RANDOM PHASED ANTENNA ARRAYS – THE NEW CHALLENGE FOR THE FUTURE MICROWAVE RETRO DIRECTIVE SYSTEMS

Veselin Demirev

Radiocommunication and Video Technology Department, TU-Sofia
Kl. Ohridski blv. № 8, 1756-Sofia
Tel. 359-887-526-936, e-mail: demirev_v@tu-sofia.bg

Abstract

Retro directive arrays are of growing interest due to their unique functionality and relative simplicity in comparison to phased array and smart antennas approaches. They have the characteristic of reflecting an incident wave toward the source direction without any prior information on the source location. The analog self-phasing function in these arrays makes them good candidates for possible wireless communication scenarios where high link gain and high-speed target tracking is desired. The main disadvantage of the retro directive arrays, used in microwave systems, is the need of high number antenna array elements, followed by complicated for the same reason distribution and signal processing networks.

In this report new and very promising applications of Random Phased Antenna Arrays (RPAA) in Microwave Retro Directive Systems (MRDS,s) are proposed by the author. By means of mathematical model of the proposed systems, based on matrix and vector algebra, it is shown that the combination of RPAA and a phase – conjugate circuits will work as simple and cheap MRDS. RPAA, based on Radial Line Antenna with random distributed and oriented slot radiators, are part of the proposed systems too.

The proposed MRDS,s have shown much potential for use in many applications. The autonomous beam steering feature of the RPAA MRDS,s make them attractive for automatic pointing and tracking systems, microwave tracking beacons, radar transponders, Radio Frequency Identification (RFID), solar power satellites, microwave power transmission, cross links for small satellite networks, as well as for complex communication systems.

1. INTRODUCTION

The retro directive arrays are of growing interest due to their unique functionality and relative simplicity in comparison to phased array and smart antennas approaches [1, 2, 3]. They have the characteristic of reflecting an incident wave toward the source direction without any prior information on the source location. The analog self-phasing function in these arrays makes them good candidates for possible wireless communication scenarios where high link gain and high-speed target tracking is desired. Conventional phased-array antennas are able to steer their beams by exciting elements with phase shifters. In contrast, retro directive arrays steer their beams automatically without any computationally intensive algorithms or hardware based phase shifters in response to an interrogating signal.

Retro directive arrays have shown much potential for use in many applications. The autonomous beam steering feature of the retro directive systems makes them attractive for automatic pointing and tracking systems, microwave-tracking beacons, radar transponders, Radio Frequency IDentification (RFID), solar power satellites, microwave power transmission, cross links for small satellite networks, as well as for complex communication systems.

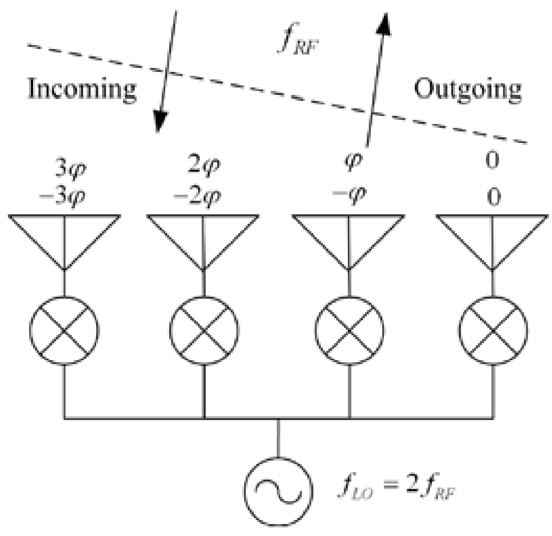

Fig. 1. Block scheme of a linear retro directive array system using HPCC

The main disadvantage of the linear retro directive arrays, used in microwave systems (fig.1), is the fact, that they have retro-directive properties only in one plane. The practical implementation of these systems needs these properties to be realized in 2D-coordinates system, which means that plane (rectangular or circular shaped arrays) should be used. Another disadvantage in the microwave frequency bands is the need of high number (in order of several thousands) identical Heterodyne Phase – Conjugate Circuits (HPCC), equal to the numbers of the used antenna array elements, as well as the complicated power distribution system for the heterodyne signals.

