RADAR AND PHASED-ARRAYS: ADVANCES, BREAKTHROUGHS AND FUTURE

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Abstract:

Moore's Law is slowing down but still has a way to go. Potential further major advances of Moore's Law via: Spintronics, Memristors, Graphene, and Quantum Computing. Advances made in metamaterials include low cost electronically scanned arrays (ESAs), stealth, cloaking (invisibility), low profile VHF/UHF antennas, focusing < λ/2. PATRIOT upgraded to GaN active electronically scanned arrays (AESAs) having 360° coverage without mechanical rotation. The S-band AMDR handles >30 times more targets and has >30 times sensitivity of the SPY-1D(V). Can now put a 256 element 60 GHz transmit array on a chip. All the RF circuitry for mm-wave radars is put on a chip. Such radars and phased arrays could cost just a few dollars in future. Major advances made toward low cost printed flexible electronic circuits with diodes operating at 1.6 GHz. A low profile dual polarized tightly coupled dipole antenna (TCDA) has been developed which provides a 20:1 bandwidth and has λ/40 thickness. The latest type of phased array is the MIMO radar phased array which was claimed to provide orders of magnitude better accuracy and resolution as well as better GMTI performance than conventional arrays. However, as summarized here, this author has shown that conventional arrays can do just as well and possibly better if properly used without suffering MIMO's signal processing load and waveform design problems.

1. Radars Upgrades and New Developments

This paper is an update to previous papers written by the author on the significant developments, trends and breakthroughs in radar and phased-arrays [1-8, 56, 65]. The big news relative to upgrades is the PATRIOT has a Gallium Nitride (GaN) active electronically scanned arrays (AESAs) which gives it a 360° coverage without mechanical rotation [57]. It uses a 9ft by 13ft main antenna that is bolted on and 2 quarter size rear antennas. It is a simple upgrade to apply to the 220 fielded systems. The back end of the PATRIOT had already been upgraded by 2012 with a $400 million investment. With these upgrades the PATRIOT is a 2015 state-of-the-art radar. The system is backwards compatible. Raytheon has spent over $200 million on the development of GaN. This upgrade reduces operation and maintenance cost by as much as 50%. The impressive performance of the Air and Missile Defense Radar (AMDR) has recently been released [68]. It has a 4-faced S-band radar for air and missile defense, a 3-faced X-band radar for horizon search; adaptive digital beam forming; handles 30 times more targets and has more than 30 times sensitivity of SPY-1D(V).; uses GaN which is 34% less costly than GaAs; GaN has 10^8 hour MTBF; antenna composed of 2x2x2 ft^3 radar module assembly (RMA) building blocks; 4 line replaceable units (LRU) per RMA; each LRU replaced in less than 6 minutes; fully programmable, 37 RMAs produce a system that is equivalent to the SPY-1D(V)+15dB, back-end radar controller built out of commercial off-the-shelf (COTS) x86 processors which allows adapting to future threats by easy upgrading with future COTS processors eliminating obsolescence; S-band antenna is scalable. Another development is the Zumwalt DDG-1000 stealth ship launched Oct. 28, 2013 with two more under development. It has the 3 faced X-band SPY-3 radar [1]. Lockheed Martin's space fence radar uses digital beam forming (DBF) at the element level for their dual polarized 86K element receive array using 172K A/Ds [71]. The JLENS (Joint Land Attack Cruise Missile Defence Elevated Netted Sensor) blimp (airship) system [1] had been deployed over Washington DC. It is nominally tethered at 10,000 ft to give it a look down capability. Has 360° coverage. It can detect a low flying cruise missile (CM) at a range of 340 nmi, cues PATRIOT and TPY-2, has demonstrated detection and tracking of ballistic missiles and intercept of CMs.

