# A Six-Elements Circularly Polarized Sequential Array for Dedicated Short Range Communications in C-band

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***Abstract*** **─** In this paper an antenna array operating in circular polarization in the C-band is presented. The array is based on the sequential rotation architecture, applied to six elements, and arranged in hexagonal shape. Thanks to its geometry, the array is suitable for tiling of surfaces as well as for regular solid arrangement. Satisfying experimental validation of a prototype based on the proposed design is observed, with a peak gain of 10.4 dB at 5.8 GHz maintained within 3 dB over a 500 MHz band, a 10 dB return loss bandwidth of 500 MHz, and a 3dB axial ratio bandwidth of almost 400 MHz, meaning 6.5% of fractional bandwidth.

***Index Terms*** **─** Antennas, Network and circuits, Circular Polarization, Dedicated Short Range Communications, C-band.

## I. INTRODUCTION

Printed antennas are the preferred choice in almost every modern application. Their advantages in terms of low profile, light weight, manufacturing easiness and conformability are well-known in science and industry.

In applications where the polarization of the source or target is arbitrary or unknown, such as indoor positioning or short-range communications, antennas operating in circular polarization (CP) are preferred [1]. This also holds for applications in complex scenarios, where the CP is a strong aid in contrasting multipath [2,3]. Furthermore, compact CP antenna with moderate to high gain are also necessary in Intelligent Transportation System applications, operating in the band centered at 5.8 GHz [4].

While it is relatively easy to design a printed antenna for CP operation, solutions based on a single antenna typically do not match adequate performance in terms of gain and polarization purity for actual applications.

One of the best and most known solution to increase the number of radiating elements is the use of the sequential rotation architecture (SRA) [5,6,7], which serves as beamforming network for the array configuration as well as an enhancer of polarization purity. This architecture is based on a sequential rotation network (SRN) which serves as the building block of the array.

SRNs are found in open literature with a number of outputs usually equal to 4, or higher powers of 4. The reason is the availability of a simple analytical approach to cope with the design of the network. Being requested with providing 90° of phase delay in each sequential step, the network can be indeed realized with quarter wavelength lines, which easily provide also impedance matching acting as quarter wavelength transformers. Networks with outputs exceeding 4 based on the SPN, however, are seldom proposed for the lack of an analytical solution. Indeed, a 5-elements SRA was proposed by the authors in [8], demonstrating the possibility of a generalized design based on $N > 4$.

We push even further the idea, presenting an array based on six elements, arranged as a hexagon. The hexagonal shape is suitable for 2D tiling, making the device suitable to be the subarray for even larger planar array. Furthermore, combining this shape with the pentagon, it is possible to build a truncated icosahedron, suitable for the problem of a sampling the sphere [9]. As far as the authors know, no such design is present in literature.

Here, the synthesis of the 6-elements SPN is addressed via numeric optimization on a custom vector-based cost-function, permitting the optimal balance of both the magnitude and the phase at each port. The SPN is then assembled with disc-based patch elements, leading to the design of a complete array. Thus, a prototype based on the proposed network has been built, arranged in a single-layer via-less hexagonal board, and experimentally validated.

## II. SEQUENTIAL ARCHITECTURE

The SPN, which serves as the feeding network of the array, is a type of structure that guarantees equal power division between the $N$ outputs of the device with a regular progression of the signal phase. The equivalent circuit of the proposed SPN is depicted in Fig. 1. This design is an evolution of the one proposed in [8], and it is treated with a similar approach, briefly summarized

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here.

The core of the network is the cascade of five transmission lines in series with characteristic impedances $Z_i$ and electrical lengths $\theta_i$, $i = 1,2,\ldots,5$. Along this cascade, six shunt output lines are considered, characterized by impedances $Z_i^o$ and electrical length Impedances $\theta_i^o$, $i = 1,2,\ldots,6$. Furthermore, six stubs are placed in correspondence of the six junctions (characterized by impedances $Z_i^s$ and electrical length $\theta_i^s$, $i = 1,2,\ldots,6$).

