Transmit/Receive (T/R) Modules Architectures for Dual-polarized Weather Phased Array Radars

Jorge L. Salazar[1], *IEEE senior member,* Rafel H. Medina[2] and Eric Loew[3]

(1) Advanced Radar Research Center (ARRC), University of Oklahoma, Norman, Oklahoma

(2) Computer and Electrical Department, University of Puerto Rico, Mayaguez (UPRM), Mayaguez, Puerto Rico

(3) Earth Observing Laboratory (EOL), National Center for Atmospheric Research (NCAR), Boulder Colorado

***Abstract*— A discussion of dual-polarized T/R module architectures and technologies for active phased array radar (PAR) for remote sensing application is presented in this paper. Three types of T/R modules developed for weather phased array radar show the evolution and trend of T/R module technology for civil applications. Factors influencing system performance are discussed in terms of the allowable technology and tradeoffs that includes cost. Performance is considered for deployable dual-polarized PAR radar systems. T/R module and antenna aperture Line Replacement Units (LRU) have been evaluated. Performance and cost are derived from affordability constraints imposed by the radar application.**

Keywords—dual-polarized; T/R modules; active phased array; -e-scanning array; weather phased array antenna.

I. INTRODUCTION

Low-profile, low-weight and low-mass antennas are required for many applications;, specially for space and airborne radar systems [1]. Two-dimensional (2-D) electronically scanning (e-scanning) arrays are the most attractive solution for many applications. Removing mechanical parts and distributing a single source power in thousand of elements makes a system more robust, reliable, and cost effective [2], [3]. Linear and dual-polarized capability enables hydrometeor classification and attenuation correction due to the atmospheric and precipitation attenuation in the radar path [4], [5], [7]. The biggest limitation of using 2-D e-scanning array antennas for civil applications is cost [5]-[7]. For an acceptable spatial resolution, a radar system requires antenna that provides less than 2^ox2^o beamwidth. Assuming a spacing of a half wavelength between elements, the aperture size requires around 4,000 elements. In the past the cost of a single transmit and receive module (T/R) could vary from $350 to $600 per module [2], [3], [6]. Based on this, the cost incurred by the T/R modules can be around $1.6M to $1.8M. Today the fast evolution of the RF industry enables the use of commercial components for the development of new phased array radar for civilian applications. Substantial progress in GaN, SiGe and CMOS technology enables a significant reduction in cost and size of the integrate circuit (IC) [6], [9]-[11].

Weather radars use the advantages of dual-polarization to improve accuracy of precipitation estimation and also to enable hydrometeor classification [4]-[6]. Dual-polarized radars for weather applications commonly use three polarization modes [6], [7]: simultaneous transmit and simultaneous receive in reception (STSR), alternate polarization in transmit and simultaneous in reception (ATSR), and alternate polarization in transmit and receive (ATAR). To make use of these polarimetric features a minimum integrated cross-polarization below -20 dB and -40 dB is required for simultaneous transmit modes. In addition, a mismatch between co-polar beam antenna patterns (between H and V) below 7% is required [4]-[7]. This requirement is difficult to achieve without a high performance antenna array and the T/R modules.

II. COST AND TECHNOLOGY CONSIDERATIONS

A representation of the most T/R modules architectures for dual-polarized radars is illustrated in Figure 1. In the case of STSR, four independent channels, two for transmission, two for reception and one T/R switch to commute the transmission and reception signals, are required. In the case of ATSR, one channel is shared for transmitting H and V signals and two independent channels are used for reception. Similar to the previous mode, ATAR a T/R switch is required to commute with the transmit and receive signals but the uses a single channel for Tx and Rx. T/R modules are sized to fit within the lattice of a phase array, which is a function of frequency. Typically the spacing between modules is chosen to be around 0.5λo for wide-antenna scanning beam performance (± 45^o). At X-band (10 GHz), C-band (5.4 GHz), and S-band (3 GHz), the spacing between modules is 1.5 cm, 2.5 cm and 5 cm, respectively. For S-band, the lattice array size can contain modules using COTS components based on the architectures illustrated in Figure 2. For higher frequencies, such as C- and X-band, the limited space requires high integration at the IC level or adopting a brick module architecture.

