5G Millimeter-Wave Wireless Communication Platform: Experimental Performance and Enhanced using Phased Array Antenna

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***Abstract*—This paper presents a millimeter-wave (mmWave) 5G communication system incorporating a phased array antenna. The testbed features a custom-manufactured planar active phased array antenna with linear polarization, housing an 8×8-element planar array BeamForming Integrated Circuit (BFIC). The 27 GHz transceiver, a prototype, is built using off-the-shelf components and engineered to upconvert signals from 3.5 GHz to 27 GHz. Furthermore, an emulation of a 3GPP-inspired gNodeB, based on the FR2 5G signal, is included. A measurement campaign was conducted in an indoor environment. Additionally, a comparison with a passive antenna was conducted for the 16-QAM modulation scheme. The obtained results support that the integration of a phased array antenna is a promising technology for the future of wireless communications.**

I. Introduction

Currently, the demand for communication services has been increasing exponentially compared with previous years [1], [2]. With the development of 5G communication networks in both Non-StandAlone (NSA) and StandAlone (SA) versions, it is expected that the growing demand can be addressed through the deployment of 5G network infrastructure.

To facilitate high-data-rate communications, 3GPP [3] has considered the millimeter-wave frequency bands (mmWaves). This vision enables 5G wireless communications, rendering mmWave frequencies a promising and advantageous choice for future cellular networks. Nevertheless, the signal experiences significantly elevated propagation losses within these frequency bands. To take advantage of the benefits of these bands by overcoming the effects of the losses, beamforming techniques are employed to focus the signal on the User Equipment (UE) using more directive and electronically reconfigurable beams [4].

In this paper, we propose a testbed for a phased array-aided 5G Communication System (5G-CS) designed to cater to the needs of UEs. We implement the physical layer (PHY) signal processing and Medium Access Control (MAC) layer for a Frequency Range 2 (FR2) 5G signal standardized by the 3GPP with signal validation using commercial equipment. Besides, a real-time practical correction of the mmWave signal through frequency and time synchronization, error correction, search Cell-ID, channel estimation, Minimum Mean Square Error (MMSE) equalization, and Low-Density Parity Check (LDPC) algorithms have been developed. Measurement campaigns are conducted in a real-world indoor environment with Non-Line-of-Sight (NLOS) and LOS propagation channels, compared to having a communication link without a phased array antenna (which is replaced by a horn antenna) considering 16-QAM modulation scheme into the data channel of the implemented FR2 5G signal.

The remainder of this paper is organized as follows. Section II presents the proposed testbed, providing comprehensive details on the phased-array antenna, mmWave transceiver, and baseband signal-processing flow. Section III discusses the design and clarification of the experimental scenario. Section IV outlines various experiments conducted to verify the Key Performance Indicators (KPIs) of the communication system. Finally, conclusions are presented in Section V.

II. Phased Array-Aided 5G Communication Testbed

In this section, an overview of our innovative 5G communication testbed, which is enhanced by phased-array technology, is provided. Fig. 1 illustrates the proposed phased array-aided 5G communication system testbed. On the gNodeB side, the PC host generates a digital FR2 5G waveform standardized by 3GPP [3], which has been implemented using MATLAB$^{\text{TM}}$ software. The host computer block is a PC with USB modem 3.0, which executes real-time PHY and MAC signal processing through MATLAB$^{\text{TM}}$ tool.

The signal processing flow of the gNodeB on the host PC is illustrated in Fig. 2. The baseband block diagram of the implemented gNodeB is delineated with a focus on three key aspects: 1) signal processing for physical, control, and data channels, 2) CP-OFDM modulation, and 3) digital upconversion. The transmitter loads data streams that were originally in a bit format. After the payload data are encoded, the Downlink Shared Channel (DL-SCH), which is defined by the 3GPP, is implemented using the LDPC channel coding chain. The PDSCH block executes the Physical Downlink Shared Channel (PDSCH) encoding. The first step is scrambling, which consists of mixing an input sequence with a pseudorandom sequence. In our testbed, we consider only one codeword per transmission. The modulation block considers

