An Innovative Way of Using Coherently Radiating Periodic Structures for Phased Arrays with Reduced Number of Phase Shifters

Elizvan Juárez, Marco A. Panduro*, David H. Covarrubias, Alberto Reyna, Brian Sanchez and Carlos del Rio

***Abstract*— This paper presents an innovative design technique for feeding phase antenna arrays using CORPS (coherently radiating periodic structures) technology for reducing the number of phase shifters (PSs) in limited-scan applications with low side lobe level (SLL). The proposed configuration is implemented taking advantage of the phase interpolation property of a CORPS network of one layer. This configuration is built by interconnecting 2 × 3 CORPS networks in a strategic way in order to provide a reduction in the number of PSs while maintaining the scanning capability. Experimental results and full-wave simulations based in CST Microwave Studio reveal that the proposed design technique reduces the recombination losses and generates a better phase slope with respect to the basic CORPS network providing a reduction in the number of PSs. As a novel contribution the paper provides the full antenna system design in order to analyze and study the PSs reduction performance and scanning capabilities of the proposed technique to feed linear antenna arrays. The proposed design technique provides a reduction in the number of PSs for a scanning range of $\pm 25°$ in linear arrays. The array design model includes the application of the raised cosine amplitude distribution to generate a radiation pattern with minimum SLL. The linear array system was validated by experimental measurements of the full system prototype and full-wave simulations results are provided to verify the accuracy of the array model and to take mutual coupling into account. The proposed case provides a good design compromise with respect to other cases in the state-of-the-art.**

***Index Terms*—Phased array, CORPS network, linear array, planar array, beam-scanning, side lobe level.**

I. INTRODUCTION

Phased arrays are extensively applied in Wireless communications [1], radar systems [2-3], satellite communications [4-5], vehicular applications [6] and recently in the 5G systems [7-8]. Most phased arrays steer the main beam over a hemisphere. These can be integrated by using different electronic devices such as: amplifiers, switches, phase shifters, etc. Depending on the configuration, phase shifters could be the most expensive components in phased arrays. As number of phase shifters is increased the cost and the complexity of the array is increased too. One amplifier device and one phase shifter in each antenna element is usually used in low SLL applications [9-10] to generate an excitation distribution across the array. This permits a wide control of the beam-scanning for a desired SLL. However, beam-scanning is very expensive and complicated for design cases with a high number of antenna elements. This is motivation to find out new design techniques for reducing the number of phase shifters in beam-scanning applications with a low SLL.

The subarrays technology is traditionally used on the state of art for reducing the number of phase shifters by feeding one or several antenna elements by only one phase shifter [11-12]. This antenna arrays technology based on uniform subarrays is limited in beam-scanning due to the appearance of grating lobes in the visible range [13].

Grating lobes were reduced in [14] for a phased array of limited scanning. Subarrays are arranged in a planar array for beam-scanning in ($\pm 10°$) over the elevation plane and ($\pm 45°$) over the azimuth plane. This design case utilizes one amplifier by each subarray to obtain a $\mathrm{SLL}_{\mathrm{PEAK}} \approx$ -20 dB in all the scanning range.

The previous work in [15-17] presents the reduction of phase shifters by applying the overlapping subarrays feeding techniques. These techniques are complex as a disadvantage for implementation in the beamforming network. Interleaved subarrays techniques have been analyzed in [18] and random subarrays configurations have been studied in [19] for applications of limited-scan arrays in order to simplify the beamforming network. The technique of cophasal subarrays was implemented in [20] for reducing the number of PSs over a wide scanning range.

Recently, randomly grouped subarrays were used in [21] for reducing the number of PSs in phased arrays of limited scanning ($\pm 15°$ elevation plane and $\pm 40°$ azimuth plane). The raised cosine distribution was used to obtain a $\mathrm{SLL}_{\mathrm{PEAK}} \approx$ -13 dB in all the scanning range.

Furthermore, the technology of CORPS (coherently radiating periodic structures) [22-27] has been applied in several

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* Marco A. Panduro (mpanduro@cicese.mx) is the corresponding author.

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previous works for feeding antenna arrays and simplify the beamforming network. The complex inputs of the feeding network were optimized in [27] to generate a scannable radiation pattern with a low SLL. A beamforming network based on CORPS was implemented in [23] to control a planar array of 9 antennas (3 × 3) with a limited scanning range in azimuth and elevation planes.

Although the previous works have generated interesting techniques to simplify the feeding network by reducing the number of PSs, much effort of research and development is still required to study and analyze more configurations that provide more beam-scanning performance in both planes with a lower SLL. The design techniques for beam-scanning with a reduction of PSs and a low SLL are still scarce considering the requirements of the new communication technologies.

Therefore, this paper presents an innovative design technique for feeding phased arrays using CORPS for reducing the number of PSs in the system. This configuration is based on blocks of CORPS networks of 2 inputs and 3 outputs. The way of interconnecting the split and recombination nodes of these blocks provides several advantages with respect to the basic scheme to feed linear antenna arrays. The proposed configuration provides a cophasal excitation in the antenna elements and generates a better phase slope with respect to the basic CORPS network providing better scanning capabilities. Experimental results and full-wave simulations based in CST Microwave Studio reveal that the proposed configuration reduces the recombination losses with respect to the basic CORPS network providing a reduction in the number of PSs.

As a novel contribution the paper provides the full antenna system design in order to analyze and study the PSs reduction performance and scanning capabilities of the proposed technique to feed linear antenna arrays. Our proposed design technique provides a reduction in the number of PSs for a scanning range of $\pm 25°$ in linear arrays. The application of the raised cosine amplitude distribution generates radiation patterns with a $SLL_{PEAK} \approx$ -20.0 dB using full-wave simulations to verify the accuracy of the array model and to take mutual coupling into account. Linear arrays were validated by experimental measurements of the full system prototype. The proposed case provides a good design compromise with respect to other cases in the state-of-the-art.

II. Proposed Design Model

A. CORPS networks

CORPS networks have been studied and analyzed in the previous work presented in [22-27]. These kind of feeding networks are defined by an alternative iteration of split (S) and recombination (R) nodes [23]. The working principle depends strictly in the power distribution across the network using these split or recombination nodes.

Basically, the reduction in the number of PSs in the CORPS networks is directly proportional to the number of layers employed. As increases the number of layers the losses are increased by energy dissipation in passive components [26], and the scanning performance is deteriorated too [27]. Therefore, a small number of layers is desirable in the CORPS network.

For example, Fig. 1(a) shows a phased array of 7 antenna elements using a CORPS network of 3 layers and 4 input ports. This figure illustrates the basic and standard scheme of CORPS networks. This array design uses amplifiers and phase shifters in the input ports (complex inputs). As illustrated in [27], the optimization of these complex inputs provides a scanning performance of $\pm 20°$ remaining a $SLL_{PEAK} \approx$ -16 dB. The use of this feeding network provides a reduction of 3 PSs with respect to a conventional phased array (Fig. 1(b)).