The trend by Raytheon and MIT Lincoln Laboratory to use commercial technology such as printed circuit boards (PCBs) and non-hermetically sealed packaging to achieve low cost AESAs for ground radars was reported on in [1]. Rockwell Collins is continuing this trend with the development of an X-band airborne radar using PCBs for the array and low cost SiGe chips [46]. South Korea is also developing a low cost X-band array [58]. DARPA has an aggressive revolutionary effort called Arrays at Commercial Timescales (ACT) program whose goal is to lower the procurement cost of new AESAs and ESAs by at least 80% [59]. The ACT program is focused on shorter design cycles and creating a commercial market approach for developing antenna arrays. This program aims to make AESAs and ESAs more affordable by offering common building block components. The common building block modules can be used for diverse AESA and ESA programs and applications – radar, signal intelligence (SIGINT), electronic warfare (EW) and communication. The building blocks would be easily upgradable so as to avoid obsolescence. They would allow flexibility in system parameters by being reconfigurable which also reduces obsolescence. The building blocks would be for the antenna, called reconfigurable electromagnetic interface blocks, and for the circuitry following the antenna building blocks, called the common module, which are digitally connected. The program is also looking at cohering AESAs and ESAs on different platforms. DARPA is investing $100 million for the ACT program with contracts having been given out to the leading AESA and ESA companies and research organizations: Raytheon, Northrop Grumman, Lockheed Martin, Boeing, Rockwell Collins, HRL Laboratories, and Georgia Tech Applied Research.

2. New Technology and Advances

2.1.Extreme MMIC and Moore's Law

Extreme MMIC has gone from 4 T/R modules with its control circuitry on a chip at X-band [1, 2] with each T/R costing about $10 to a whole 256 element arrays on a chip at 60 GHz, [9, 10]. These phased array chips will not require calibration or will use built in test circuits. What is driving this technology is the cell phone and WiFi business. From 2010 to 2020 the bandwidth demand is predicted to increase 1000 fold and the number of mobile connected devices from 5 to 50 billon [10]. These array chips are expected to find in the next decade wide uses: for garage door openers, videos players and computers [10]. They will all talk to each other via high BW Wi-Fi. In the future compact, ultra-low cost MIMO mm-wave multi-beam AESAs will be in everyday devices [10]. Car radars are also benefiting from extreme MMIC [11-13]. The 77 GHz car radar chip of [11] has all the RF circuitry needed: 2 transmitters, 4 receivers and LOs. Some feel in the future such car radar will cost only a few dollars. Ref.13 gives a commercial 24 GHz multi user single chip radar. Autoliv has a car radar on a 3.5in by 2.25in board which includes a radar chip and a Texas Instruments signal processing chip that does Kalman Filter tracking [14]. They have manufactured over 2 million of them with the cost of the board being less than $100 [14]. Valeo Raytheon has developed a 25 GHz blind spot 7 beam phased array radar costing only $100s of dollars from the car dealer in purchases of one [1,15,16]. So who said phased arrays are expensive! Over 2 million of these have also been produced [16]. The car radars market is large. Over 70 million cars were built in 2014. Assuming 4 radars per car we get a potential total of over 210 million. Google has developed a radar for a smartwatch.

Gordon Moore predicted the above application of MMIC to radar and phased arrays. The last sentence in his now famous Moore's Law paper [17] is: "The successful realization of such items as phased-array antennas, for example, using a multiplicity of integrated microwave power sources, could completely revolutionize radar." DARPA is funding the development of commercial FPGAs at microwave frequencies [1]. Commercial FPGAs now have clock speeds of 1 GHz.

Figure 1.