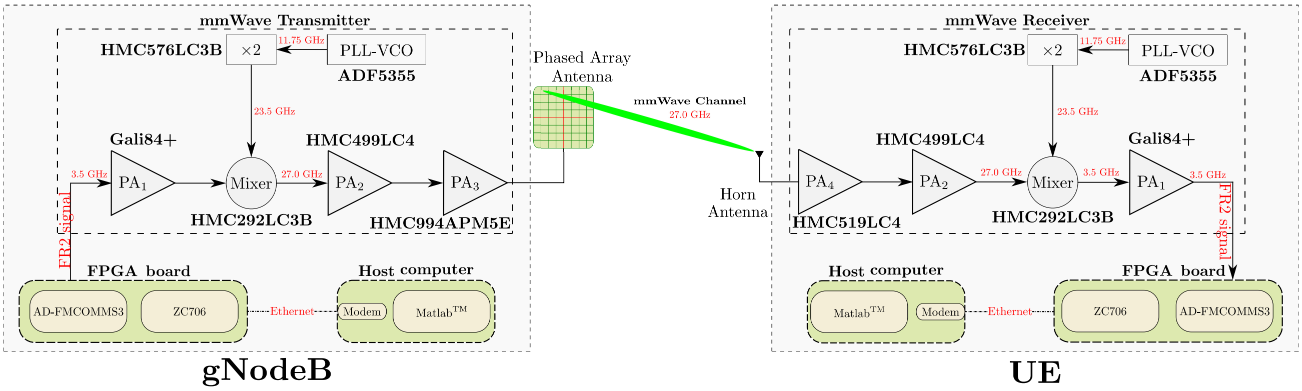

Fig. 1. Block diagram of phased array-aided 5G communication system testbed.

the modulation order, and in our proposed system, the 16-QAM modulation scheme is implemented.

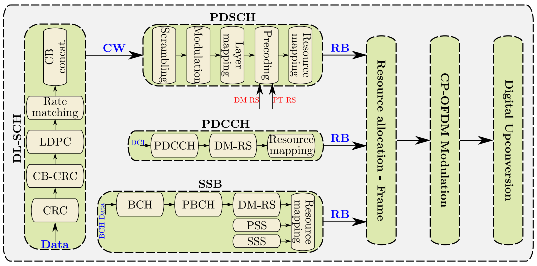

Fig. 2. Baseband block diagram of implemented gNodeB.

Furthermore, the proposed testbed introduces various practical challenges, particularly concerning the hardware implementation of the mmWave technology. Addressing this context and aligning with the 3GPP recommendations, we devised Phase Tracking Reference Signals (PT-RSs). These signals serve the crucial function of tracking the phase of the local oscillator at both the receiver and transmitter, specifically within challenging mmWave frequency bands. The following part introduces the Physical Downlink Control Channel (PDCCH) and Synchronization Signal Block (SSB) implementations using PDCCH and SSB blocks, respectively. The PDCCH block carries out the downlink control information, which allows decoding of the implemented data channel at the receiver node. On the other hand, the SSB block considers synchronization signals and the physical broadcast channel. After the payload data is encoded, resource blocks

TABLE I
MAIN PARAMETERS TO IMPLEMENT THE EMULATED GNODEB.

Parameters	FR2 5G signal
F_s	50 MHz
Carrier Frequency, f_s	27 GHz
Modulation	16-QAM
Samples Rate	61.44 MHz
Allocated RBs	32
Subcarriers × RB	12
N_{symb}^{slot}	14
Slots × Subframe	8
n_f^{μ}	80
SS/PBCH Block	slot 0
Subcarrier Spacing	120 kHz
Number of Cell ID	0

are allocated to a frame. Subsequently, Orthogonal Frequency-Division Multiplexing (OFDM) modulation is applied, which converts the frequency-domain parallel signals to time-domain serial signals. The main parameters of the FR2 5G waveform, which were implemented by considering the block diagram shown in Fig. 2, are presented in Table I.

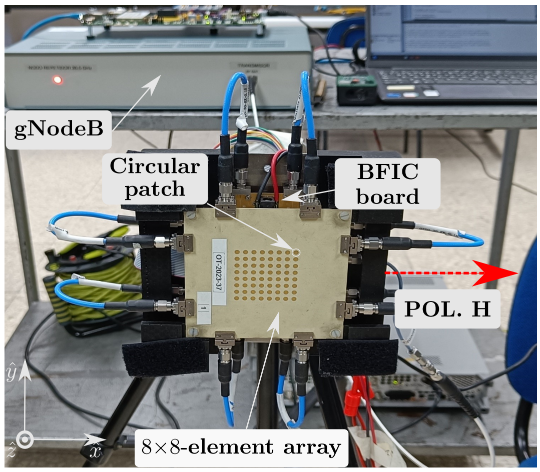

Fig. 3. 64-element linearly polarized phased array antenna prototype [6].