We propose the configuration illustrated in Fig. 1(c) as an innovative way of using CORPS for phased arrays. This configuration is based on blocks of CORPS networks of 2 inputs and 3 outputs as shown in this figure. The way of interconnecting the S and R nodes of these blocks (CORPS networks of 2 inputs and 3 outputs, 2 × 3) provides several advantages with respect to the basic scheme (Fig. 1(a)) that are explained next.

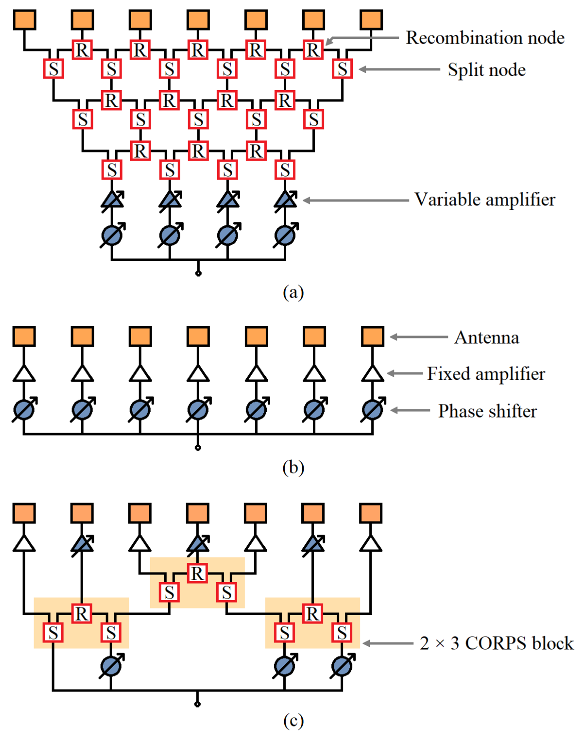


Fig. 1. Antenna array configurations: (a) Phased array using a basic CORPS network of 3 layers, (b) Conventional phased array, and (c) Phased array using the proposed configuration of the CORPS network using three 2 × 3 CORPS networks (of one layer).

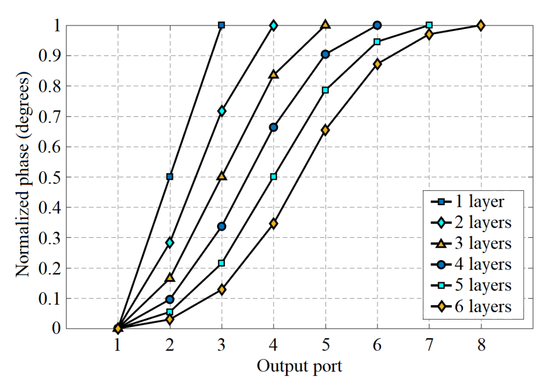


Fig. 2. Normalized phase values considering different number of layers in a basic CORPS network of two input ports.

The proposed configuration provides a cophasal excitation in the antenna elements with only 3 PSs and 3 blocks of 2 × 3 CORPS networks, i.e., the same phase slope generated by a conventional phase array (using 7 PSs) can be generated by using only 3 PSs. This is achieved by the phase interpolation in each block of 2 × 3 CORPS network. Each block delivers the average phase value for the phase values received at its two input ports. This average phase condition is only presented in CORPS networks of one layer [26] as shown in Fig. 2. This figure shows the normalized phase values generated by a CORPS network of two inputs as increasing the number of layers. If the number of layers is increased the behavior of the phase at the outputs of the CORPS network is like a sinusoidal function. The behavior of linear phase can be generated in a simpler way by using CORPS networks of one layer. This provides a better phase control increasing the scanning possibilities.

The total losses caused by energy dissipation in the R nodes (a disadvantage of the basic scheme as illustrated in Fig. 3(a) [26]) are lower for the proposed configuration considering a 75% less of R nodes employed in the feeding network, as shown in Fig. 3(b). In addition to, the amplitude values of the obtained signals at the extremes of the network present less attenuation.

Furthermore, the use of 3 variable amplifiers (as shown in the proposed configuration) contributes to generate a raised cosine amplitude distribution at the array elements. This yields a radiation pattern with low SLL characteristics.

B. *Proposed configuration of 4 × 7 CORPS feeding network*

The feeding network configuration can be implemented taking advantage of the phase interpolation property of a CORPS network of one layer as explained in the previous section. This configuration is built by interconnecting three 2 × 3 CORPS networks in a strategic way (as shown in Fig. 1(c)) in order to provide a reduction in the number of PSs while maintaining the scanning capability.

Fig. 4(a) shows the design of the proposed configuration of 4 × 7 CORPS network in CST Microwave Studio. The substrate (FR4) dimensions are 280 mm × 89 mm and a thick of 1.6 mm with relative permittivity ε_r = 4.2 and loss tangent of 0.025. This configuration uses Gysel power dividers [28] with surface mount resistors of 50 Ohms (Vishay FC0603). The SMA connectors and the resistances are considered for the full-wave simulation. The separation between output ports is $\lambda/2$, this will facilitate the implementation of the full antenna system proposed for linear antenna arrays (shown in the next Sections). The phase shifts set as short transmission lines (before output ports) provide phase values to be equal at the output ports when phase values are equal at input ports.

Fig. 5 shows the power flux (full-wave simulated) when a signal is fed by the input port 1 (Fig. 5(a)), a signal is fed by the input port 3 (Fig. 5(b)), and when all input ports are fed simultaneously by a 6 GHz signal with the same phase value and unit amplitude (Fig. 5(c)). This figure illustrates the power distribution in the S nodes (an attenuation of ≈ -3 dB is produced in the signal power), and the power losses by dissipation in the R nodes, i.e., part of the signal flows to the resistors of Gysel power dividers (≈ -3 dB of power losses). major part of the power losses of signal are presented in the R nodes nearest the input ports. This is because as the power is distributed across the network the power losses in the other R nodes are less significant. This is analyzed in detail in [26].

The proposed design block of 4 × 7 CORPS network uses 9 Gysel power dividers (six S nodes and three R nodes), while a basic CORPS network (of 4 inputs and 7 outputs) uses 27 Gysel power dividers (fifteen S nodes and twelve R nodes). A reduction of the 66% in the number of Gysel power dividers and a 75% in the R nodes required in the feeding system.

