DoA Estimation Using Reconfigurable Antennas in Millimiter-Wave Frequency 5G Systems

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Abstract— **To achieve low latency and high throughputs, future 5G systems will have to utilize complex antenna systems able to provide beamforming and direction-of-arrival (DoA) estimation capabilities. Most of the concepts available in the literature rely on analog or digital beamforming, which is well developed and can be used both at a base station and in a user terminal. However, in applications, in which energy-efficiency or cost is one of the key concerns, the use of traditional beamforming systems is limited. To overcome this limitation, reconfigurable antennas can be used as they rely on a simple but effective concept, in which a transceiver is connected to a single input port and beamforming capabilities are enabled by a number of passive elements electronically switched via transceiver's digital input-output ports. In the article, we show how simple single-input mm-wave reconfigurable antenna can be used to provide not only beamforming but also DoA capabilities relying on received signal strength measurements. Therefore, the proposed approach can be applied in future 5G millimeter-wave nodes or gateways, in which low-cost and power-efficiency are important.**

Keywords—Reconfigurable antenna, switched-beam antenna, ESPAR antenna, direction-of-arrival estimation, internet-of-things, wireless sensor networks, 5G

I. Introduction

Future 5G systems have the potential to provide very wide bandwidths and ultra-low latencies. It is expected, to reach approximately 1000 higher capacity than currently available in 4G systems [1], which will rely on extensive use of millimeter-wave (mm-wave) antennas and systems [2], [3]. One of the key technologies considered in the field of antennas is phased arrays or digital beamforming that allow for efficient and stable wireless communication in challenging multi-user scenarios [4]. Unfortunately, both commonly used beamforming techniques cannot easily be used in all possible 5G applications due to high costs and energy consumption. Especially, the most flexible and already planned to become a part of 5G base stations digital beamforming technique, which requires a number of digital signal processing (DSP) units, as it enables to use popular and well established technologies that improve the communication efficiency such as orthogonal frequency-division multiplexing (OFDM) and multiple-input-multiple-output (MIMO) together with new ones proposed for mm-wave 5G systems [1]-[4].

To enable new applications, in which costs or energy consumption can play an important role, reconfigurable antennas have been proposed [5], [6]. In such antennas, operational frequency, radiation pattern and polarization can be modified using a number of elements including radio-frequency microelectromechanical systems (RF-MEMS), PIN diodes or varactors [5]. Particularly important is radiation pattern reconfigurability as, when combined with direction-of-arrival (DoA) estimation functionality, it can improve connectivity, coverage and energy efficiency of the whole network [7]-[9] but it can also be used in scalable and low-cost indoor localization systems [10], [11] that provide real-time positions of assets or people in smart building, smart factory or smart hospital applications [11], [12]. Because many solutions of such reconfigurable antennas are available for the most popular industrial, scientific and medical (ISM) RF bands [5], [11] they can easily be adapted to 5G systems working below 6 GHz [13]. Additionally, there are simple yet effective DoA estimation methods available, which can be implemented in transceivers having simple microcontrollers to provide single degree accuracies [14], [15].

Several compact designs of reconfigurable antennas are available for mm-wave 5G systems [16]-[18]. Due to many unwanted effects present at mm-wave frequencies, beam-steering capabilities are usually limited in such antennas. In consequence, the main beam can usually be steered by a few degrees only [16] and, in most cases, it is difficult to control radiation pattern shape while changing its direction [17], [18]. Therefore, to the best of the authors' knowledge, such mm-wave reconfigurable antennas have never been used to provide DoA estimation functionality, which requires that monotonic drop from the maximum and low side lobe level (SLL) are present in all antenna radiation patterns [19], [20].

In this paper, we propose a new mm-wave antenna design having directional and symmetrical, with respect to horizontal angle, radiation pattern, which can be switched in four directions using simple PIN diodes. The antenna can be integrated within simple internet-of-things (IoT) nodes or cost-effective and power-efficient base stations to improve connectivity in challenging environments, like industrial sites containing numerous metallic objects. Moreover, it has been shown, for the first time, how mm-wave reconfigurable antenna can be used to provide DoA estimation functionality, which can be used to find IoT nodes' positions, using a modified version of power-pattern cross-correlation (PPCC) algorithm relying solely on received signal strength (RSS) values recorded at the antenna output port.