A Circular Random Phased Antenna Array (CRPAA) for Microwave Retro Directive Systems (MRDS) is proposed in this report. Using mathematical model of the proposed system, based on matrix and vector algebra, it is shown that the combination of a CRPAA and only one HFCC, supplied by heterodyne signal at double frequency, will work as simple and cheap 2D MRDS.

2. CRPAA-MRDS THEORY

2.1. Introduction in CRPAA

The CRPAA is an entirely new approach in the field of microwave antenna theory, used and patented by the author one decade before. The goal was solving of the problems of the tracking microwave antenna systems for mobile satellite communications. The CRPAA were used in receive mode (SCP technology) [4, 5] and in transmit mode (RPSC technology) [6] in order to phase spread in random manner the microwave signals and to communicate with noise like signals. The random phase spreading is followed by correlation signal processing to obtain high antenna gain and spatial directive properties. In this report only the random phased antenna array of the SCP-RPSC technology is used, followed by heterodyne signal processing. The goals here are also quite different – to obtain retro directive properties with high gain.

2.2. Basic matrix expression of the signals in a CRPAA retro directive system using heterodyne phase conjugating circuit

The CRPAA-MRDS system can be represented by a block diagram, shown in fig. 2. It involves interrogators ($I_1, I_2, I_3 ... I_m ... I_M$), random distributed in the space with angular positions, given with their angular coordinates in a coordinate system, centred in the centre of the transponder antenna and shown in fig. 3. To analyze such a system, the most suitable mathematical tools available involve matrix and vector algebra.

The corresponding interrogator signals $c_{1,2..m..M}$ are at frequency f_{RF} .They will travel through space to reach the CRPAA, where they will be picked up by every antenna array element and collected by the antenna array power divider to the input of the HFCC mixer. Here, the collected signals will mix with a heterodyne signal with frequency $f_{LO} = 2f_{RF}$. The interrogating signal sources are located correspondingly at azimuth angles ϕ_c , zenith angles θ_c and distances R_c .

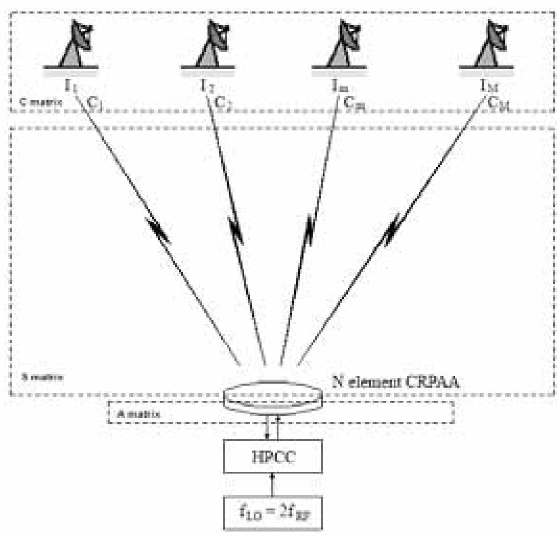

Fig. 2. Block scheme of a CRPAA-MRDS

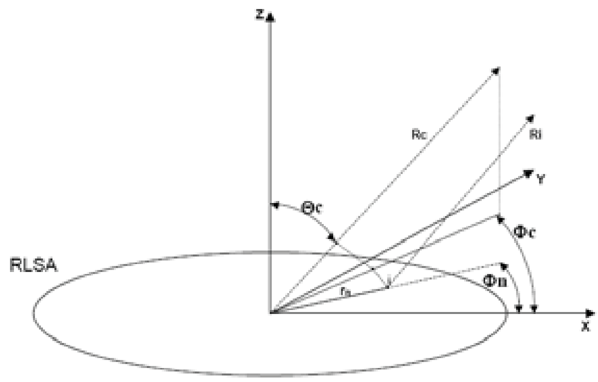

Fig. 3. Coordinate system of a CRPAA-MRDS

Each element of the N-elements CRPAA will pick up signals from all the interrogating signal sources and deliver them to its output. Thus the CRPAA output will carry signals from all the signal sources. Let s_{nm} be the transfer function between m-th interrogating signal source and the n-th element of the CRPAA. Then:

$$s_{nm} = L_{snm} \cdot e^{j\psi_{nm}} \quad (1)$$

Where L_{snm} are the free space propagation losses, $\psi_{nm} = k r_n \sin\theta_m \cos(\phi_m - \phi_n)$ is the phase of the signal received by n-th element of CRPAA relative to its centre, $k = 2\pi/\lambda$ - free space phase constant, r_n, ϕ_n - the coordinates of the n-th element of CRPAA, ϕ_m, θ_m - the angular coordinates of m-th interrogator.