Along the 5G signal chain, the FR2 5G baseband signal generated by the PC host is converted to analog waveforms by the FPGA board block. The processing within the FPGA board block, the signals emerge at an Intermediate Frequency (IF) of 3.5 GHz, requiring subsequent upconversion to reach the 27 GHz carrier frequency. Our research group performed a custom-developed RF front-end transmitter to facilitate the upconversion process. The 27 GHz transmitter/receiver modules were manufactured using off-the-shelf components, allowing for easy characterization and integration into the high-level testbed. The electrical parameters of the various RF subsystems are listed in [5]. The phased array antenna, which illuminates the UE, is connected to the output of the mmWave front-end transmitter module. The phased array antenna prototype utilized in the 5G testbed proposed within this work is depicted in Fig. 3. The phased array antenna consists of a passive planar array antenna integrated with a BeamForming Integrated Circuit (BFIC). The passive part of the phased array consists of a 64-element planar array arranged in a square grid of 8×8 elements. The radiating elements are linearly polarized circular printed patches. As can be seen in Fig. 3, the linear polarization of the antenna is horizontal along the $\hat{x}$-axis. The active part of the phased array comprises a BFIC board, which allows the control of the complex feeding coefficients of the radiating elements to control the radiation properties of the integrated assembly.

For the signal reception chain, the signal processing at the implemented UE node reverts the steps undertaken in signal processing at the gNodeB. Frequency conversion from mmWave to IF was realized using a custom-developed mmWave back-end receiver module, which considers a horn antenna operating from 22 GHz to 33 GHz and providing a gain of 20 dBi. Subsequently, post-processing of the FR2 5G baseband is executed on the host computer for the signal received at the output of the FPGA receiver chain, where several algorithms for demodulating and decoding a standardized 5G signal and KPIs are implemented and obtained, respectively.

III. Indoor Propagation Environment

In this section, a brief description of the indoor scenario used to perform the measurements of the proposed 5G system is given. The selected scenario is one of the laboratories of the Departamento de Señales, Sistemas y Radiocomunicaciones (SRR) of the Universidad Politécnica de Madrid (UPM). The

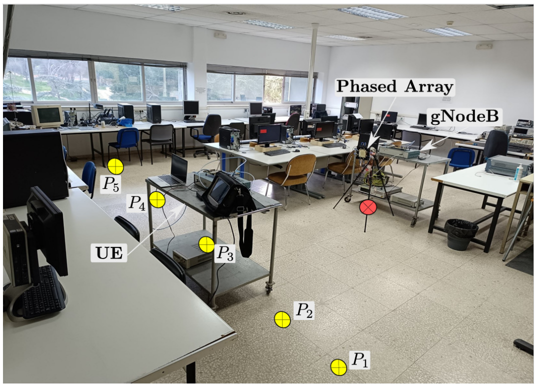

Fig. 4. Indoor Validation Scenario: Picture with the setup of the proposed 5G testbed.

size of this laboratory is $10 \times 10\ m^2$. A schematic view of the laboratory arrangement can be seen in Fig. 4. Thus, the following setup of the 5G proposed testbed is deployed:

- The transmitter gNodeB is placed at one side of the laboratory, approximately in the center of the room.
- The UE node is placed at the other side of the laboratory, at a distance d_{TR} from the gNodeB.
- The gNodeB and the UE will be at a distance of d_{TR} = 2.3 m when facing each other in a direct line of sight.
- During the experiments, the UE will progressively move in the direction perpendicular to the direct line of sight, no longer facing gNodeB and establishing an azimuth viewing angle θ between the two modules.
- Several measuring points labelled as P_n will be defined. In particular, five measurement points will be established for the experiments presented in the next section. Note that the central point, which means the measurement point with a direct line of sight between gNodeB and UE, is denoted as P_3.

Table II shows the geometric parameters d and θ corresponding to each of the five measurement points established.

TABLE II
Distance and azimuth viewing angle between gNodeB and UE corresponding to each of the five measurement points in the indoor scenario.

Meas. point	**Distance** (d_{TR})	**Viewing angle** (θ)
P_1	3.6 m	$-50°$
P_2	2.7 m	$-30°$
P_3	2.3 m	$0°$
P_4	2.7 m	$30°$
P_5	3.6 m	$50°$

IV. Experimental Results and Discussion

This section comprehensively presents and analyzes all of the experimental results outlined in this work, providing a detailed examination that validates the performance of the proposed testbed. We offer a comparative analysis with a 5G communication system without a phased array antenna (which is replaced by a horn antenna), showing the advantages of the phased array in the communication system.