II. Antenna Design

The proposed antenna, that consists of two substrate layers, is presented in Fig. 1. The layer with symmetrically spaced microstrip patches is located at the bottom, while the feeding lines are within the top layer and the ground plane containing coupling slots is located between them. The antenna has been designed using $0.127\,mm$ height RT/duroid® 5880 dielectric substrate having $\varepsilon_r = 2.2$.

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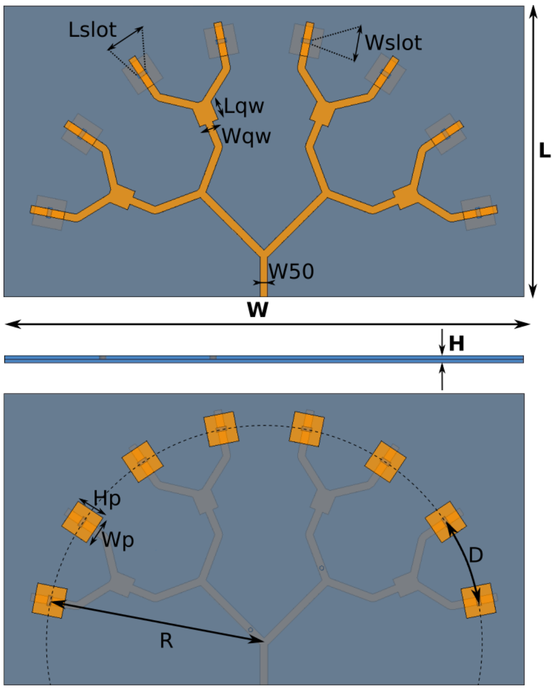

Fig. 1. Proposed mm-wave reconfigurable antenna design: top layer with corporate feed network and bottom layer with radiating elements (see test for explanations).

TABLE I
DIMENSIONS OF THE PROPOSED ANTENNA (SEE TEXT FOR EXPLANATIONS).

Dimension	Value [mm]	Value [λg]
λg	3.67	1
W50	0.37	0.10
Wp/Hp	1.44	0.392
Wslot	0.2	0.055
Lslot	0.5	0.136
Lqw	0.9175	0.25
Wqw	0.95	0.259
R	10.5	9/π
D	4.129	9/8
W	25	6.812
L	14	3.815
H	0.254	0.069

The radiating elements are eight aperture-coupled square microstrip patches that use the corporate feed network located on the top layer. The microstrip patches are grouped into four pairs where each section is fed through the common branch of the feeding network and quarter-wave transformer. Both patches in each section are excited with the same amplitude and phase. The input impedance of one pair seen from the feed line is about 25 Ω and the quarter-wave transformer provides proper antenna matching. The patches are equally spaced on the circumference of a half-circle with radius R. The distance between the patches on the circumference is D and has been chosen so that the mutual coupling between the microstrip patches is reduced and the radiated waves from both patches of a pair are almost in-phase. The proposed structure has been designed and optimized in Altair FEKO simulator at the center frequency of 62 GHz. The resulting antenna dimensions are shown in table I.

The beam steering between four available configurations in the horizontal plane is realized by switching the sections of active (radiating) pairs of microstrip patches. Switching is realized by shorting the branches of the feed network to the antenna groundplane so that the selected pair of patches is not powered. In our numerical simulations, the arms of the feeding network were shorted to the groundplane by via-holes. The shorting points are located at the quarter-wavelength distance from the power splitter, so these shorted branches are seen by the power divider as an open-circuit. In Fig. 2, the location of shorting points of the feeding network together with an exemplary configuration for one of the considered switching states have been presented. In practical implementations, PIN diodes can be used for switching as they can act as a good approximation of short- or open-circuit depending on DC bias, which can be controlled by external digital input/output (DIO) signals. In consequence, the proposed antenna having only a single RF input can provide four radiation beams that can be switched using 6 DIO ports controlling the shorting points of the feeding network. Therefore it can easily be integrated with inexpensive mm-wave transceivers containing simple microcontrollers.