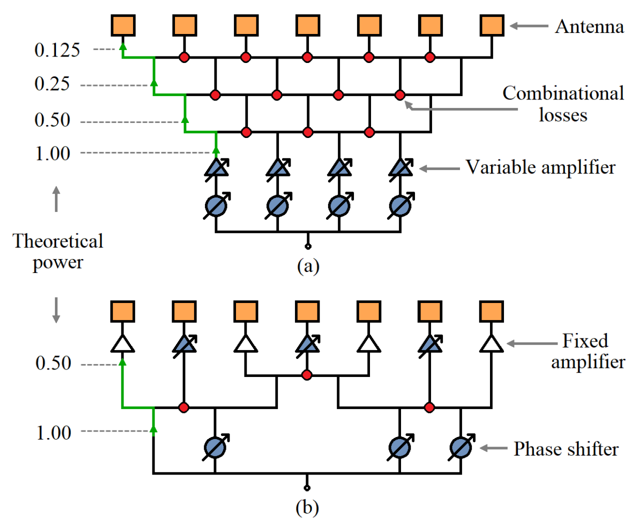


Fig. 3. Recombination node losses (a) Basic CORPS network of 4 inputs and 7 outputs, and (b) Proposed design configuration.

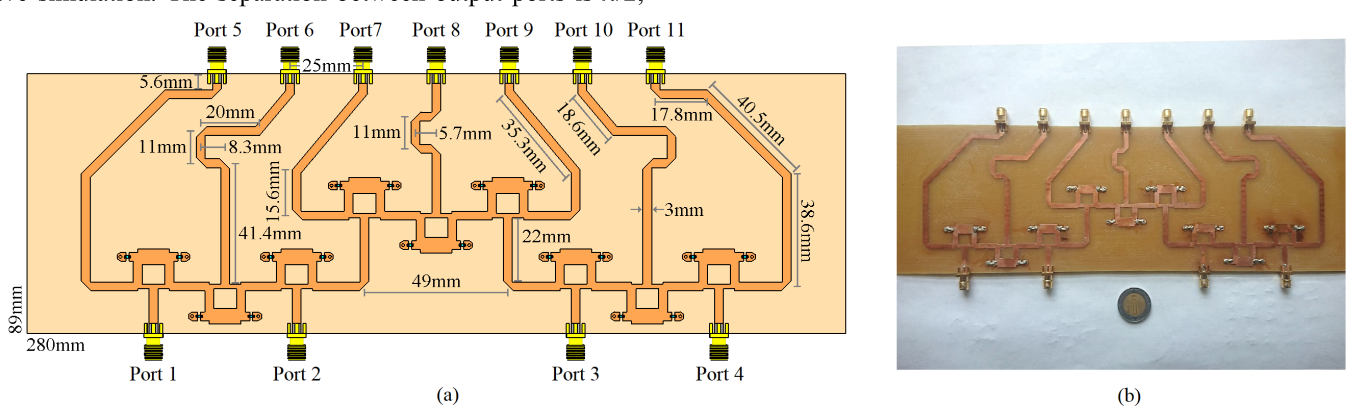


Fig. 4. Proposed configuration of 4 × 7 CORPS for a design frequency of 6 GHz: (a) Design in CST Microwave Studio, (b) Fabricated.

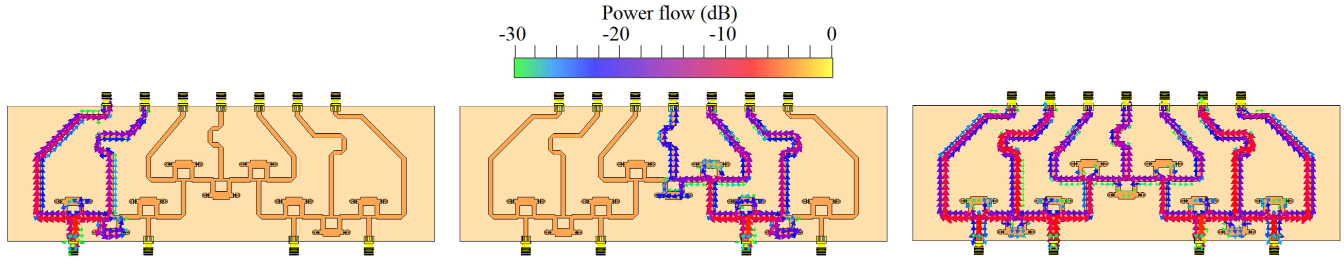


Fig. 5. Full-wave simulated power flux when: (a) a signal is fed by the input port 1, (b) a signal is fed by the input port 3, and (c) when all input ports are fed simultaneously by a 6 GHz signal with the same phase value and unit amplitude.

Therefore, the proposed configuration could reduce the quantity of recombination node losses with respect to a basic CORPS network.

C. Model and design configuration for linear antenna array

It will be analyzed the PSs reduction performance and scanning capabilities of the proposed technique for linear antenna arrays. Then, next we set the model and design configuration for the linear antenna array.

Figure 6 shows the proposed configuration for a linear array of 7 antenna elements. The array factor (AF) for this geometry as a function of θ is given by the next expression [29]:

$$AF(\theta) = \sum_{n=1}^{N} I_n\, e^{j(kd(n-1)sin(\theta)+\alpha_n)} \quad (1)$$

Where I_n is the nth amplitude excitation, N is the number of antenna elements of the array, k is the wave number, d is the separation between antenna elements, and α_n is the cophasal excitation for beam-scanning at the desired direction θ_0, α_n is given by:

$$\alpha_n = -kd(n-1)\sin(\theta_0) \quad n = 1,2,\dots,N \quad (2)$$

The amplitude excitation is considered uniform for the input ports of the proposed configuration and the phase values P_1, P_2, P_3 and P_4 are calculated by using the next expression:

$$P_m = -k2d(m-1)\sin(\theta_0) \quad m = 1,2,\dots,M \quad (3)$$

where M is the number of the input ports and m is the index of the input port of the network. Since the phase value P_1 is zero for all scanning directions, a phase shifter is not set at the input port 1.

As a phase slope is required (or a phase difference) among the input ports of the network for beam-scanning, the amplitudes values (in the recombination nodes) varies as a function of the beam-scanning direction.

Therefore, variable amplifiers are necessary at the output ports that result from a recombination node to generate an adequate distribution of amplitude at the outputs of the network. As A_1, A_3, A_5 and A_7 are fixed amplifiers (these output ports result from a split node and the amplitude value remains fixed during beam-scanning), the variable amplifiers A_2, A_4 and A_6 contribute to generate an adequate amplitude distribution for all scanning directions.

The value of the amplitude excitation in each antenna element (I_n) is calculated by the product of the amplitude value at the output port of the 4 × 7 CORPS Block (Io_n) and the amplifier value (A_n). Therefore, I_n is given by the next expression:

$$I_n = A_n Io_n \quad n = 1,2,\dots,N \quad (4)$$

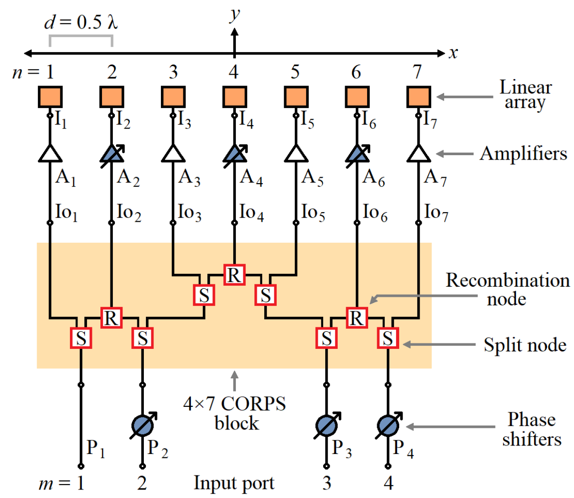


Fig. 6. Proposed configuration by using a 4 × 7 CORPS Block for a linear array of 7 antenna elements.