Brick modules are a very common architecture in military radars. They are placed vertically to the antenna aperture, not having any constraint with the antenna unit size. In phased array radars, the cost of T/R modules is between 50% and 60% of the overall cost of the antenna array panel. The T/R modules cost can vary as a function of frequency, polarization mode, technology, functionality, and production volume. Short wavelength radars (C- and X-bands for example) require a more compact design which demands high component integration and low power consumption modules with acceptable RF performance level. The cost of X-Band T/R modules based on COTS components is

978-1-4799-8275-2/15/$31.00 ©2015 IEEE

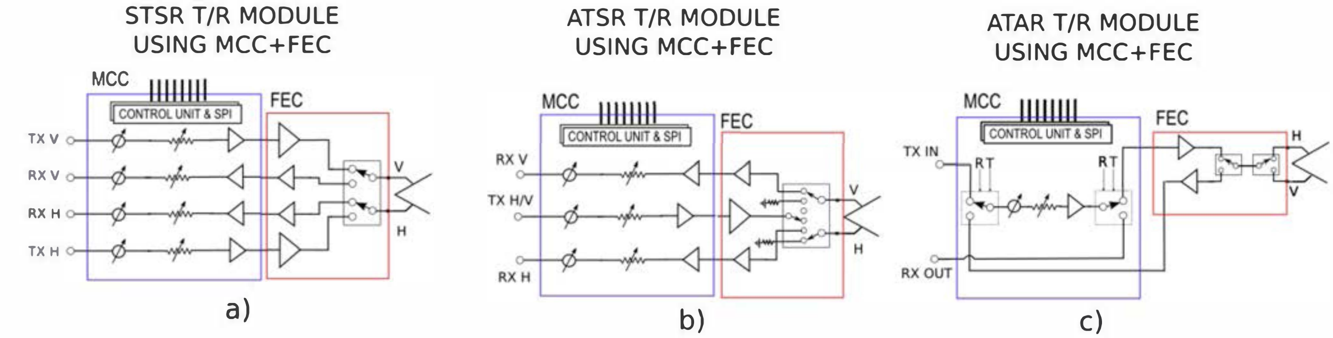

Figure 1. Dual-polarized T/R receive modules for weather phased array radars.

$567 for 100 units, which can be reduced to $341 if large quantities (>1000 units) are produced [11]. Similarly the cost of a C-band ATSR T/R module based on COTS components is $399, which can be reduced to $188 for a production volume of 10,000 units [6],[8].

The fast evolution of technology, especially in CMOS, SiGe, and GaN has enabled the integration of most of the components of T/R modules (Figure 2) into one or two small chip commonly called core chips (CCs) or multicore chips (MCCs) and front-end chips (FECs). Small chips (<10 mm^2) enable the possibility of integrating the electronics in the back of the antenna and reduce the cost of the phased array antenna system. Currently, ATAR multi-core chip modules in X-band can be found on the market for $70-$100 per unit for a production volume of 10,000 units. Adding the cost for the high power amplifier, LNA, and switches, the overall cost per T/R module can be between $100 to $180 per unit. Figure 2a-b illustrates the brick modules developed in CASA for one-dimensional scanning active array and for NCAR Airborne Phased Array Radar (APAR) based on COTS components [8],[6]. Brick modules in general provide excellent RF performance, considering the large area available for distributing the component for high RF and thermal isolation. A drawback of brick modules involves the size, weight, cost, mechanical design complexity, and intensive labor required for integration and testing. Figure 2c shows the high integration modules in a single chip in a tile configuration. Brick modules typically make use of connector and cables with the antenna and other subsystems.

III. T/R MODULE DVELOPMENTS

A. X-band brick T/R module

The NSF CASA Engineering Research Center at the University of Massachusetts developed an X-band 1-D e-scanning phased array antenna composed of 72 x 32 elements where the 64 elements in azimuth plane were excited by ATAR T/R modules [8]. The Tx block consists of a high-power amplifier (PA) and medium-power amplifier (MPA), where as the Rx block consists of a low-noise amplifier (LNA) and gain block (GB1). The transmit channel is designed to have a net gain of about 30 dB at room temperature and provide a maximum peak output power of 1.25W when the module is operating in compression. The duty cycle is limited to 30% to protect the power amplifier from excessive heat. The receive channel is designed to have a net gain of approximately 29 dB and a noise figure of 4.3 dB. Both channels use a 6-bit 32 dB digital attenuator with attenuation steps of 0.5 dB and a 6-bit digital phase shifter that provides 360° phase coverage with a phase shift step of 5.625°. Figure 4 shows a picture of the front end and back end of the CASA X-band dual-polarized phased array antenna using the ATAR T/R modules.