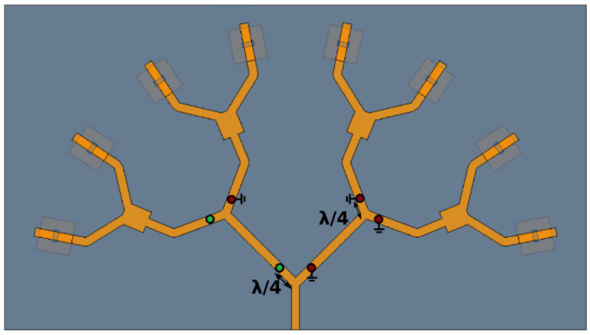

Fig. 2. Feed network steering points positions for the proposed antenna. In every considered antenna configuration, four points are shorted (marked red), while the remaining two are left open (see text for explanations).

The resulting simulated 3D antenna radiation patterns together with the corresponding 2D patterns in horizontal φ plane and $\theta \in \{130°, 140°, 150°, 160°\}$ for four switching states are presented in Fig. 3 and Fig. 4. The proposed antenna has almost omnidirectional pattern in the φ plane for $\theta \in \langle 160°,180° \rangle$, independently of the switching state, while it has directional radiation patterns for $\theta \in \langle 130°,160° \rangle$. Therefore, the antenna can be applied in ceiling-mounted IoT gateways operating in dense and harsh spaces like aircraft cabin or powertrain testbed. Moreover, due to simple steering capabilities, it can also be applied in mm-wave IoT nodes.

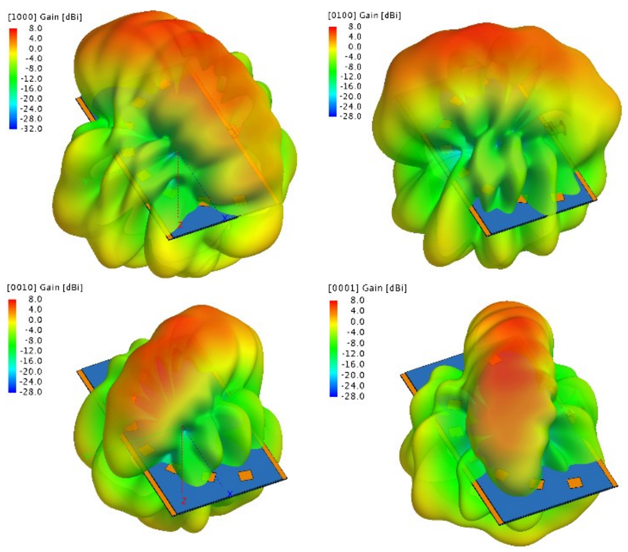

Fig. 3. Simulated 3D antenna radiation patterns (see text for explanations).

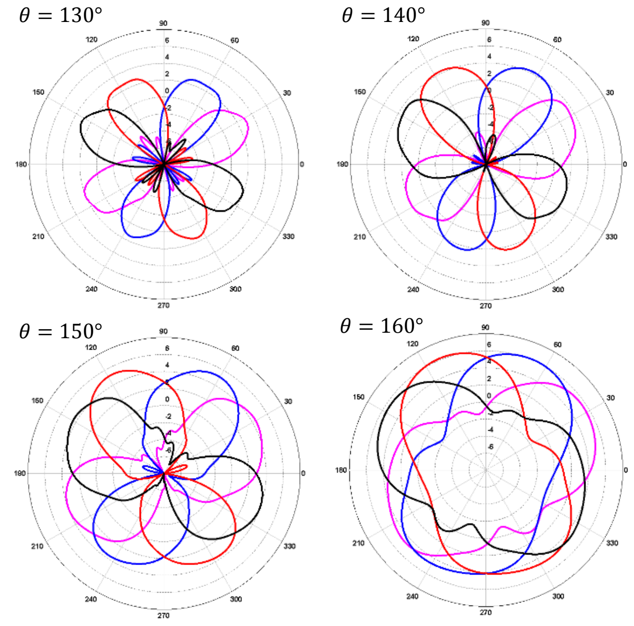

Fig. 4. Simulated 2D antenna radiation patterns (see text for explanations).