A raised cosine distribution is proposed and generated for the values of I_n. This amplitude distribution generates radiation patterns with low SLL in all analyzed scanning range. The raised cosine distribution is calculated by the next expression:

$$I_n = \frac{1+\cos\left(\dfrac{d_n cos^{-1}(2a-1)}{0.5L}\right)}{2} \quad n = 1,2,\dots,N \quad (5)$$

Where L is the array longitude in the x axis, d_n is the distance from the nth antenna element to the array center and a is a constant value. The values of I_n are in the range of $a < I_n < 1$. Therefore, the dynamic range of the linear array is a function of the value of a. It is observed that as SLL reduces beam-width (BW) increases. A value of SLL of -20 dB could be desired in our study. Therefore, a value of a = 0.45 is chosen to achieve the radiation and desired SLL characteristics. Given that Io_n represents the amplitude value of the signal at the output of the 4 × 7 CORPS network and I_n is the vector of amplitudes, the amplification vector is obtained from (4) as follows:

$$A_n = \frac{I_n}{Io_n} \quad n = 1,2,\dots,N \quad (6)$$

Table 1 shows the values of amplification for different scanning directions using the proposed configuration with a value of a = 0.45. It is observed that the amplification values of A_1, A_3, A_5 and A_7 remain fixed during beam-scanning. The amplification value of A_2, A_4 and A_6 increases as the main beam is scanned far from broadside or the natural response of the array. This behavior is due to the power loss produced when two signals of different phase value are combined in the R nodes.

Table 2 illustrates the amplitude and phase values for all the output ports obtained by full-wave simulation considering the structure of Fig. 4 a (CST Microwave Studio) and theoretically in scanning directions of (θ_0=-25° and θ_0 =15°). The amplitude values generated by electromagnetic solver present lower values with respect to the ideal or theoretical case. The maximum errors of phase and amplitude are 4.1% (9.4°) and 23% (on variable port Io_4), respectively. This is due to the energy dissipation and recombination losses through the network. However, the performance of the antenna array is not affected, as shown in the next Sections.

TABLE I
AMPLIFICATION VALUES FOR DIFFERENT SCANNING DIRECTIONS USING THE PROPOSED CONFIGURATION WITH A VALUE OF $a = 0.45$.

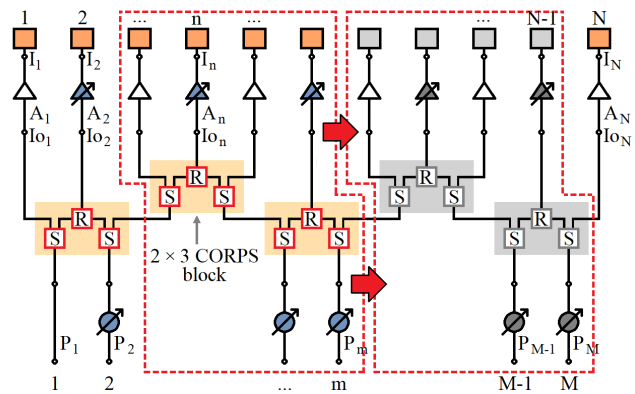
	Amplification value						
θ_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
−5°	0.64	0.75	1.85	1.47	1.85	0.75	0.64
0°	0.64	0.72	1.85	1.41	1.85	0.72	0.64
5°	0.64	0.75	1.85	1.47	1.85	0.75	0.64
10°	0.64	0.84	1.85	1.65	1.85	0.84	0.64
15°	0.64	1.05	1.85	2.06	1.85	1.05	0.64
20°	0.64	1.51	1.85	2.97	1.85	1.51	0.64
25°	0.64	2.99	1.85	5.88	1.85	2.99	0.64

TABLE II
AMPLITUDE AND PHASE VALUES FOR ALL THE OUTPUT PORTS OBTAINED BY FULL-WAVE SIMULATION AND THEORETICALLY AT θ_0 = -25° AND θ_0 = 15°

Theoretical case $\theta_0 = 15°$	Io_n	0.71, 0.69, 0.50, 0.49, 0.50, 0.69, 0.71
	Phase values	0, -46.59, -93.17, -139.76, -186.35, -232.94, -279.52
	A_n	0.64, 1.05, 1.85, 2.06, 1.85, 1.05, 0.64
Full-wave simulation $\theta_0 = 15°$	Io_n	0.36, 0.33, 0.25, 0.22, 0.23, 0.33, 0.37
	Phase values	0, -49.68, -98.93, -136.30, -191.16, -236.09, -284.69
	A_n	0.64, 1.15, 2.03, 2.41, 1.95, 1.15, 0.64
Theoretical case $\theta_0 = -25°$	Io_n	0.71, 0.24, 0.50, 0.17, 0.50, 0.24, 0.71
	Phase values	0, 76.07, 152.14, 228.21, 304.29, 380.36, 456.43
	A_n	0.64, 2.99, 1.85, 5.88, 1.85, 2.99, 0.64
Full-wave simulation $\theta_0 = -25°$	Io_n	0.39, 0.12, 0.25, 0.07, 0.26, 0.12, 0.38
	Phase values	0, 76.03, 151.85, 218.81, 304.13, 379.08, 458.35
	A_n	0.64, 3.42, 2.03, 7.97, 1.95, 3.19, 0.64

The proposed configuration of the CORPS network can be implemented in linear arrays with more antenna elements by adding more blocks of 2 × 3 CORPS networks, as shown in Fig. 7(a). A linear array of 11 antenna elements is fed in this configuration by using 6 input ports, i.e., 5 blocks of 2 × 3 CORPS networks and 5 PSs for beam-scanning in the range of ±25°. This configuration could provide a reduction in the use of PSs of 54% with respect to the conventional case of cophasal excitation. The fixed and variable amplifiers generate a scannable radiation pattern with a SLL_{PEAK} ≈ -20 dB. Fig. 7(b) shows the array factor for different linear array configurations (d = 0.5λ) at θ_0 = 25° using the CORPS feeding network configuration. The results illustrate that the SLL performance could be remained below -20 dB for all the analyzed cases.