When I built my radio and oscilloscope for my high school laboratory class in the 1940's I used vacuum tubes. They were about 1x1x2 in^3. Now 130 billion transistors go on a 128 GB memory stick 0.5X0.8X2 in^3, smaller than one of my vacuum tubes. The memory stick fits in my pants back pocket. If you used the tubes I used in high school for this memory stick, when stacked sideways one on top of the other they would extend to a height 9 times the distance to the moon or equivalently about 90 times synchronous altitude and have a 1X2 in^2 footprint!!! This certainly would not fit in my back pocket. My 128 GB memory stick containing 130 billion transistors cost me only $35. Using tubes it would cost $130 billion at $1 per tube. The power needed to run these tubes would be 130 GW each tube needing about one watt. This is equivalent to 130 nuclear power plants. This comparison between what we get using transistors and what it would take using tubes is summarized in Fig. 1. This puts in perspective the amazing achievement made with integrated circuits for memory storage over the last 70 years. This same comparison applies to our smart phones that have 128 GB of memory. We talk about inflation. Because of inflation what used to cost $1 in the mid-forties now typically cost ten times as much or $10. But this is not true for electronics. With that dollar we can today buy ~4 billion transistors, the equivalence of 4 billion tubes!!! What inflation? When it comes to electronics we have here extreme deflation. The number of transistors produced worldwide in 2014 was 250 billion bil-billion ($2.5X10^{20}$). Using vacuum tubes stacked one on top of each other sideways this would extend to 40 million times the distance to sun!!! The above advance in integrated circuits is due to Moore's Law which states that the density of transistors will increase a factor of two every two years [18]. This has been going on for several decades. Some have said it is dead but indications are that it is slowed down and we still have a way to go. Specifically it is predicted that the density of transistors will increase by about a factor of 50 over the next 30 years with the power per transistor going down by about a factor of 75 [19]. Very impressive.

Helping with advance in extreme MMIC will be the revolutionary DARPA Compound Semiconductor Materials on Silicon (COSMOS) program [1, 20] and its follow on Diverse Accessible Heterogeneous Integration (DAHI) program [21]. The COSMOS program has demonstrated for the first time the integration of GaN and CMOS on the same

Si substrate without bonded wires [20, 21]. Helping with the advance of signal processing capability are the technologies of nanotechnology, spintronics [54], graphene and carbon nanotubes [1, 22], memristors [2], synaptic transistors [23], quantum computing and the possibility in the future of the transmission of data optically on the chip. The ability to transmit electrical and optical signals over the same wire has been demonstrated [24]. Ref. 25 indicates the alternate possibility of the use of IR beams in a Si chip (which is transparent to IR) for transmission of signals without ohmic loss and at the speed of light. Graphene and carbon nanotubes (CNT) have the potential for terahertz transistor clock speeds instead of a few gigaherz, nearly 3 orders of magnitude faster. The manufacture of graphene transistors on CMOS has been demonstrated. Could allow Moore's law to march forward using present day manufacturing techniques. Spintronics could revolutionize the computer architecture away from the 1945 John von Neumann model of separate logic and memory units. Instead could be one and the same for some parts with logic being low cost nonvolatle memory. Spintronics has the potential to replace hard drive with low cost, low power, more reliable memory having no moving parts and faster access time for the data. And then there is potential of doing computations the way the brain efficiently and amazingly does, going analog by perhaps using synaptic transistors and/or memristors.

We are very proud of our accomplishments in signal processing and memory. Remember though that our brain only weighs about 2-3 pounds and uses only ~20 W. It has been estimated that to do even what a mouse's brain does would require a computer the size of a small city and require several nuclear power plants to run it [55]. We have a long way to go yet. We are still in the horse and buggy days when it comes to computer capability. The future should bring us to a capability closer to what our brain can do. **As mentioned above technologies that potentially will help in this direction are memristors, quantum computing, graphene transistors operating at terahertz clock speeds and synaptic transistors that mimic our brain [1, 55].** It took man 70 years to go from a single tube to a memory stick with the equivalent of 130 billion tubes. It took nature 4 billion years of evolution to create our brain. Memristors can be made very small. They function like our brain synapses. They could possibly enable us to build analog electronic circuits that solve the astronomical number of coupled partial differential equations that our brain does. A mouse's brain could then fit in a shoebox and function according to the same physical principles as its brain [55]. Quantum computing has the potential of an orders of magnitude increase in computer power every generation instead of a factor of two that Moore's law provided [53, 64].