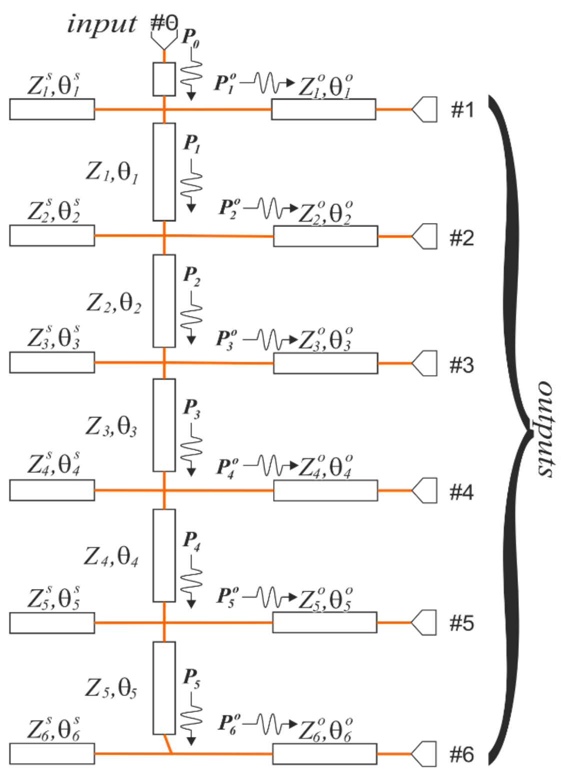


Fig. 1. Representation of the sequential rotation network with $N = 6$ outputs.

In the ideal case, the six output transmission parameters $\hat{S}_n$ exhibit identical module $|\hat{S}_n| = \sqrt{1/6}$ as well as identical phase sequential increment equal to $\angle \hat{S}_n - \angle \hat{S}_{n-1} = \frac{2\pi}{6}$. Therefore, it is assumed a relative error metric which measures the distance between such an ideal value and the numerically computed one, $S_n$ , at the $i^{th}$ step:

$$E_n = \frac{|S_n - \widehat{S_n}|}{|S_n|}. \qquad (1)$$

The large number of geometrical parameters (17 transmission line sections, hence 34 parameters among widths and lengths) and the natural multi-objective nature of the problem (one goal per output parameter), makes the design process suitable for the Taguchi multi-objective optimization method [10,11].

Figure 2 shows the conditions on the amplitudes and phases of the parameters of transmission realized for 6 outputs at central frequency after a full-wave simulation carried out with a commercial CAD. Since the final optimization has to be carried including the antenna elements, hence the unavoidable mutual coupling, the shown results are adequate as a starting point for the final optimization.

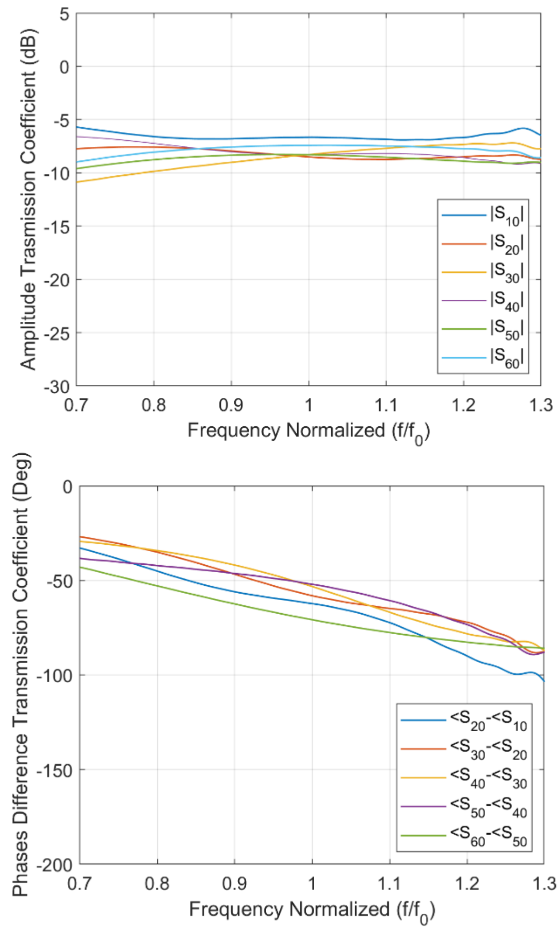


Fig. 2. Amplitudes and differences of phase of transmission coefficients for $N = 6$ outputs. Center frequency is 5.8 GHz.