Table 3 illustrates values of directivity, main beam width and the value of a for different number of elements in the linear arrays with a SLL_{PEAK} = -20 dB and a scanning range of ±25°. As shown in Table 3, the value of a (in (5)) must be as lower as the number of elements of the array increase to remain a SLL performance of -20 dB. The dynamic range increases for larger antenna arrays for maintaining the same SLL characteristics.



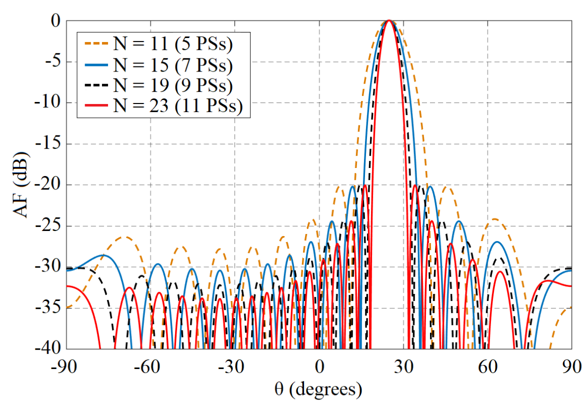


Fig. 7. (a) Proposed configuration for a linear array of 11 antenna elements. (b) Array factor calculated for different linear array configurations

TABLE III
VALUES FOR DIFFERENT LINEAR ARRAY CONFIGURATIONS OF THE CORPS NETWORK WITH A SCANNING RANGE OF ±25° AND A SLL_{PEAK} = -20 DB.

Number of Elements	Number of Phase Shifters	Number of 2 × 3 CORPS Blocks	D_{MIN} (dBi)	BW_{MAX}	a Value
7	3	3	12.6	47.9°	0.45
11	5	5	14.6	29.5°	0.42
15	7	7	16.0	21.4°	0.40
19	9	9	17.0	16.4°	0.40
23	11	11	17.8	13.9°	0.39
27	13	13	18.6	11.7°	0.39
31	15	15	19.1	10.3°	0.38
35	17	17	19.7	9.2°	0.38
39	19	19	20.2	8.3°	0.38
43	21	21	20.6	7.6°	0.37
47	23	23	21.0	6.8°	0.37
51	25	25	21.3	6.5°	0.37

The directivity and beam-width values improve as the number of antenna elements increases. Furthermore, the number of 2 × 3 CORPS networks employed for the different cases is equal to the number of PSs and variable amplifiers required.
The best and the worst case of PSs reduction is of 57% and 51%, respectively. The numerical values illustrate that the proposed configuration of the CORPS network could be applied for reducing the number of PSs in different configurations of linear arrays with a low SLL performance and limited scanning range.

III. Experimental Results

The full antenna system using the 4 × 7 CORPS feeding network for the linear array configuration was fabricated and measured to evaluate its performance. First, the experimental measurements of the CORPS feeding network are presented, and then the details of the prototype and experimental measurements are given for the linear antenna array.

A. *Measurements of the CORPS feeding network*

Fig. 4(b) shows the prototype fabricated with (FR4), relative permittivity $\varepsilon_r = 4.2$ and loss tangent of 0.025. Fig. 8 shows the reflection coefficients measured and full-wave simulated (CST Microwave Studio) for the 4 × 7 CORPS network. The bandwidth measured is of 2.66 GHz (values below -10 dB) from 4.68 GHz to 7.34 GHz. Measurements illustrate a maximum value of reflection coefficient of ≈ -20.5 dB in the design frequency of 6 GHz.
The obtained value in the full-wave simulation was ≈ -16.4 dB. The bandwidth obtained by simulation (2.84 GHz) and measurements are very similar. The measured results agree with the electromagnetic simulation results.

Fig. 9 shows the transmission coefficients simulated and measured in the ports 5, 6, 7, 8, 9, 10 and 11 that represents the output ports 1, 2, 3, 4, 5, 6 and 7 of the 4 × 7 CORPS network, respectively. The best performance is obtained at the ports 5 and 11 (≈ -8.2 dB simulation and ≈ -8.5 dB measurements). This is because the signal flows through only one Gysel power divider (≈ -3 dB of attenuation). There is a power loss associated to the energy dissipation of ≈ -4.5 dB, and ≈ -1 dB of losses in the SMA connectors. It is obtained by measurements a minimum transmission value of ≈ -12 dB (≈ -11.7 dB by simulation), i.e., ≈ -6 dB are associated to the signal split in the S node and to the recombination node, ≈ -5 dB to the energy dissipation in the network, and ≈ -1 dB to the losses in the SMA connectors. The highest value of attenuation is presented in the port 8 (≈-15 dB measured and simulated). This represents ≈ -6 dB of attenuation caused by two S nodes S, ≈ -3 dB caused by one R node, ≈ -5 dB of losses caused by energy dissipation, and ≈-1 dB of losses caused by the SMA connectors.

It is important to mention that the transmission parameters are obtained by feeding a signal in each input port in sequential way. Then, the output ports that result from a recombination node (ports 6, 8 and 10) could present a different value of transmission power depending on the phase difference between the two recombination signals. This makes necessary the use of variable amplifiers to generate an adequate distribution of amplitude at the outputs of the network. Certainly, the power losses caused by energy dissipation could be reduced by employing high performance substrates.

The measured results agree with the electromagnetic simulation results with a certain divergence in high frequencies.

Fig. 10 shows the phase values obtained by CST Microwave Studio and the theoretical case considering different directions of beams-scanning. The next phase values are considered at input ports [1, 2, 3, 4]: [0°, 0°, 0°, 0°], [0°, 50°, 100°, 150°], [0°, 100°, 200°, 300°] and [0°, 150°, 300°, 450°], respectively. The simulation results present a good agreement with respect to theoretical case. The highest value of phase error is ≈ 4%. Therefore, the proposed configuration of the feeding network generates a better phase slope with respect to the basic CORPS network providing a reduction in the number of PSs. In addition to, the proposed configuration reduces the recombination losses.

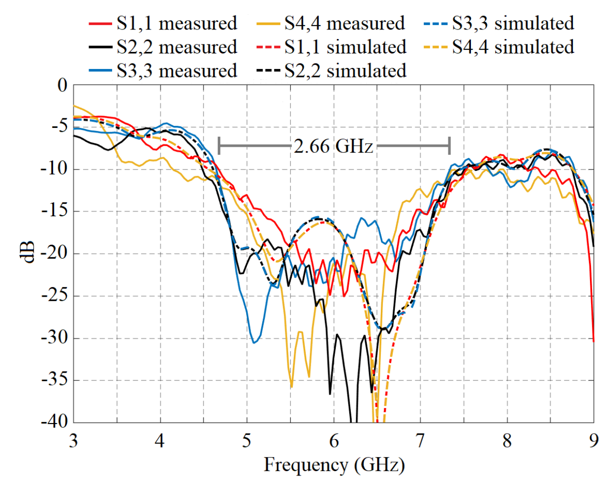


Fig. 8. Reflection coefficients obtained by full-wave simulation and measured experimentally for the proposed configuration of 4 × 7 CORPS network.