Antenna measured patterns for scanning positions 0^{o}, 15^{o}, 30^{o}, and 45^{o} were used in reception mode, and for both polarizations were calibrated for an amplitude taper distribution that corresponds to Taylor -25 dB for n=4. Figure 4 shows the measured (co-polar and cross-polar) patterns normalized to broadside beam for H and V polarizations. The first sidelobe levels for both polarizations are below -25 dB, except at 15^{o} and 30^{o} in V polarization, where the first sidelobe levels are 1.8 dB higher (-23.2 dB). The sidelobe roll-off for H and V decrease from the main beam, indicating small errors in the excitation of the array elements. The cross-polarization levels corresponding to each beam position are below -30 dB for H polarization and below -27 dB for V polarization.

B. C-band brick T/R module

The Earth Observing Laboratory (EOL) of the National Center for Atmospheric Research (NCAR) is conducting a two-year project to develop a small prototype array that will be used as proof of concept for the future airborne phased array radar (APAR). This project consists of developing one line replacement unit (LRU) of the 224 LRUs required for the full four-aperture APAR system [6]. The LRU architecture was originally conceived to be in a tile configuration in order to meet the low-profile requirement of APAR. The proposed T/R module architecture will operate in ATAR polarization mode. A block diagram for the proposed Brick T/R module is shown in Figure 4. The module contains eight transmit/receive (T/R) modules providing eight pairs of bidirectional ports that can be connected to individual dual polarized antennas.

978-1-4799-8275-2/15/$31.00 ©2015 IEEE

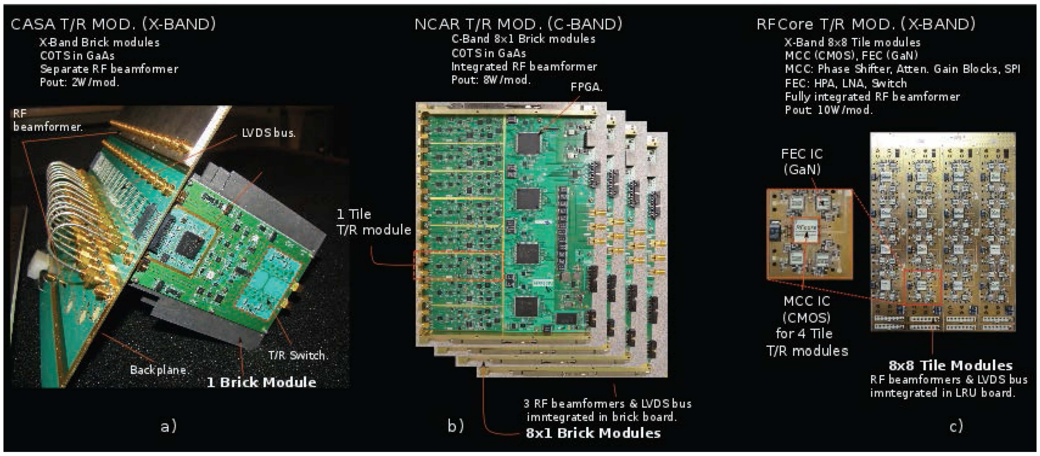

Figure 2. T/R modules for weather phased array radars. a) CASA low power ATAR brick module based on COTS components. b) NCAR Airborne Phased Array Radar ATAR 8x1 brick module based on COTS components. c) RFcore 8x8 X-band CMOS and GaN tile module.

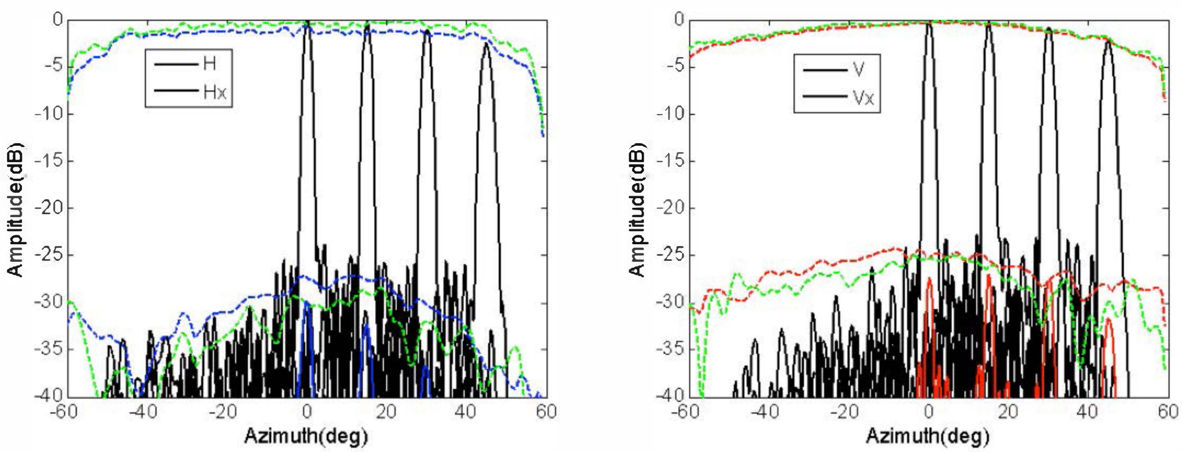

Figure 3. Measured scanned antenna patterns in azimuth plane overlapped with embedded element pattern of column 32 and also with average element pattern for H and V polarization. About 64 ATAR calibrated T/R modules were used.