## III. ANTENNA ELEMENT

The radiating element of the proposed antenna is, in view of integrating pentagonal and exagonal subarrays on a bucky-ball structure, the same implemented in [8]. The element consists of a circular patch centrally slitted by an elliptical cut, splitting the fundamental $TM_{11}$ mode into two detuned modes, $TM_x$ and $TM_y$, Figure 3 shows the geometry of the circular patch antennas and Fig. 4 shows the real and imaginary part of the element input impedance simulated tuning the angle of rotation θ of the central split ellipses with respect to the feeding line.

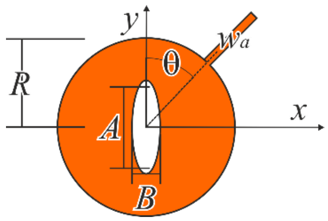


Fig. 3. Element antenna geometry.

With the aid of a parametric simulation. the optimal angle of rotation is found as θ = 48°, measured with respect to the central axis of the central ellipse. In the second analysis, the complete array with sequential feeding and patches was assembled, as it follows in the next Section.

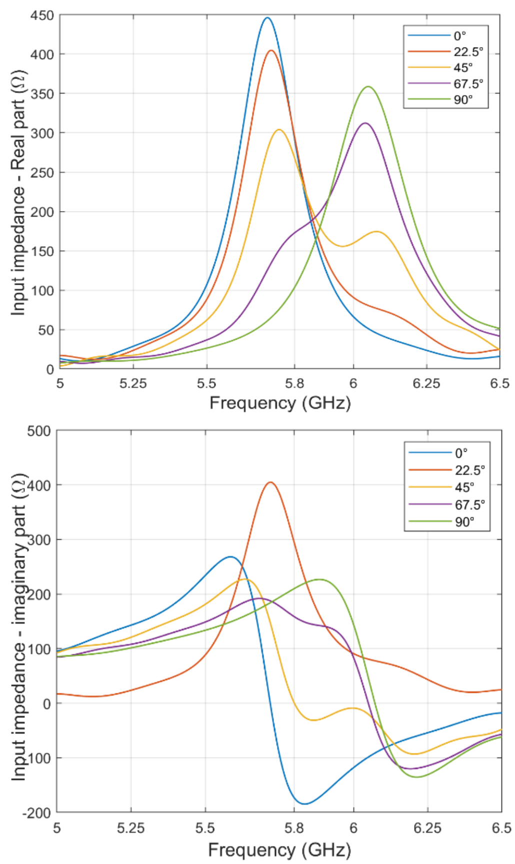


Fig. 4. Real and imaginary part of the input impedance of the circular patch antenna with elliptical split.

## IV. IMPLEMENTATION AND EXPERIMENTAL VALIDATION

With the feeding design procedure previously discussed and the tuning of the circular patches, this section describes the implementation and the experimental validation of the sequential array based on 6 microstrip patches. With the aid of the full-wave suite by Computer Simulation Technologies, the assembly comprising the SPN and the six rotated patch is analyzed.

Figure 5 shows the hexagonal printed prototype measured with the N5242 VNA from Keysight inside an anechoic structure. The realized prototype is a hexagon of side equal to *39* mm, (hence inscribed in a circle of radius *39* mm) and thickness equal to *1.6* mm, fabricated with a photo-etching process on commercial substrate (Isola FR-408 $\epsilon_r$ = 3.75, tan$\delta$ = 0.001). The actual dimensions of the prototype are reported in Table 1, with reference to the parameters defined in Fig. 3 and Fig. 5. For the sake of clarity, only the branch #5 is graphically quoted, being identical the definition for each of them.