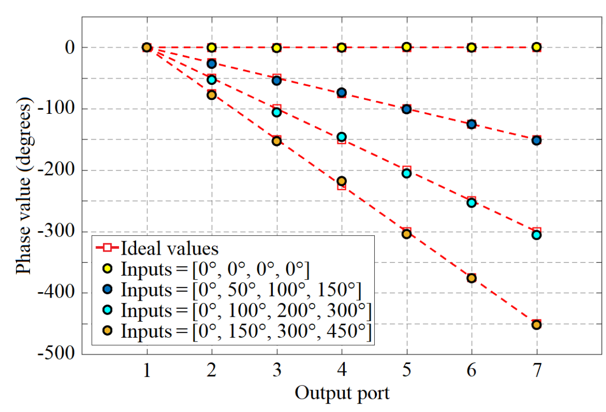


Fig. 10. Phase values obtained by the full-wave simulation and theoretical case for the proposed configuration of 4 × 7 CORPS network.

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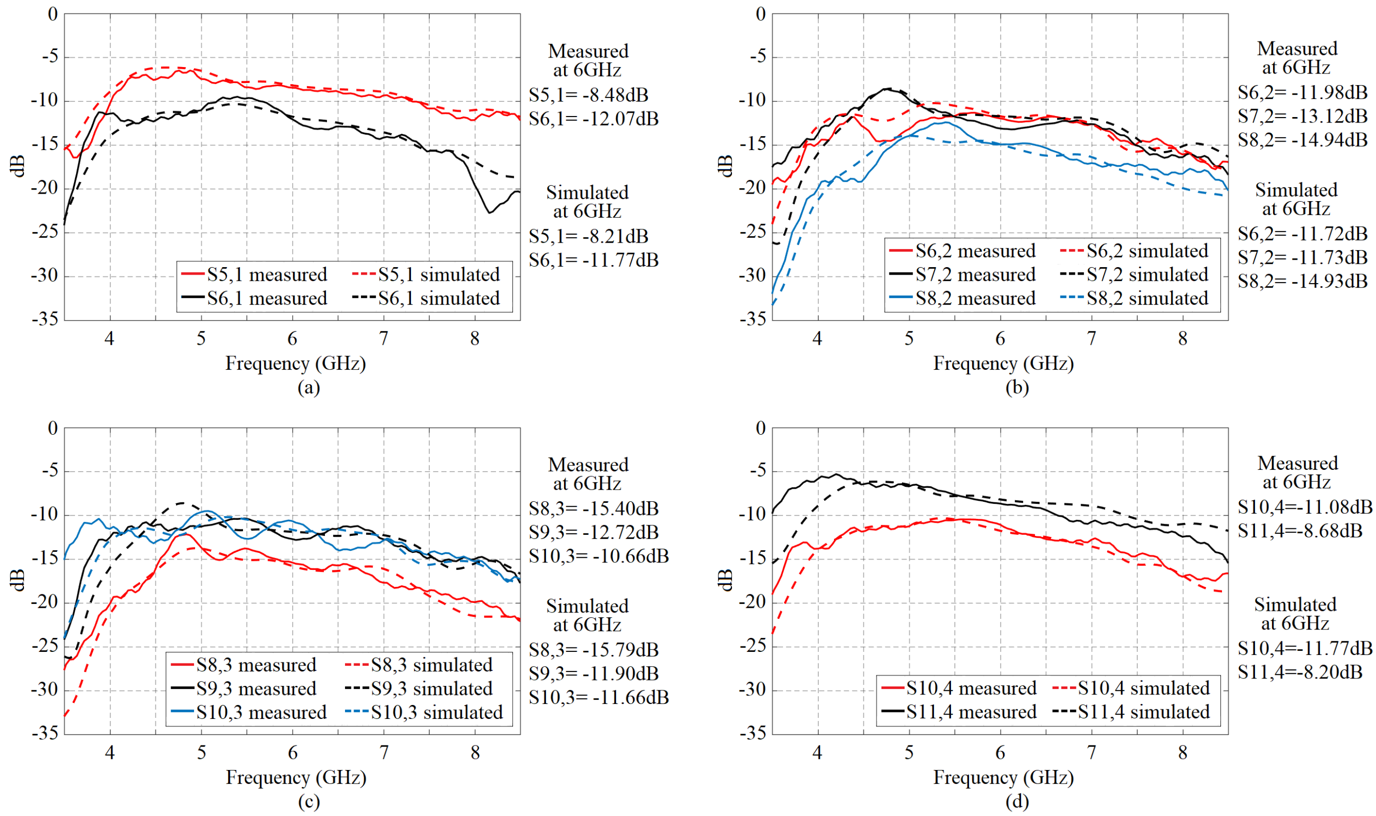

Fig. 9. Transmission coefficients obtained by full-wave simulation and measured experimentally for the proposed configuration of 4 × 7 CORPS network: (a) input port 1, (b) input port 2, (c) input port 3 and (d) input port 4.

B. Experimental measurements for the linear array system

A linear array system was designed and fabricated using a circular patch with a central frequency 6 GHz and dimensions of: r = 13.02 mm, h = 1.6 mm (FR4 substrate) and p' = 2.07 [29]. Fig. 11 shows the full system design for the linear array configuration. The linear array system comprises: the power divider network with PSs, the CORPS feeding network, the block of attenuators and the antenna elements. The PSs, attenuators and power divider are constructed on FR4 substrate too. Each block must be designed to be well impedance matched and to provide the working requirements.

Fig. 12 shows the behavior of the active reflection coefficients for the linear array considering a scanning direction of θ_0 = -25°. Every scanning direction was examined (of the scanning range $-25° < \theta_0 < 25°$) far from the natural radiation response of the array. This is the furthest scanning direction from the natural radiation response of the array and the case of worst performance for active reflection coefficients (the best performance case is obtained at θ_0 = 0°). As shown in the figure especially for the farthest direction the active reflection coefficient of 7 antenna elements is remained below -10 dB (for all scanning directions) at 6 GHz, from 5.90 GHz to 6.13 GHz. The elements show a good matching performance and the reflection coefficient of all elements is lower than -10 dB in the frequency of interest, which is acceptable for many applications.

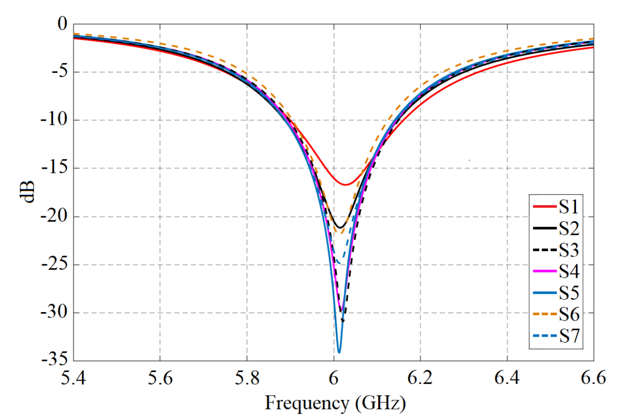

Fig. 12. Active reflection coefficient of the linear array of 7 elements with scanning direction in θ_0 = -25°.