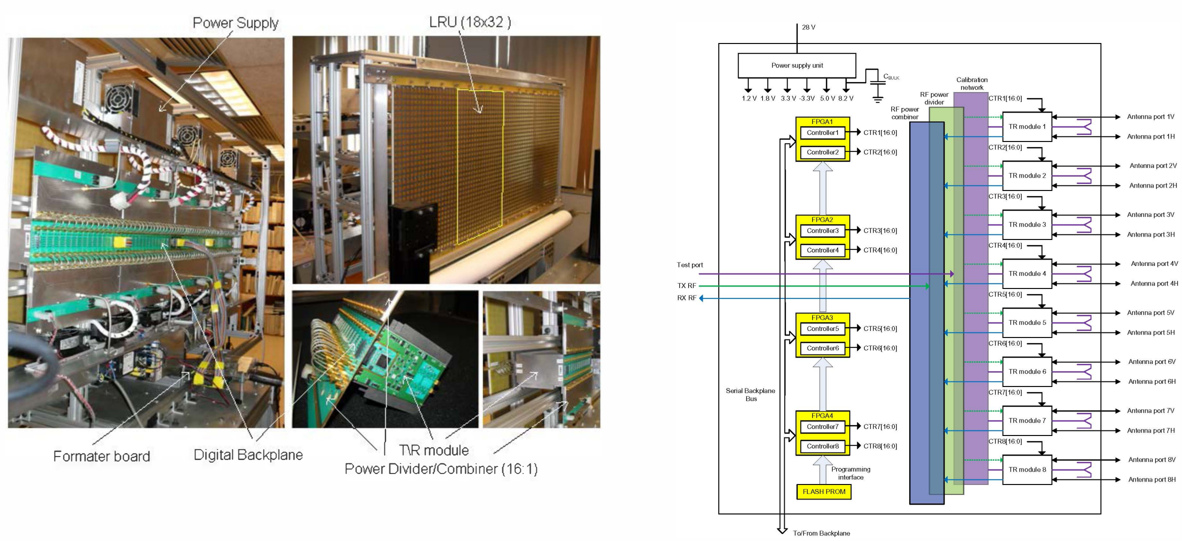

Figure 4. a) Picture of the front end and back end of the CASA X-band dual-polarized phased array antenna. b) Block diagram of the C-band dual-polarized APAR NCAR brick module.

978-1-4799-8275-2/15/$31.00 ©2015 IEEE

Two independent RF distribution networks (an 8-way power divider and an 8-way power combiner) that split and combine the RF signals to and from the T/R modules, respectively, allowing the implementation of analog beamforming in the phased array. In addition to the main functions, the module includes a built-in test system that allows measuring the individual characteristics of each T/R module. The system can be used for two purposes: for monitoring the T/R module health and for calibration of the T/R modules. Transmit and receive transfer functions of individual T/R modules are obtained by injecting calibration signals with a calibration distribution network and couplers at the T/R module antenna ports. Both channels share a common control circuitry for the RF signal, allowing the design to reduce the number of control components with respect to other architectures. To minimize the cross-polarization degradation of the dual-polarized antenna designed by NCAR, the polarization switch must have high isolation between the diversity ports. It is known that the cross-polarization of isolated antennas can be affected when their terminals are connected to a single pole double throw switch (SPDT). In particular, the switched antenna obtained from the connection of a dual-polarized antenna having 25 dB isolated cross-polarization and a SPDT switch having 45 dB of isolation will have a cross-polarization level of 24 dB, which is equivalent to 1 dB of cross-polarization degradation.