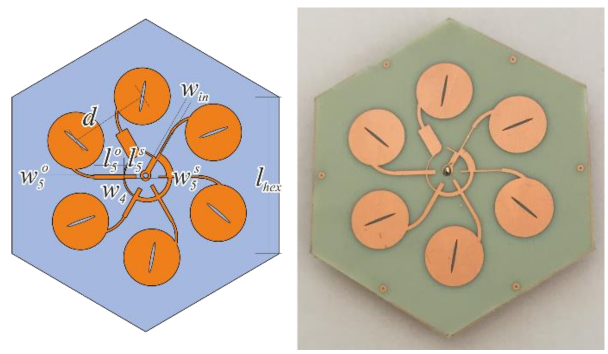


Fig. 5. Printed hexagonal array realized with sequential architecture (SRA).

Table 1: Parameters of the proposed antenna (lengths in millimeters, angles in degrees)

| $R$ | $A$ | $B$ | θ | $w_a$ | $w_{in}$ |
|---|---|---|---|---|---|
| 7.05 | 8 | 0.6 | 48 | 0.9 | 1.4 |
| $w_1$ | $w_2$ | $w_3$ | $w_4$ | $w_5$ | $d$ |
| 1.781 | 0.861 | 0.993 | 0.397 | 0.270 | 3.170 |
| $l_1^o$ | $l_2^o$ | $l_3^o$ | $l_4^o$ | $l_5^o$ | $l_6^o$ |
| 7.537 | 5.94 | 7.8 | 5.0 | 7.217 | 7.183 |
| $w_1^o$ | $w_2^o$ | $w_3^o$ | $w_4^o$ | $w_5^o$ | $w_6^o$ |
| 0.39 | 0.4 | 0.82 | 1.06 | 1.50 | 3.29 |
| $l_1^s$ | $l_2^s$ | $l_3^s$ | $l_4^s$ | $l_5^s$ | $l_6^s$ |
| *3.167* | *4.214* | *2.357* | *3.10* | *2.583* | *0.015* |
| $w_1^s$ | $w_2^s$ | $w_3^s$ | $w_4^0$ | $w_5^s$ | $w_6^s$ |
| 3.17 | 4.214 | 4.214 | 4.214 | 4.214 | 4.214 |

Figure 6 shows the reflection coefficient of the proposed prototype. Despite a small shift in value and frequency, attributed to the process of fabrication, and to the tolerances in permittivity value, a good matching between simulations and measurements is observed. A return loss exceeding 15 dB is measured at the center design frequency $f$ = 5.8 GHz, as well as a performance exceeding 10 dB from 5.6 GHz to 6.25 GHz.

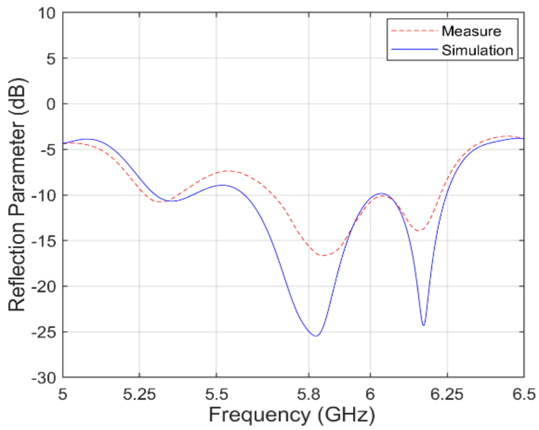


Fig. 6. Comparison between measurement and simulation of the reflection parameter ($S_{11}$).

Figure 7 presents the *LH (co-polar)* and *RH (cross-polar)* realized gain versus frequency in *broadside* direction. A maximum level of cross-polarization ratio of 23 dB is observed at 5.8 GHz frequency, and very high levels of polarization purity are observed within the C-band, kept over 10 dB from 5.3 GHz to 6.2 GHz. The level of cross-polarization observed is a proof of to the effectiveness of the proposed feeding network.