Fig. 11(a) presents the general structure of the full array system. The input power is divided using a cascaded equal Gysel network. As described in previous sections a raised cosine tapering of -6.9 dB (a = 0.45) is used to obtain a SLL of -20 dB. Each attenuator is realized using unequal Wilkinson power divider [30] and surface mount resistors of 50 and 100 Ohms as illustrated in Fig. 13. The phase shifts are fabricated using different length transmission lines. These phase shifters generated by transmission lines could be replaced by electronic PSs without change in the radiation pattern. The system could have different PSs boards that result in fixed directions of the scanning range ($-25° < \theta_0 < 25°$).

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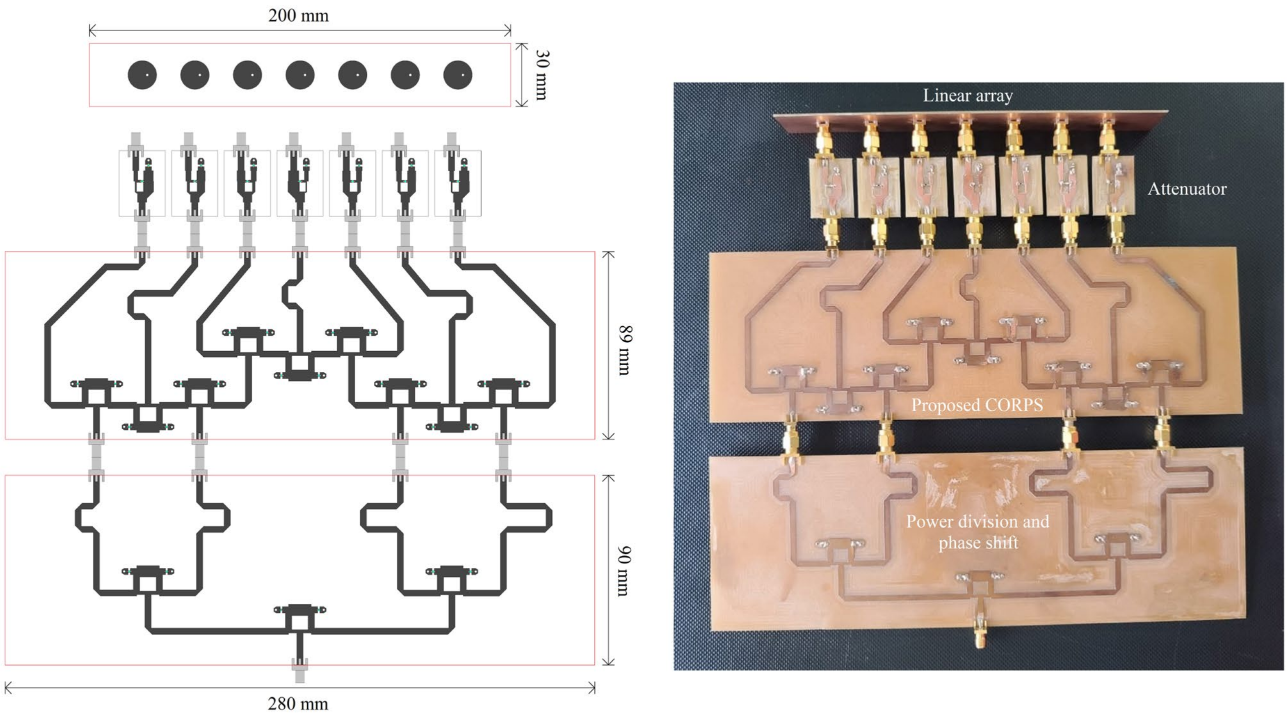

(a) (b)

Fig. 11. Full system design for the linear array configuration: a) general structure and b) fabricated array prototype

Then, the CORPS network is controlled (fed) by the phase-shifter block. The output of the CORPS feeding network is connected to the block of attenuators. Finally, the output of the block of attenuators is connected to the antenna elements. The fabricated array prototype is shown in Fig. 11(b).

Experimental measurements of the radiation pattern for the prototype were performed in a far field anechoic chamber. Furthermore, full wave simulations by using CST Microwave Studio were performed for the full system.

Figure 14 illustrates the radiation pattern obtained by experimental measurements and full-wave simulations for different scanning directions (a) $\theta_0 = 0°$, b) $\theta_0 = 15°$, c) $\theta_0 = -25°$ and d) $\theta_0 = 25°$) of the linear array system. The results demonstrate that the proposed design technique using the linear array provides a reduction of PSs with a low SLL (≈ -20 dB) performance in all the scanning range of $-25° < \theta_0 < 25°$. Furthermore, the linear array system was validated by experimental measurements with a slight deviation in the SLL (≈ -18 dB), as shown in Figure 14 e).

As downsides with respect to the conventional CORPS network the proposed design technique increases the number of amplifiers used and more attenuation is required to realize the raised cosine distribution. The attenuators consider a taper value of 11.5 dB in the fabricated linear array. The losses for the attenuators board are extracted from S-parameter measurements and are ≈ -1.85 dB. However, the application of the raised cosine amplitude distribution generates radiation patterns with low side lobe level.

Table 4 shows a performance comparison of the proposed design technique with respect to other existing techniques. This comparison is achieved in terms of the reduction of PSs, number of antenna elements, scanning range, side lobe level and array geometry. The proposed design technique presents a reduction in phase shifters of 57% for a scanning range of ±25° with a peak side-lobe level of -20 dB obtained by full-wave simulations and -18 dB by experimental measurements. The proposed case provides the best design compromise with respect to other cases in the state-of-the-art.

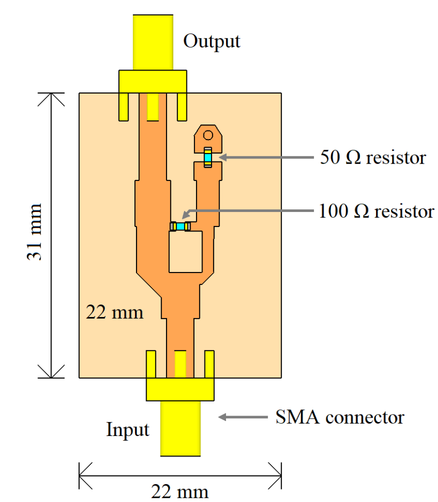

Fig. 13. Schematic layout of the fabricated attenuators (case of -2.55 dB).