III. DoA Estimation Using PPCC Algorithm

To perform DoA estimation using the proposed reconfigurable antenna one can use power pattern cross-correlation (PPCC) method that relies on received signal strength (RSS) measurement. The method relies on the cross-correlation coefficient introduced in [19], which, after adaptation to the proposed antenna, can be written in the following vector form [14], [15]:

$$\boldsymbol{g} = \frac{\sum_{n=1}^{4}\left(\boldsymbol{p}^n\, Y(V_{max}^n)\right)}{\sqrt{\sum_{n=1}^{4}(\boldsymbol{p}^n \circ \boldsymbol{p}^n)}\ \sqrt{\sum_{n=1}^{4} Y(V_{max}^n)^2}} \tag{1}$$

where $\{\boldsymbol{p}^1, \boldsymbol{p}^2, \boldsymbol{p}^3, \boldsymbol{p}^4\}$ are the antenna's radiation pattern measured with the angular step precision 1° for the steering vectors $\{V_{max}^1, V_{max}^2, V_{max}^3, V_{max}^4\}$ in an anechoic chamber at chosen calibration plane θ_c during calibration phase before the actual DoA measurements, the symbol '∘' stands for the Hadamard product, which is element-wise product of vectors, and $\{Y(V_{max}^1), Y(V_{max}^2), Y(V_{max}^3), Y(V_{max}^4)\}$ are output power values recorded for a signal impinging the antenna from an unknown direction during the actual DoA estimation process. In consequence, each of the vectors $\{\boldsymbol{p}^1, \boldsymbol{p}^2, \boldsymbol{p}^3, \boldsymbol{p}^4\}$ contain 360 discretized antenna's radiation pattern values corresponding to discretized horizontal angles $\varphi \in \langle 0°, 359° \rangle$ and the resulting vector $\boldsymbol{g}$ will contain discretized values of PPCC cross-correlation coefficient associated with the same horizontal angles. Therefore, to find the estimated DoA angle $\hat{\varphi}$ one has to find a horizontal angle corresponding to the highest value in $\boldsymbol{g}$ [14], [15]. Additionally, because the proposed reconfigurable antenna has symmetry in the horizontal direction, to further adapt PPCC method, we propose to accept two possible solutions: $\hat{\varphi}$ and $\hat{\varphi} \pm 180°$ as it has no impact on the overall antenna performance both form the connectivity and DoA-based localization perspectives.

IV. Numerical Simulations

To verify, DoA estimation accuracy of the proposed reconfigurable mm-wave antenna, numerical simulations in Matlab were conducted. To this end, the antenna design has been simulated in Altair FEKO simulator to generate its 3D radiation patterns for considered steering vectors $\{V_{max}^1, V_{max}^2, V_{max}^3, V_{max}^4\}$ with 1° angular step precision at $62\,GHz$ As a result, 4 antenna radiation patterns $\{\boldsymbol{p}^1 = P(V_{max}^1, \varphi, \theta), \ldots, \boldsymbol{p}^4 = P(V_{max}^4, \varphi, \theta)\}$ for $\varphi \in \langle 0°, 359° \rangle$ and $\theta \in \langle 90°, 180° \rangle$, associated with four main beam directions, were generated.

In all Matlab simulations, the power of a test signal impinging the antenna has been set to $10dBm$, and the possible signal's directions have been considered with a discreet angular step equal to 10°, which is commonly used in the available literature. During simulations, for each of 36 horizontal directions of impinging signal $\varphi_t \in \{0°, 10°, \ldots, 350°\}$ and 4 elevation planes $\theta_t \in \{130°, 140°, 150°, 160°\}$, 4 output power values $\{Y(V_{max}^1), Y(V_{max}^2), Y(V_{max}^3), Y(V_{max}^4)\}$ were recorded for the steering vectors $\{V_{max}^1, V_{max}^2, V_{max}^3, V_{max}^4\}$ corresponding to the considered main beam radiation patterns. Moreover, to easily compare results with those already available in the literature, for every considered direction 10 snapshots were generated and additive white Gaussian noise has been added to all recorded output power values to generate a specific signal-to-noise ratio (SNR).

To estimate DoA of signals in the performed simulations, modified PPCC algorithm for symmetrical radiation patterns proposed in this paper has been implemented. For the test signal coming from 36 test directions within the horizontal plane, the values of estimation errors were calculated for all the considered horizontal directions $\varphi_t \in \{0°, 10°, \ldots, 350°\}$, which resulted in 36 values. From these values, total root-mean-square (RMS) error equal and precision being the maximum error value have been calculated. Such calculations has been conducted for every considered elevation plane θ_t. Moreover, cumulative error values have been calculated for every calibration plane, as they are considered the best indicator of the overall DoA estimation accuracy [15] when signals coming from different elevation planes are considered.