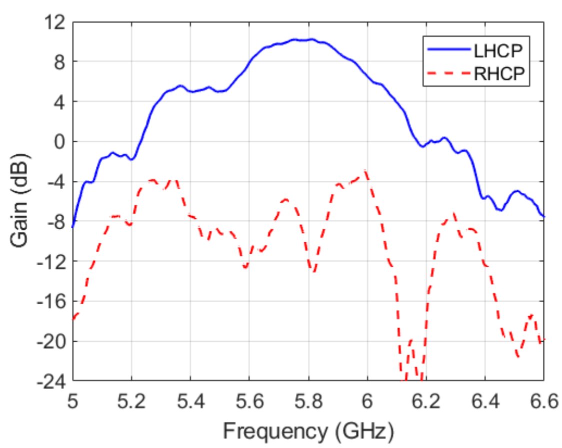


Fig. 7. Co-polar (LHCP) and cross-polar (RHCP) measured realized gain vs frequency.

The *LH* gain has a peak of 10.4 dB at 5.8 GHz and remains above 7 dB over an 18.4% bandwidth. The *RH* gain has a value of –13 dB at 5.8 GHz. With reference to Fig. 8, the high level of cross polarization is also revealed by the axial ratio (AR), depicted against the angle theta at center frequency.

In Figs. 9, 10 and 11, the measured and simulated pattern are compared at center frequency. Three cuts are considered, corresponding to the cuts ϕ = 0°, 120°, 240°, measured in anechoic chamber with a Keysight N5242 Vector Network Analyzer. The lobe is quite symmetric and invariant for each considered cut, maintaining a HPBW of about 45° in the main lobe of radiation. The lobe in broadside is the result of the sequential feeding of the patches perfectly phased.

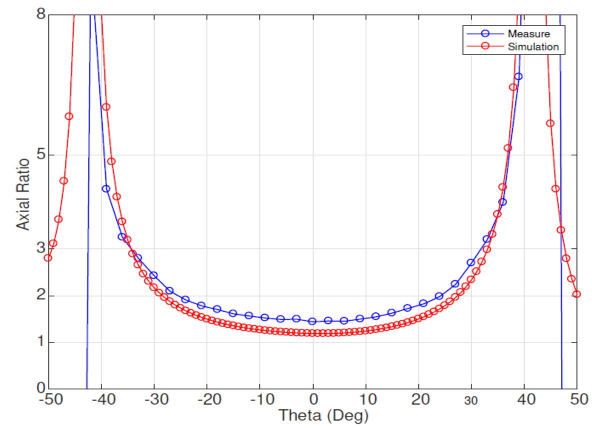


Fig. 8. Comparison between measurement and simulation of Axial Ratio (AR).

Figure 12 presents the antenna gain, measured for the cut to $\phi$ = 0°, as a contour plot. The plot presents frequency on the abscissa's axis, and the theta angle in the ordinate. This plot demonstrates the symmetry and the good frequency behavior, with the peak performance at 5.8 GHz and θ = 0, i.e., the *broadside* direction at the center frequency.

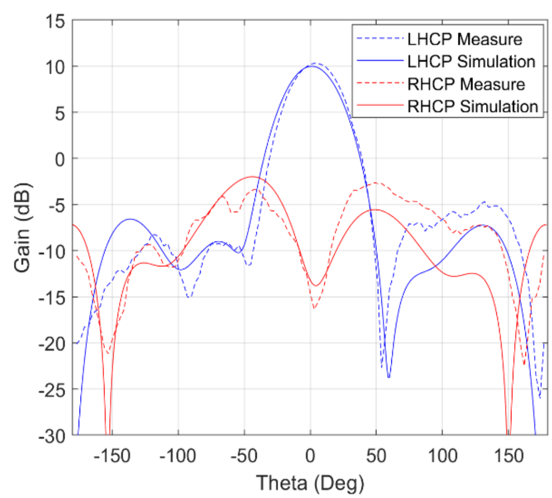


Fig. 9. Comparison between simulation and measure of radiation pattern $\phi$ = 0° at 5.8 *GHz*.