The PSs reduction performance of the proposed technique could result more significant to feed planar antenna arrays. Several configurations of planar arrays can be set by using the proposed linear array system as a block. This topic could be very interesting to be studied in another research paper as many and different configurations can be set. A performance analysis of the different planar array configurations can be interesting.

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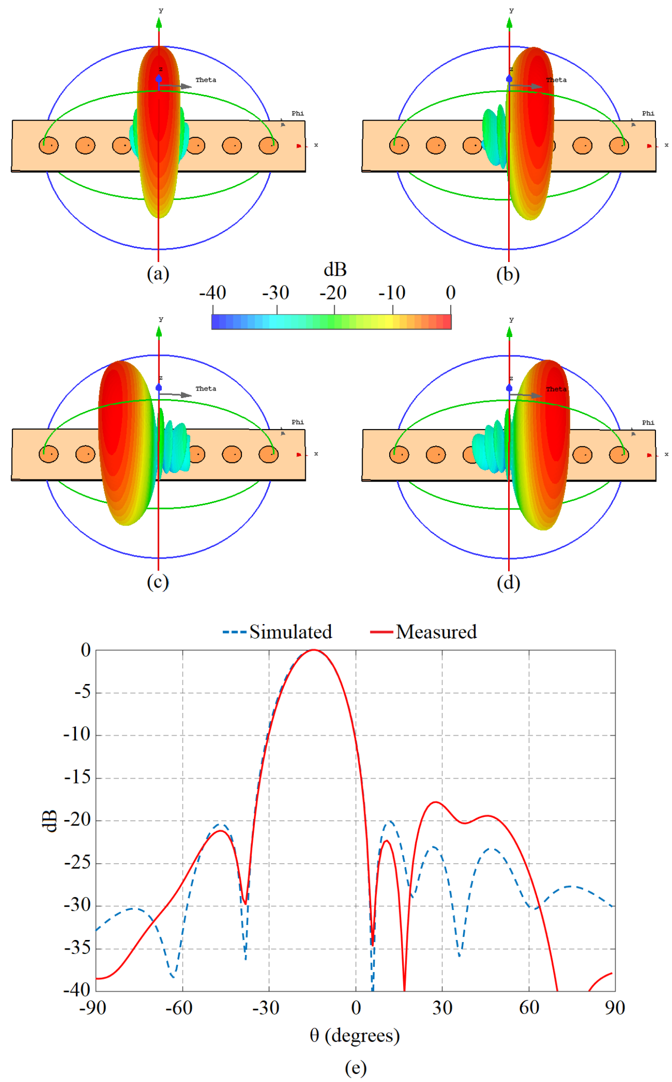

Fig. 14. Radiation pattern obtained by using full-wave simulation (a) θ_0=0°, b) θ_0=15°, c) θ_0=-25° and d) θ_0=25°) and e) experimental measurements for the linear array system.

Although only linear arrays are dealt with in this paper, the proposed design technique could be applied for reducing the number of PSs of different array configurations. Depending on the cophasal excitation required different CORPS network configurations could be set as feeding system. This could lead to simpler antenna systems and less complex maintaining its performance.

IV. Conclusions

The proposed design technique was implemented taking advantage of the phase interpolation property of a CORPS network of one layer. This configuration was built by interconnecting 2 × 3 CORPS networks in a way by providing a reduction in the number of PSs while maintaining the scanning capability. This novel feeding network was designed, simulated and fabricated to analyze its performance. The proposed design block of 4 × 7 CORPS network used 9 Gysel power dividers (six S nodes and three R nodes), while a basic CORPS network (of 4 inputs and 7 outputs) uses 27 Gysel power dividers (fifteen S nodes and twelve R nodes), a reduction of the 66% in the number of Gysel power dividers and a 75% in the R nodes required in the feeding system. Experimental results illustrated that the proposed configuration reduces the recombination losses and generates a better phase slope with respect to the basic CORPS network providing a reduction in the number of PSs.

Furthermore, the full-wave simulation results demonstrated that the proposed design technique using the linear array provides a reduction of PSs with a low SLL (≈ -20 dB) performance in all the scanning range of -25° < θ_0 < 25°. Furthermore, the linear array system was validated by experimental measurements with a slight deviation in the SLL (≈ -18 dB). As a downside with respect to the conventional CORPS network the proposed design technique increases the number of amplifiers used. However, the application of the raised cosine amplitude distribution generates radiation patterns with low side lobe level.

The proposed design technique presented a reduction in phase shifters of 57% for a scanning range of ±25° with a peak side-lobe level of -20 dB obtained by full-wave simulations and -18 dB by experimental measurements. The proposed case provides the best design compromise with respect to other cases in the state-of-the-art.

TABLE IV
COMPARISON BETWEEN LINEAR ARRAYS WITH A REDUCED NUMBER OF PHASE SHIFTERS

	Optimization	Number of elements	Number of phase shifters	Reduction of phase shifters (%)	Number of variable amplifiers	Number of fixed amplifiers	Scanning range	Peak side lobe level
Conventional phased array (raised cosine taper)	No	7	7	0 %	0	7	± 42°	-20 dB (AF)
This work	No	7	3	57 %	3	4	± 25°	-20 dB (Full-wave) -18 dB (Meas.)
[27]	Yes	10	8	20 %	8	0	± 30°	-19 dB (AF)
[19]	Yes	30	12	60 %	0	12	± 12°	-15 dB (AF)
[17]	No	28	14	50 %	0	14	± 24°	-15 dB (Meas.)
[31]	No	8	2	75 %	8	8	± 12.5°	-10 dB (Meas.)
[32]	Yes	8	2	75 %	8	8	± 18.5°	-9 dB (Meas.)
[33]	No	5	2	60 %	0	0	± 8°	-15 dB (Meas.)

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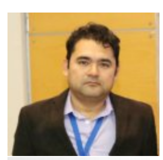
Elizvan Juárez is currently pursuing Ph.D. degree with Scientific Research and Higher Education at Ensenada (CICESE), Baja California, Mexico. His research interest includes telecommunications systems, antenna array systems and feeding networks.

Marco A. Panduro Mendoza was a Professor on the Communications Department at UAT from 2005 to 2015, and he is currently with the CICESE Research Center in Mexico. His current interests include antenna arrays, smart adaptive antennas, microwave devices and optimization via different evolutionary algorithms.

David H. Covarrubias is a full professor at CICESE research center. His research area is 5G wireless communications in antennas array and radio channel propagation.



Alberto Reyna Maldonado works at the University Autonomous of Tamaulipas in Mexico. His current interests include antenna arrays, optimization and computational electromagnetics.

Brian Sanchez is currently pursuing Ph.D. degree with Scientific Research and Higher Education at Ensenada (CICESE), Baja California, Mexico. His research interest includes telecommunications systems, antenna array systems and feeding networks.

Carlos del Rio develops his research and docent activities in the Public University of Navarra. Nowadays, he is associate professor in the Electronic and Electronic Engineering Department of the Public University of Navarra.