Advanced Millimeter-wave Multifunction Systems and the Implications for Semiconductor Technology

H. Bruce Wallace
Strategic Technology Office
DARPA
Arlington, VA, USA
Bruce.wallace@darpa.mil

Abstract—As military combat platforms take on more challenging roles and missions, their need for advanced communications and sensors for both survivability and lethality has increased. Unfortunately, the size, weight, and power (SWAP) available to accommodate these new capabilities has not grown proportionately, nor is it likely to. Many of these new capabilities are required to operate in the radio frequency (RF) spectrum as the need to operate in degraded visual environments increases and in order to reduce antenna sizes and increase available bandwidth, the millimeter-wave (MMW) portion of the spectrum is being examined to address these needs. DARPA has recently started a program in multifunction RF systems to address these needed capabilities while also addressing SWAP through the use of common apertures and exciter/receiver technology. This presentation will discuss how this need for a millimeter wave (MMW) multifunction system may influence our investment strategy in MMW components and ICs to enhance functionality and reduce cost while maintaining performance.

Keywords—millimeter wave, silicon, phased array, multifunction

I. INTRODUCTION

Aircraft are crashing in conditions of degraded visibility due to the pilots inability to discern obstacles, cables, or each other during flight or while landing. Sensors to solve these problems are available but not carried on platforms due to issues with Size, Weight, and Power (SWAP). Beyond the issue of SWAP is these sensors are usually point solutions to specific problems and individually have their own processors, power supplies and antennas which vie for space on the aircraft. As an example, various helicopters in the US military are carrying target acquisition radars and terrain and weather avoidance radars while at the same time requiring new radars providing for landing in degraded visual environments (DVE), cable and obstacle avoidance, and collision avoidance with other aircraft. The need for a sensor to provide landings in DVE is non-trivial as it has been determined that significant numbers helicopter losses can be attributed controlled flight into terrain and objects in dust, clouds and fog[1]. The DARPA Sandblaster program[2] demonstrated a W-Band radar system which provided an improved capability for landing in these conditions but was not adopted by the military due to its weight (greater than 40 kg) and large physical footprint on the airframe. These characteristics have been judged to negatively impact the performance of the aircraft to the point that the military have not incorporated them into their platforms.

A new program[3] has been initiated at DARPA investigating techniques for combining multiple functions into common hardware as a means to provide currently required capabilities without negatively impacting the current SWAP available. To reduce the size of the apertures required to satisfy these functions, systems will be built in the millimeter wave (MMW) region of the electromagnetic spectrum. While extremely high frequencies are desired to reduce the size impact on platforms, the highest frequency will be limited by both the atmospheric propagation effects and the availability of component technology to produce a sensor with the desired performance characteristics. The following sections will address the tradeoffs of performance vs. atmospheric effects and lead to a discussion of component characteristics needed to meet the military requirements.

II. PHENOMENOLOGY DRIVING THE PROBLEM

The two primary concerns of sensor developers in the millimeter (MMW), sub-MMW and THz regions are atmospheric attenuation and scattering from atmospheric particulates, typically rain and fog. While it is generally assumed that there are well defined propagation windows in the atmosphere which limits operating frequencies to specific values, under adverse weather conditions the available frequencies regions are quite broad. Figure 1 is a plot of the one way attenuation from 30 to 300 GHz under several typical DVE conditions.

It can be readily discerned that under these degraded conditions, attenuation gradually increases with frequency. What in fact ultimately limits the frequency of operation are the frequencies that have been set aside by the frequency allocation community which assigned regions where radio location functions can be legally executed; the most popular in the MMW region being around 35 and 95 GHz which were historically based on the availability of magnetrons developed in the 1950’s.

A second element of phenomenology which must be considered for MMW sensors is the level of clutter in the region where sensing is to be accomplished. The two most significant contributions to radar clutter are backscatter from terrain and falling rain. Backscatter from other atmospheric particulates, such as fog, dust, or snow, tend to be significantly less. This is a double edged sword for a true multifunction
system as you may wish to reject this clutter when searching for obstacles or this scattering may actually be the desired target of interest; in one case being the terrain you wish to see or in another the heavy rain a helicopter may wish to avoid. This diversity of requirements therefore means that a multifunction sensor must be able to dynamically change the beam width or polarization as the various functions are exercised. By reducing the beam width, backscatter can be reduced. By modifying the polarization, it may either be enhanced or reduced. This can place significant demands on the component technology chosen for realizing the sensor.