2.2 Metamaterials

Metamaterials are man-made materials consisting of an array of repeated structures having a size less than a wavelength. These materials have properties not found in nature, like a negative index of refraction. Kymeta is developing a low cost ESA metamaterial antenna for communications via satellites. They are commercializing a product that operates in the Ku band (10-15 GHz). Overall data rates for the antennas depends on a number of factors like the size and operating frequency of the antenna. The RF radiated power is on the order of a few watts. Transmission from the ground to the satellites and back has been demonstrated. Kymeta originally received about $65 million in funding, mostly from Intellectual Ventures, about $10 million of which is from Bill Gates. They have received more funding since then. For details on the Kymeta's collaborations see their website.

Explanations of how the antenna could do its scanning based on the published material is now given. The array is formed from several rows of travelling wave feeds which could be a leaky wave guide over which a metal cover is placed which has slots [26, 63]. Think of it as a slotted waveguides. The antenna consists of rows of these slotted waveguides which are end fed. Assume one wants to radiate in a specified direction. One then determines at which slots the signals have the desired phase shift to form a beam in that direction. Then only from those slots is the signal allowed to radiate. The signals from the other slots are blocked. A narrow band LC filter is placed over each slot to control whether signal is radiates from the slot or not. When the filter's center frequency is at the frequency of the signal coming out of the slot it lets the signal pass through to radiate. If it is shifted away from the signal frequency the signal from that slot is blocked and will not radiate. The filters use a liquid crystal whose dielectric constant is controlled by a bias voltage to shift the filter frequency, allowing the signal to radiate or not [26]. The rows of leaky waveguide are end fed. One way to scan the beam for an end fed slotted wave guide is to use frequency scanning [72, 73]. This is not a desirable approach for the communication application intended. An alternative way to scan in the row direction is to use a metamaterial surface for the traveling guide as done in [74]. Another way is to use a high dielectric constant material in the guide whose dielectric constant can be controlled by varying the voltage between the leaky waveguide cover and the leaky waveguide. This controls the speed of propagation down the feed. This allows the beam to be scanned in the row direction by changing the dielectric constant. This allows the slotted wave guide antenna to operate like an end fed slotted array with a serpentine feed to achieve large scan angles using small changes in frequency except here we would use changes in the dielectric constant [73]. To scan in the direction perpendicular to the rows different sets of slots are used from row-to-row-to achieve a phase gradient in the direction perpendicular to the rows. The spacing between the slots in each row is much less than the conventional ~ /2. This helps the scanning orthogonal to the rows. It is also possible to scan in the direction perpendicular to the rows by having the signals feeding each row have a different phase shift, but this does not appear to be their choice.

For this antenna each resonator is controlled independently as an on-off switch. It is a novel and clever concept wherein one achieves phase shifting without the use of active phase shifters at every element. It is a new type of electronically scanning array (ESA). The resonators were developed in the metamaterial world to create a negative permittivity metamaterial [62]. Because there are no active components the cost of building this antenna with many slots or elements should be low. For more details see [75]. Instead of a covered leaky waveguide other traveling waveguide structures can be used [63].

In addition to using orbiting satellites for internet access these antennas could be used for internet access over a limited area through the use a constellation of high flying (65,000 ft) drones [67]. A potential competing technology to the Kymeta approach is to use a conventional AESA built using low cost extreme MMIC like discussed above [10, 56].

Echodyne is developing metamaterial antennas and radars for facility protection and for UAVs for collision avoidance. [30]. The radar application requires faster switching times for the beam. Metawave, a spinoff from PARC a Xerox Co., is developing metamaterial electronically steered antennas for self-driving cars using and cell towers.