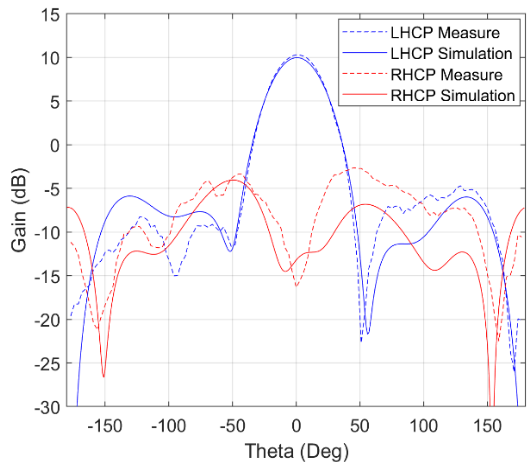


Fig. 10. Comparison between simulation and measure of radiation pattern $\phi$ = 120° at 5.8 *GHz*.

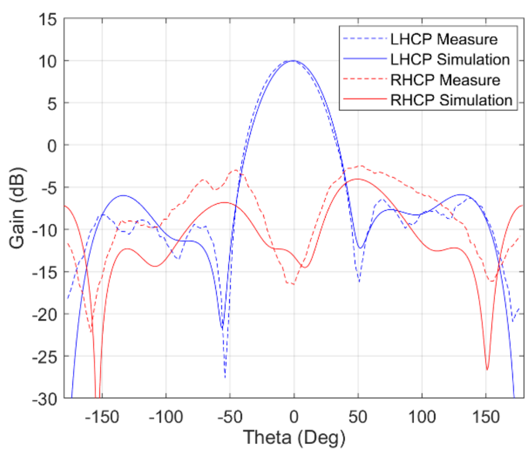


Fig. 11. Comparison between simulation and measure of radiation pattern $\phi$ = 240° at 5.8 *GHz*.

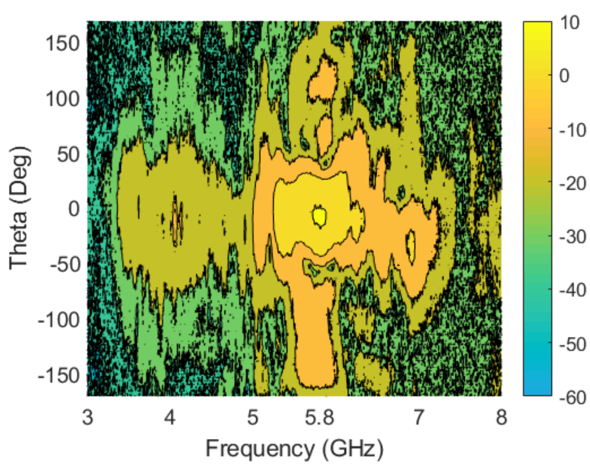


Fig. 12. Co-polar gain versus frequency and pointing angle $\theta$.

## V. CONCLUSION

A compact circularly polarized array for C-Band application was designed, simulated, and fabricated. The antenna is arranged in a hexagon of side 39 mm, hence a surface of $2\lambda_0{}^2$ at the center frequency of 5.80 GHz. The fabricated device exhibits a peak gain of 10.4 dB at 5.8 GHz, maintained within 3 dB within the range 5.5–6.0 GHz. The axial ratio is 0.1 dB at the central frequency, and below 3 dB from 5.6 GHz to 6.0 GHz. A cross polarization ratio exceeding 15 dB is observed between 5.75 GHz and 5.85 GHz, the central band of DSRC communications. The latter performance, the moderately high gain, and the single-layer via-less design makes the proposed antenna suitable for integration with compact commercial tag.

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