Let $\mathbf{s_m}$ represents the transfer functions between m-th signal source and all elements of the CRPAA, then:

$$\mathbf{s_m} = \begin{vmatrix} s_{1m} \\ s_{2m} \\ \cdots\cdots \\ s_{nm} \\ \cdots\cdots \\ s_{Nm} \end{vmatrix} \quad (2)$$

Where $\mathbf{s_m}$ is called a column matrix or vector. The transfers functions among all interrogators and CRPAA elements could be represented by means of matrix $\mathbf{S}$, given by:

$$\mathbf{S} = \begin{vmatrix} \mathbf{s_1} & \mathbf{s_2} & \cdots & \mathbf{s_m} & \cdots & \mathbf{s_M} \end{vmatrix} =$$

$$= \begin{vmatrix} s_{11} & s_{12} & \cdots & s_{1m} & \cdots & s_{1M} \\ s_{21} & s_{22} & \cdots & s_{2m} & \cdots & s_{2M} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ s_{n1} & s_{n2} & \cdots & s_{nm} & \cdots & s_{nM} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ s_{N1} & s_{N2} & \cdots & s_{Nm} & \cdots & s_{NM} \end{vmatrix} \quad (3)$$

If $c_1, c_2, \ldots\ldots, c_m \ldots\ldots c_M$ are the signals transmitted by the interrogating sources $1, 2, \ldots, m, \ldots, M$ respectively, then the signals at the n-th CRPAA element due to the signals from the m-th interrogating signal source will be given by:

$$x_{nm} = s_{nm} . c_m \quad (4)$$

Therefore the signal vector, combining the signals from all interrogating signal sources, at the n-th element of the CRPAA is:

$$\mathbf{x_n} = \begin{vmatrix} x_{n1} & x_{n2} & \cdots & x_{nm} & \cdots & x_{nM} \end{vmatrix} =$$

$$= \begin{vmatrix} s_{n1}c_1 & s_{n2}c_2 & \cdots & s_{nm}c_m & \cdots & s_{nM}c_M \end{vmatrix} \quad (5)$$

Considering the interrogating signals, the signal vector at all elements of CRPAA due to interrogating signal sources can be represented by:

$$\begin{vmatrix} \mathbf{x_1} \\ \mathbf{x_2} \\ \cdots\cdots \\ \mathbf{x_n} \\ \cdots\cdots \\ \mathbf{x_N} \end{vmatrix} = \begin{vmatrix} s_{11} & s_{12} & s_{13} \cdots s_{1m} \cdots s_{1M} \\ s_{21} & s_{22} & s_{23} \cdots s_{2m} \cdots s_{2M} \\ \cdots & \cdots & \cdots \\ s_{n1} & s_{n2} & s_{n3} \cdots s_{nm} \cdots s_{nM} \\ \cdots & \cdots & \cdots \\ s_{N1} & s_{N2} \cdots & s_{Nm} \cdots s_{NM} \end{vmatrix} X \begin{vmatrix} c_1 \\ c_2 \\ c_3 \\ \cdots \\ c_m \\ \cdots \\ c_M \end{vmatrix} \quad \text{or}$$

$$\mathbf{x} = \mathbf{S.c}, \text{ where } \mathbf{x} = \begin{vmatrix} \mathbf{x_1} \\ \mathbf{x_2} \\ \cdots\cdots \\ \mathbf{x_n} \\ \cdots\cdots \\ \mathbf{x_N} \end{vmatrix}$$

and (3)

$$\mathbf{c} = \begin{vmatrix} c_1 \\ c_2 \\ c_3 \\ \cdots \\ c_m \\ \cdots \\ c_M \end{vmatrix} \quad (6)$$

Thus the column vector $\mathbf{x}$ represents all signals from all interrogating signal sources at all elements of the CRPAA, while column vector $\mathbf{c}$ represents all signals transmitted by all interrogating signal sources.