Target cloaking wherein the target is made invisible has been demonstrated using metamaterials. With cloaking the object to be made invisible is surrounded by the metamaterial with the result that the electromagnetic wave signal transmitted by a radar goes around the target making it invisible. This has been first demonstrated at microwaves by Duke Un. using metamaterials. Here the object to be made invisible was placed inside a 5 cm diameter cylinder surrounded by a 5 cm thick metamaterial composed of split ring resonators. The Duke cloaking was only achieved over a narrow bandwidth. Cloaking has also been demonstrated by the company Fractal Antenna Systems located in the Boston area using a thin fractal layer to cover the cylinder [31, 32]. They made an engineer effectively invisible by placing him in a cylinder covered with a fractal metamaterial. With the fractal approach the engineer at the company was placed first in the path between the transmitter and receiver with the result that the signal was blocked being reduced by 6 to 15 dB over the band from 750 to 1250 MHz. Next the engineer was placed inside a cylinder with the fractal metamaterial coating and placed again in the path between the transmitter and receiver with result that the signal was no longer blocked, only being attenuated by a fraction of a dB over the same 50% bandwidth at L-band.

One can stealth a target having its surface absorb the incident radar signal. This has been demonstrated by Iowa State Un. using a stretchable, flexible metamaterial sheet consisting of silicon with split ring resonators embedded in it that provided a 6 dB target cross section reduction from 8-10 GHz and larger reductions over narrower bandwidths. It should be possible to apply this material conformally over the object to be stealthed. Stealthing has also been simulated using a fractal coating that is < 1 mm thick [33]. Absorption of 90% (10dB) was achieved from 2 to 20 GHz and about 99% (20dB) from about 9-15 GHz. Good absorption was achieved for all incident angles and polarizations.

With metamaterials it is now possible to replace the tall highly visible Army jeep antennas with a flush mounted antenna [34]. Other capabilities of metamaterial like ability to achieve focusing beyond $\lambda/2$ diffraction limit, provide higher isolation and increased scan angle for arrays are covered in [1, 2, 75].

2.3 MIMO

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, thus is 10 times or 100 times or 1000 times better than a conventional array for N=10, 100, and 1000 [35, 36]. It has since been shown [37, 38] that a conventional array radar can do as well as a MIMO full/thin array radar. 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 [38, 70]. More recently another conventional array was presented which also has the same resolution and about the same angle accuracy as the MIMO full/thin array radar and has no grating lobes [39, 40, 70]. 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, thin/full and full/full MIMO array radars and their conventional equivalent array radars are elaborated on in [39, 40, 70] 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 was also pointed out that MIMO radar systems do not have any advantages relative to barrage jammer, hot clutter jammer or repeater jammer suppression [38-40]. Most recently it was 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 [40, 70]. Recently [76] it was shown by the author that a car MIMO thin/full array for which the full receive has NR=5 elements with $\lambda/2$ spacing and the thin transmit array has NT=2 elements with $5\lambda/2$ spacing has about the same angular resolution as a conventional array having the same number of elements of $N_C=N_T+N_R=7$, see Fig. 2. In addition the conventional antenna has lower peak sidelobes, 26 dB vs 13 dB down; see Fig.2. When the MIMO thin/full array has NR<5 elements the conventional

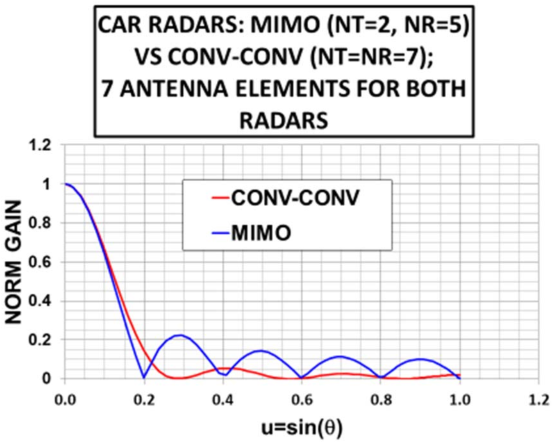

Figure 2. MIMO vs Conv-Conv Auto radars both having the same number of antenna elements of seven [76].