TABLE II

DoA Estimation Errors Obtained for the Proposed mm-Wave Reconfigurable Antenna and Modified PPCC Algorithm for Different Calibration Planes (see text for explanations).

θ_c	θ_t	RMS	prec.
130°	130°	0.44°	1°
	140°	5.17°	16°
	150°	8.95°	18°
	160°	11.83°	24°
	Cumul.	7.86°	24°
140°	130°	4.13°	9°
	140°	0.65°	1°
	150°	5.54°	14°
	160°	9.36°	20°
	Cumul.	5.83°	20°
150°	130°	6.67°	12°
	140°	4.08°	7°
	150°	0.76°	2°
	160°	6.17°	14°
	Cumul.	4.99°	14°
160°	*130°*	*6.61°*	*12°*
	140°	*3.17°*	*7°*
	150°	*3.88°*	*7°*
	160°	*1.43°*	*4°*
	Cumul.	*4.21°*	*12°*

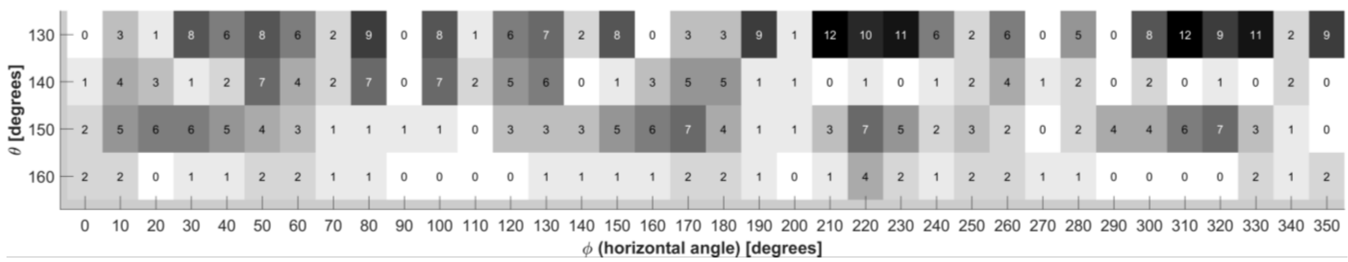

Fig. 5. Absolute values of DoA estimation errors (in degrees) obtained from measurements at SNR = 20 dB for angles in horizontal and elevation directions used in the test measurements of the proposed PPCC-based DoA estimation algorithm involving calibration plane at $\theta_c = 160°$. These values correspond to RMS and precision values in table II for the text in italic.

The results gathered for the performed simulations for different calibration planes θ_c has been gathered in table II. It is easily noticeable that the lowest DoA estimation errors appear at elevation planes, for which the calibration took place, and they tend to increase if an elevation plane is different than θ_c as, for those planes, calibration results are not well aligned with the actual antenna's radiation patterns. What is interesting, cumulative values of errors for different calibration planes have the lowest values for $\theta_c = 160°$. It means that when the DoA estimation algorithm will be calibrated using the proposed mm-wave reconfigurable antenna patterns at $\theta_c = 160°$, one obtains the most accurate DoA estimation results for signals incoming from the considered unknown elevation planes. Additionally, to visualize DoA estimation errors, the values of estimation errors calculated for all the 36 horizontal directions and for 4 considered elevation planes have been shown in Fig. 5.

V. Conclusions

In the paper, a new single-input mm-wave reconfigurable antenna that has 4 radiation patterns and can provide DoA estimation capability to simple low-cost and energy-efficient IoT nodes and gateways in future 5G systems has been proposed. Simulation results indicate, that the antenna can be used not only to increase connectivity in future mm-wave 5G networks but may also be used in DoA-based localization algorithms. Because, the patterns can be switched by 6 DIO ports controlling the shorting points of the feeding network via PIN diodes, the steering circuit of the proposed antenna can be integrated with silicon on insulator (SOI) technology known for high-performance in RF applications. This may lead to new inexpensive mm-wave integrated circuits (IC) having enhanced connectivity, adaptation and localization capabilities when installed in demanding environments.

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