As it was mentioned above, the CRPAA will transport all the signals, received by different antenna elements, to the CRPAA output and to the input of the HPCC. Let the transfer functions between all CRPAA elements and its output be represented by the column vector a:

$$\mathbf{a} = \begin{vmatrix} a_{\square} \\ a_{\square} \\ a_{\square} \\ \ldots\ldots \\ a_n \\ \ldots\ldots \\ a_N \end{vmatrix} \qquad (7)$$

Where $a_n = L_{an} \square e^{j\varphi n}$, L_{an}- gain of a single element, propagation losses of the CRPAA splitter are included, $\varphi_n = \square\pi \square r_n \square\lambda_g + \Delta\varphi_n$,where $\square\pi . r_n / \lambda_g$ – phase shift due to antenna array power divider, $\Delta\varphi_n$- phase shift due to the element inclination if Circular Polarization (CP) is used.

Due to the finite transfer function that exists between the input and output ports of a CRPAA, the signals appearing at its output will be those at the antenna elements, modified by the transfer function a. The signal vector I , combining all interrogating signals appearing at the CRPAA output, is:

$$I = \big| \; a_{\square}\square\square_{\square} \quad a_{\square}\square\square_{\square} \quad a_{\square}\square\square_{\square} \square\square\square \; \square\square\square a_n \square\square_{\square} \square\square\square \; a_N \square\square_{\square} \; \big| = \square\square\square \qquad (8)$$

The received by the CRPAA signals I are mixed in the HPCC with a local oscillated signal S with $f_{LO} = \square f_{RF}$. The mixer output signals contain the following frequency components:

$$f_{\Sigma} = f_{RF} + \square f_{RF} = \square f_{RF} \text{ and}$$
$$f_{\Delta} = f_{RF} - \square f_{RF} = -f_{RF} \qquad (9)$$

The first component with $\square f_{RF}$ is low pass filtered. The second component T with frequency f_{RF} is with negative signs, which means, that it is phase conjugated with the signal vector I .

The output signal of the multiplication process in HPCC will be:

$$I \square H = G \begin{vmatrix} i_{\square} \square H \\ i_{\square} \square H \\ \square\square\square\square \\ i_n \square H \\ \square\square\square\square \\ i_N \square H \end{vmatrix} \qquad (10)$$

Where the term n consists of:

$$\square i_n \square H \square = i_n \square e^{j\left[\omega t - k r_n \square\square\square \theta_c \square\square\square(\phi_c - \phi_n) + k_g \square r_n\right]} \square e^{j\square\omega t} \qquad (11)$$

Where i_n is the amplitude of the information signal per antenna element (uniform distribution of the amplitudes of the antenna elements is considered), the same for the heterodyne signal ***H*** is chosen to be 1, for simplicity only one interrogator with angular coordinates $\phi_c \square \theta_c$ is considered, $\omega = \square\pi f_{RF}$, G is the conversion gain of the HPCC.

By means of eq.

$$\mathbf{cos}\, A.\mathbf{cos}\, B = \square,\square\mathbf{cos}(A-B) + \square,\square\mathbf{cos}(A+B)$$

eq. (11) can be represented in real form as:

$$\square\square i_n \square H \square\square \; \square\square\square i_n \square$$
$$\square\square\square\square\omega t \; \square k \square r_n \square\square\square\theta_c \square\square\square\square\varphi_c \quad \varphi_n \square \; k \square r_n \square\square \qquad (12)$$
$$\square \; \square\square\square i_c \square\square\omega \; t \; \square \; \square\square\square\square$$

Where the second term of eq. (12) is with triple RF frequency and after Low Pass Filtering (LPF) it cancels. Obviously:

$$T = G \square I^H = G \square a^H \square X^H \qquad (13)$$

Where $\left(\; I \square a \square X \; \right)^{\square}$ are the Hermitian (transpose and conjugate) matrix of $I \square a \square X$.