CAR RADAR: MIMO VS CONV-CONV

NR	NMV=2*NR	NCC=(NR+NT)√2 =(NR+2)√2	NMV/NCC= (RESOL CONV-CONV)/ (RESOL MIMO)
3	6	7.07	0.85
4	8	8.49	0.94
5	10	9.90	1.01
6	12	11.31	1.06
7	14	12.73	1.10
8	16	14.14	1.13
9	18	15.56	1.16
10	20	16.97	1.18

CONCLUSION: ANGULAR RESOLUTION OF MIMO NOT ALWAYS BETTER THAN CONV-CONV

NR= NUMBER OF MIMO THIN/FULL ARRAY RECEIVE ELEMENTS
NT=NUMBER OF MIMO THIN/FULL ARRAY XRMT ELEMENTS=2
NMV=NUMBER OF MIMO VIRTUAL ARRAY ELEMENTS=2NR
NCC=EFFECTIVE NUMBER OF CONV-CONV ARRAY ELEMENTS =(NR+NT)√2=(NR+2)√2

Table 1. MIMO vs Conv-Conv Radars having the same number of elements [76].

equivalent having the same number of elements gives better resolution and accuracy [76]; see Table 1. The √2 for the NCC of the conv-conv array in Table 1 is because it is a 2-way array. The conventional array here is called a conventional-conventional (conv-conv) array to distinguish it from the conventional equivalents given by this author where the conventional had the same performance as the MIMO array it using the same thin/full array for the conventional as used for the MIMO; see [37-39]. The conv- conv array here is using a full array having the same number of radiating elements as the MIMO array with all the elements used for both transmit and receive. The MIMO radar architecture here of a thin/full array with NT=2 is a very good one for the auto application because orthogonality is only needed for two elements. This is easily achieved by transmitting at the same time an up chirp from one of the elements and a down chirp from the other. Another option is to transmit alternately from one element and then the other (ping-pong) at half the PRF [77].

2.4 Digital Beam Forming (DBF)

Besides the DBF at every element S-band shipboard AESAs of Elta in Israel and CEA Technologies in Australia mentioned in [2], Thales now has an S-band ~1000 element one [41]. LM's space fence array having 172K channels and A/Ds was covered in Sect. 1.1. Raytheon is developing mixer-less direct RF A/D having >400 MHz instantaneous bandwidth that is reconfigurable being able to switch between S and X-band [42]. Instead of using down converters followed by a low frequency A/D it uses a sample and hold chip followed by a low frequency A/D. IMST has developed for the on the move SANTANA internet communication system AESAs using 29.75 GHz uplink and 19.95 GHz down links between satellites and airplanes, railroad trains and cars that utilize an A/D and D/A for every element channel [43]. Instead of PCBs they use LTCC stackups.

2.5 Additional Advances

It was shown recently that a low thickness wideband antenna can be built using tightly coupled dipole antennas (TCDA) [44, 45]. The high power microwave tubes used for active denial systems may soon be replaced by solid state power devices. The magnetrons in microwave ovens are being replaced by transistors. MIT Lincoln Laboratories increases receiver spurious free dynamic range as limited by intermods due to receiver and A/D nonlinearities by 40 dB, a 40 year advance because advance in A/Ds is 1 bit per 6 years and 1 bit gives us 6dB [47]. Printable electronics is making great strides and should make major advances soon because of the large market for wearable, flexible electronics. Several approaches are being investigated: 1. Use of metal-insulator-metal (MIM) diodes [48]. 2. 2D MoS_2 ink [49]. 3. Si and $NbSi_2$ particles which have produced diodes operating at 1.6 GHz with the goal being 2.4 GHz, the Wi-Fi band [50]. Research is going on with a quantum radar that uses microwave-optical entanglement and is claimed to provide better false alarm rate and SNR than a conventional radar [51]. It possibly could detect stealth targets and small tumors in the body.

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