III. MULTIFUNCTION SYSTEM CHARACTERISTICS

The DARPA Multifunction RF program (MFRF) grew out of the need to provide a capability to provide for safe landings, obstacle avoidance, and collision avoidance in a manner that will not adversely affect the SWAP of helicopter platforms. In order to achieve this capability; it is necessary for this system to incorporate functions that are currently executed by lower frequency radars operating at Ka and Ku-band.

The initial requirements for a DVE landing systems were for a 3 dimensional imaging resolution of approximately 0.3 meters at a range of 100m an update rate of 10 Hz or faster. Given that the available space for an antenna was approximately 0.3 meters, the operational frequency would have to be around 94 GHz (where the FCC permits licensed operation) assuming that monopulse processing could be used to enhance spatial resolution. Achieving update rates of 10 Hz set a requirement for electronic scanning rather than electro-mechanical. Since range resolution is also required for the sensor, frequency scanning cannot be applied to scanning in one of the lateral dimensions. To achieve the desired range resolution of 0.3 meters, an RF bandwidth of at least 500 MHz would be required which would set the maximum antenna size at 0.3 m to prevent excessive frequency scanning of the antenna beam when using phase shifters for scanning.

If we assume the aperture is circular, the number of radiating elements required to provide unambiguous imaging over large angles can be determined by assuming that the element spacing is one-half wavelength. For the 0.3 meter aperture, this would require greater than 28,000 elements. It is interesting to examine this number in light of the potential transmitter power that could be generated with this many elements. But the first question to be answered should be how much power is required to meet the requirements of the targeted system. Given that the operating range is short, the total power required for the DVE landing application is minimal. For the multifunction RF system being developed for the DARPA program, the most stressing application is in fact the weather radar application. Figure 2 is a plot of backscatter-to-noise ratio for a radar system with a 50 W, 10% duty factor waveform using the antenna size used in the previous example and an effective Noise Figure (NF) of 10 dB. For this plot the power level was assumed constant but the gain of the antenna scaled with frequency.

Figure 1 – Atmospheric attenuation at sea level pressures for six different conditions of temperature, humidity, and atmospheric particulates

Figure 2 – Backscatter to noise ratio vs. frequency for a 0.3 meter antenna, transmitting 50 W at 10% duty factor. The required line represents a 95% probability of detection with a 10^-6 probability of false alarm.

While the 50W transmitter power may seem significant at W-Band, it represents a per element power level of less than 2 mW. Another important point to realize is these calculations are based on using co-polarized linear polarization. If we wanted to reduce the contribution of the rain to the backscatter, perhaps so we could detect an air target, then we would prefer to receive the orthogonal polarization. This could potentially improve the signal-to-clutter ratio from the target by 20 dB[4]. If cable detection was the function we wished to accomplish, we would wish to use yet another polarization which would maximize the backscatter from the twisted cables which make up the most dangerous wires[5].

Having gone through this thought process, we have defined a phased array radar antenna operating at W-Band, with over 28,000 radiating elements, each capable of 2 mW on transmit and NF of 10 dB, and the ability to operate in any polarization basis. While it is common practice to select specific polarizations for building antennas for specific functions, it is also possible to calculate any polarization basis function using two orthogonal receiver channels and two alternating orthogonal transmit channels. The transformation from the operating polarization to the desired functional polarization is then just a 2x2 matrix multiply[6].

While the process of defining this array concept was straightforward, realizing an array with these characteristics may appear daunting to systems developers. The practical questions for doing this are:

1) How could we fabricate such an array?  
2) How much power would it consume and dissipate?  
3) How much would it cost?
The first question can be addressed by considering creating the array as a collection of sub-arrays. If we consider a tile approach so that each tile consists of an integrated circuit with a 4x4 radiators, then we can integrate the tiles onto a substrate which furnishes power combining transmission lines, heat sinking, and serves as a sub-array with additional circuitry for up and down conversion, RF drive poser for the tiles, digital control circuits, and even power conditioning. This sub-array may now represent a fully integrated phased array in its own right. If made up of 8x16 of the tiles, we would now have an electronically scanned array generating 5W of power. This sub-array concept has two additional advantages. First it could be used for applications which require less antenna gain, such as a perimeter collision avoidance sensor. Secondly, by assembling the large array as a collection of these smaller sub-arrays, they could be controlled to form either a single large array or could be individually controlled to simultaneously provide different functions. An example of this could be using one sub-array as a transmitter and another as a receiver to achieve 100% duty factor in communications. Two pairs of sub-arrays could maintain two communication links in different directions.