C. *X-band tile T/R module*

T/R modules are key components in the radar system that represents a significant portion of the overall cost. Therefore, cost and size reduction of a T/R module is one of the main issues for the next-generation phased array system. Currently, core chips based on GaAs pHEMT are commercially available in the market. GaAs provides excellent RF performance; RMS phased errors, and gain and transmit powers are better than other developments in SiGe [11] and CMOS [10]. For ATAR, GaAs core chips are two times bigger than SiGe 0.25 um and almost seven times bigger than CMOS 0.13 um. Power consumption in GaAs is about 3 times higher that SiGe 0.25 um and CMOS 0.13 um. It seems that the fast progress in silicon core chips become promising with lower cost, acceptable RF performance, and higher integration levels. Another advantage of silicon-based core chips is the fact that digital and analog components can be easily integrated in a single core chip. In terms of cost, a GaAs core chip price is around $120 to $140 for a QFN single-channel chip core for a volume of 10,000. However SiGe and CMOS can offer an attractive cost not higher than $45 apiece for the same volume. Figure 2 c) presents a T/R module designed for a tile 8x8 LRU in X-band using CMOS 0.13um for the MCC and GaN for the front-end-chip (FEC).

IV. CONCLUSIONS

Current technology enables the development of active phased array radars for civil application. The cost and module performance levels that have been achieved demonstrate the possibility of developing active phased array antennas for dual-polarized radar systems for atmospheric applications. Phased array antennas can make a significant contribution to remote sensing research. Extremely fast scanning updates and dual-polarization capabilities can significantly impact the study of atmospheric events. During the past five years the use of T/R modules for active phased array antennas for civil application shows the cost and complexity of modules for different polarization modes can be feasible.

REFERENCES

[1] Jothiram Vivekanandan, Wen Chau Lee, Eric Loew, Jorge L. Salazar and Vanda Grubišić., "Design trade-offs for airborne phased array radar for atmospheric research." 2013 Manuscript accepted in Geosci. Instrum. Method. Data Syst. Journal, 2013.

[2] D. McLaughlin, D. P. et al., "Short-wavelength technology and the potential for distributed networks of small radar systems," Bulletin American Meteorological Society, vol. 90, pp. 1797-1817, Dec. 2009.

[3] M. E. Weber, J. Y. N. Cho, J. S. Herd, and J. M. Flavin, The next-generation multimission U.S. surveillance radar network," Bulletin American Meteorological Society, vol. 88, pp. 1739-1751, Nov. 2007.

[4] V. N. Bringi and V. Chandrasekar, 2001: Polarimetric Doppler Weather Radar: Principle and applications, Cambridge University Press, 2001.

[5] R. J. Doviak, V. Bringi, A. Ryzhkov, A. Zahrai, and D. Zrnic, "Considerations for polarimetric upgrades to operational WSR-88D radars," J. Atmos. Ocean. Tech., vol. 17, no. 3, pp. 257–278, Mar. 2000.

[6] Jorge L. Salazar, Eric Loew, Pei-Sang Tsai, Jothiram Vivekanandan, Wen Chau Lee, and V. Chandrasekar. "Design trade-offs for airborne phased array radar for atmospheric research." 2013 IEEE International Symposium on Phased Array System & technology. Boston, US. August 2006.

[7] D. S. Zrnic, J. F. Kimpel, D. E. Forsyth, A. Shapiro, G. Crain, R. Ferek, J. Heimmer, W. Benner, T. J. McNellis, and R. J. Vogt, "Agile-beam phased array radar for weather observations," Bull. Amer. Meteor. Soc., vol. 88, no. 11, pp. 1753–1766, Nov. 2007.

[8] R. Medina, E. Knapp, J. Salazar, and D. J. McLaughlin. "T/R module for CASA phase-tilt radar antenna array." 42nd European Microwave Conference (EuMic), Oct. 29 - Nov. 1, 2012, Amsterdam, Netherlands.

[9] Dong-Woo Kang, Jeong-Geun Kim, Byung-Wook Min, and G. Rebeiz, "Single and Four-Element Ka-Band Transmit/Receive Phased-Array Silicon RFICs With 5-bit Amplitude and Phase Control," IEEE Trans. Microwave Theory and Techniques, Vol. 57, No. 12, pp. 3534–3543, Dec. 2009.

[10] Sanghoon Sim, Laurence Jeon, and, Jeong-Geun Kim, "A Compact X-Band Bi-Directional Phased-Array T/R Chipset in 0.13 um CMOS Technology," IEEE Trans. Microwave Theory and Techniques, Vol. 61, No. 1, pp. 562–569, Jan. 2013.

[11] N. Carosi, A. Bettidi, A. Nanni, L. Marescialli, and A.C. Entronio, "A mixed-signal X-band SiGe multi-function control MMIC for phased array radar applications," in Proc. 39th Eur.Microw. Conf., Oct. 2009, pp. 240–243.

978-1-4799-8275-2/15/$31.00 ©2015 IEEE