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 lower the level of the signal retransmitted by the repeater at the frequency being used to detect the target and thus reduce the effectiveness of the spoofer, potentially to the point of being ineffective. Using spoofing for the monostatic MIMO radar and its ubiquitous equivalent is 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 easy. If MIMO subarraying is used it is easier but the widths of the nulls will be wide. In addition it results in loss of coverage at these angles. Repeater jammers are equivalent to strong clutter interferers. The use of MIMO radar to reject strong clutter interference is covered in [28].

The thin/full MIMO radar and its conventional equivalents have the disadvantage of a wide receive mainlobe of width $2/N$ (11.5^o on boresight) vs $2/N^2$ (1.15^o) for the full array of length N^2. The full/thin array has narrow ALs of width $2/N^2$ (1.15^o) but there are N of them so the total angle main beam

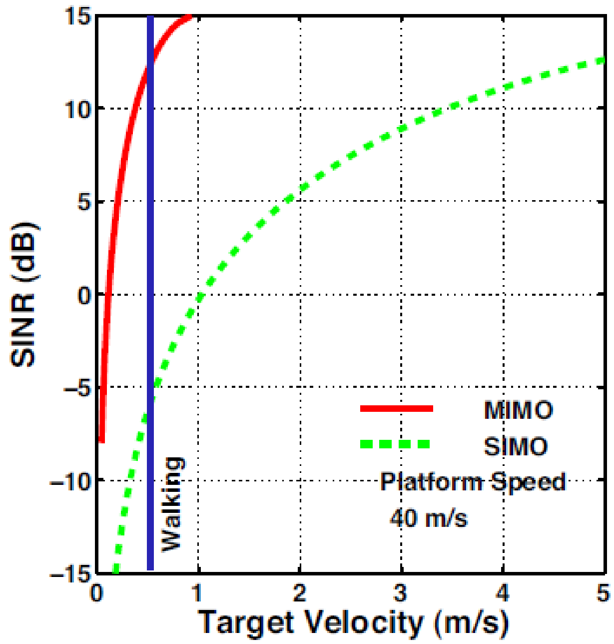

Figure 6. Comparison of MIMO and conventional GMTI systems. Assumptions: MIMO: thin/full array, N=5; Conventional: full array, N=5. From [28].

jammed is still 2/N (11.5º). 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.

6. Airborne Radars

It has been shown that MIMO can provide a lower minimum detection velocity (MDV) for an airborne GMTI system, the MIMO system being able to detect a man walking while the conventional could not; see Fig. 6 from [29]. The reason given for the MIMO providing a better MDV is that it has a longer coherent dwell time and a larger antenna. The conventional array they used was a full array; see Fig. 6 [29, see also 30]. If they used their MIMO thin/full array as a conventional array in the manner described in Sect. 2 above then the conventional array would have the same coherent dwell time and antenna aperture length as the MIMO thin/full array and one should expect that its MDV would be the same as for the MIMO system. The conventional thin/full array needs a waveform modification for use in a GMTI radar. Its waveform shown in Fig. 4 is a single pulse. For GMTI this single pulse would be repeated at a fixed pulse repletion frequency (PRF) to become a pulse doppler waveform having the same number of pulses and PRF as for the MIMO GMTI radar so as to have the same coherence time. We have not addressed the detailed waveform issues here for the MIMO GMTI system. Ref. 31 indicates that MIMO GMTI systems require higher PRFs with result that it may only find use for short range applications. It is worth emphasizing that the conventional thin/full GMTI system uses a conventional pulse doppler waveform that can be comprised of standard chirp pulses. There is no waveform design issue.

7. Applications of MIMO

For discussion relative to near term uses of MIMO radar the reader is referred to [2, 3]. I am sure that MIMO will find other uses. MIMO has the potential to be applied to large radars when subarraying is used as described in [2, 15] to reduce N and in turn the computation complexity.

7. Acknowledgment

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