The second and third questions now become dependent upon the type of technology applied to the problem. The type of array described requires complex RF circuitry per element beginning with two receive channels, a switched transmitter channel, phase shifter and attenuators on each channel for beam steering, and receiver protection during transmit. This circuitry would also require digital elements to not only control the RF functions but also enable a means to control the arrays to optimize antenna performance.

At W-Band, adequate RF performance has been obtained using SiGe technology[6] but not at the level of complexity called for here. Likewise, at lower frequencies, levels of complexity approaching this have been obtained[7]. Historically III-V semiconductor ICs have been developed as a means of obtaining high performance MMW systems through higher power and lower noise figure. But for multifunction MMW systems, complexity of circuitry will become the over riding concern. This must also be coupled with the cost of the circuits. Silicon technology with unity gains approaching 500 GHz[8] are becoming available now which are suitable for operating frequencies over 100 GHz while III-V devices have exceeded unity gain frequencies of 1 THz[9] but have not obtained the circuit density of silicon. Additionally, due to prevalence of silicon foundries, costs for silicon circuits that can operate up to frequencies of 100 GHz approach $10 per cm^2 while GaAs and InP are a minimum of $200 per cm^2. This cost difference may become the overriding consideration as to whether this class of multifunctional RF system can ever be practically produced and integrated into military systems.

A suitable compromise in performance vs. cost may be eventually realized through exploitation of the work funded under the COSMOS program[10] which is striving to develop a viable high-yield process for the transistor-scale heterogeneous integration of compound semiconductor devices with standard Si CMOS. Whichever technology becomes the most practical will have to address the issue that performance of the circuitry can no longer be based on the maximum power capability of minimum NF attainable but will be based on the complexity of the circuitry available for achieving the functionality and on the total power consumed by the circuitry to perform the multiple functions.

IV. SUMMARY

DARPA has initiated a program to consolidate multiple functions into a common sensor system which will address both these needs for flight in degraded visual environments but will also provide new capabilities to perform combat missions. This sensor program will depend heavily on the ability of integrating significant circuit functions into array tiles where the inter-element spacing provides for broad electronic scanning at frequencies up to 100 GHz. This program will address the needs of MMW phased arrays by constructing functional building blocks so that different sized arrays with different capabilities can be assembled from common modules. Given the current maturity of RF ICs and the performance required to execute these multiple functions, silicon technology may be the only affordable technology available for demonstrating this multifunction capability.

V. REFERENCES

[1] “Study on Rotorcraft Survivability”, Office of the Under Secretary of Defense, September 2009
[2] Carlucci, F, “Making Sense of Sandblaster,” Vertiflite, Summer, 2009
[3] DARPA BAA 11-50, www.fbo.gov
[4] V.W. Richard, J.E. Kammerer, and H.B. Wallace, "Rain Backscatter Measurements at Millimeter Wavelengths," Trans. on Geosci. Remote Sensing, Vol 26, No. 3, May 1988.Sarabandi cable
[5] K. Sarabandi, F. T. Ulaby, and M. A. Tassoudji. “Calibration of polarimetric radar systems with good polarization isolation”. IEEE Transactions on Geoscience and Remote Sensing (GRS), 28(1):70-75, January 1990
[6] L. Gilbreath, V. Jain, H. Yao, L. Zheng, P. Heydari., “A 94-GHz passive imaging receiver using a balanced LNA with embedded Dicke switch,” in IEEE RFCIC Symp., May 2010
[7] S.K. Reynolds, et al., “A Silicon 60-GHz Receiver and Transmitter Chipset for Broadband Communications,” IEEE Journal of Solid-State Circuits, Vol. 41 No. 12, Dec. 2006
[8] E. Öjefors and U. R. Pfeiffer, “A 650 GHz SiGe Receiver Front-End for Terahertz Imaging Arrays,” IEEE International Solid-State Circuits Conference, Feb. 2010, San-Francisco, CA
[9] J. Albrecht, M. Rosker, H. Wallace, T. Change, “THz electronics projects at DARPA: Transistors, TMICs, and amplifiers,” Microwave Symposium Digest (MTT), 2010 IEEE MTT-S International, 23-28 May 2010
[10] S. Raman, T. Chang, C. Dohrmann, M. Rosker, “The DARPA COSMOS program: The convergence of InP and Silicon CMOS technologies for high-performance mixed-signal,” 2010 International Conference on Indium Phospide & Related Materials (IPRM), May 31 2010-June 4 2010