The retransmitted signal vector B by the CRPAA at the antenna array elements is the sum of the diagonal elements (or the trace) of the square matrix $a \square T$, as follows:

$$B = trace \square a \square T \square = G \square trace \square a \square a^H \; X^H \square =$$
$$= G \big| a_{\square} \square a_{\square}^H + a_{\square} \square a_{\square}^H \square\square + a_N \square a_N^H \; \big| X^H = G \square N \square L_a^{\square} \square X^H \qquad (14)$$

The non-diagonal terms of the squared matrix $a \square T$ are statistical independent zero mean quantities and their sum according Central Limit Theorem (CLT) is zero too. The diagonal terms $a_n \square a_n^H = L_{an}^{\square}$ are in phase, which means that the CRPAA, followed by a HPCC, works as phased array antenna with total receive-retransmit gain $G \square N \square L_a^{\square}$ (consider for simplicity equal gain of the different antenna elements).

Bearing in mind that for simplicity only the $m-th$ interrogator is active, then the retransmitted signal vector towards him is:

$$B_m = G \cdot N \cdot L_a^{*} \cdot X_m^H \qquad (15)$$

The signal at the output of the interrogator receive antenna with gain G_m^{rec} will be c_m^{rec}, as follows:

$$c_m^{rec} = G_m^{rec} \cdot G \cdot N \cdot L_a^{*} \cdot c_m \cdot trace\left(s_m \cdot s_m^H\right) \qquad (16)$$

The non-diagonal terms of the squared matrix (16) are statistical independent zero mean quantities and their sum according CLT is zero too. Equation (16) proves the idea, that the CRPAA, followed by a HPCC, works as retro directive system with maximum of the received signal c_m^{rec} equal to:

$$c_m^{rec} = G_m^{rec} \cdot G \cdot N^{*} \cdot L_a^{*} \cdot c_m \left| s_{nm} \right|^2 \qquad (17)$$

3. CONCLUSION

In this report new and very promising applications of Random Phased Antenna Arrays in Microwave Retro Directive Systems are proposed by the author. By means of mathematical model of the proposed systems, based on matrix and vector algebra, it is shown that the combination of RPAA and a phase – conjugate circuits will work as simple and cheap MRDS. RPAA, based on Radial Line Antenna with random distributed and oriented slot radiators, are part of the proposed systems too.

Only one interrogator is considered to be active for simplicity in the report. More complicated case of multiple active interrogators will be discussed in future works, as well as the equivalent radar cross section and the parameters of the retransmitted antenna patterns

The proposed MRDS,s have shown much potential for use in many applications. The autonomous beam steering feature of the RPAA MRDS,s make them attractive for automatic pointing and tracking systems, microwave-tracking beacons, radar transponders, Radio Frequency IDentification (RFID), solar power satellites, microwave power transmission, cross links for small satellite networks, as well as for complex communication systems.

References

[1] *Y. Guo, X. Shi, L. Chen, “Retrodirective Array Technology”,* Progress in Electromagnetics Research B, *Vol.5, Internet, 2008, pp. 153-167.*

[2] *M.Kevin, H. Leong, R. Miyamoto, T. Itoh, “Moving Forward in Retrodirective Antenna Arrays”,* IEEE Potentials, *Internet, August-September 2003, pp.16-21.*

[3] *D. Jorgensen, C. Loadman, Z. Chen, “Retrodirective Antenna Systems for Wireless Communications”,* CNSR 2003 Conference, *Monston, Canada, May 15-16, 2003, pp. 20-23.*

[4] *V. Demirev, "Spatial Correlation Processing - the New Approach in the Broadband Satellite Tracking Systems",* Journal of Electrical and Control Engineering, *V.3, N 5, October, 2013, pp. 55-64.*

[5] *V. Demirev, "Some Important Parameters of the Spatial Correlation Processing Technology",* Journal of Electrical and Control Engineering, *V.3, N 5, October, 2013, pp. 49-54.*

[6] *V. Demirev, "Random Phase Spread Coding - the New Way to Communicate with Noise Signals at Microwaves", Journal of Electrical and Control Engineering, V.4, N 2, April, 2014, pp. 1-9.*