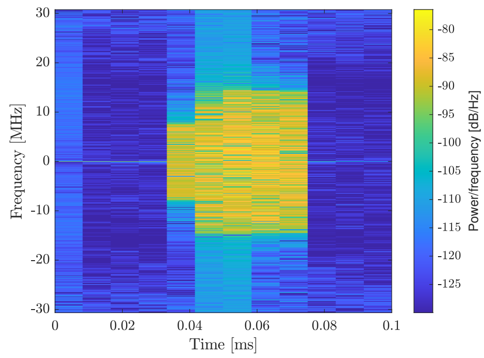

Fig. 5. Representation figure illustrating the detected SSB when considering the proposed phased array-aided 5G communication system at P_1.

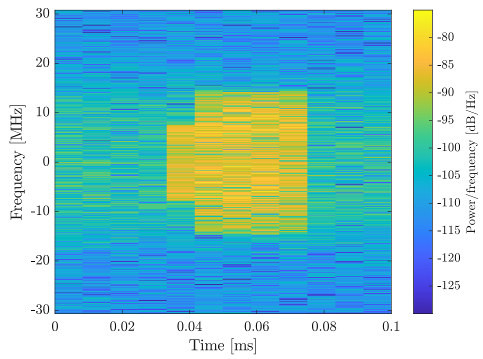

Fig. 6. Representation figure illustrating the detected SSB when considering a horn antenna in transmission in the 5G communication system at P_1.

Fig. 5 depicts the spectrogram illustrating the detected SSB, transmitted by the gNodeB to start the initial communication with the UE node. This corresponds to receiver position 1 (P_1) in the indoor validation scenario, as shown in Fig. 4. For comparison, we introduced a 5G communication system with a horn antenna for transmission; therefore, the SSB detected by the UE node in P_1 is shown in Fig. 6. Based on the figures, it can be concluded that the transmitted signal when considering the horn antenna suffers from higher loss propagation. However, the proposed phased array-aided 5G communication gradually increases the received signal power. Note from Fig. 5 that the noise over and around the SSB detected is considerably low in comparison with the achieved with a horn antenna.

Fig. 7 illustrates the reached throughput of the proposed mmWave phased array-aided 5G communication system considering the 16-QAM modulation scheme over the data channel. It can also be noticed that a curve taking into consideration a 5G-CS testbed without the phased array has been presented as a comparison. The results clearly indicate that the proposed phased array testbed consistently attained the maximum throughput across all viewing angles for both modulation schemes. These achieved capacity peaks align

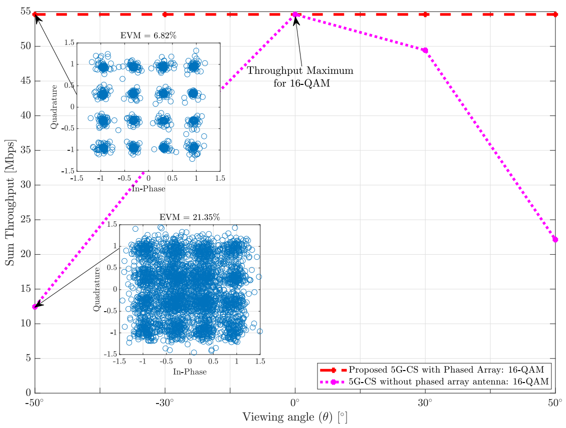

Fig. 7. Throughput performance comparison of the proposed 5G-CS testbed with the phased array antenna.

with the throughput maxima specified by the 3GPP for the FR2 5G, as emulated in the implemented gNodeB. From Fig. 7, it is evident that the sum throughput of the 5G-CS without the phased array experiences a notable performance decline for $\theta = [-50°, -30°, 30°, 50°]$. This degradation can be attributed to the fact that in these positions, the radiation patterns of the transmitter and receiver antennas are not aligned in the front direction. As an illustration, when considering the 16-QAM modulation scheme and $\theta = -50°$, the minimum throughput recorded was approximately 12.16 Mbps, representing a system capacity loss of 77.73%. Finally,

TABLE III
BLER PERFORMANCE FOR THE PROPOSED TESTBED.

Modulation Scheme	-50°	-30°	0°	30°	50°
With phased array	0	0	0	0	0
Without phased array	0.77	0.17	0	0.09	0.60

a comprehensive Block Error Rate (BLER) comparison is presented in Table III, clearly illustrating the superior robustness performance of the proposed testbed in comparison to the 5G communication system without the phased array antenna. Consequently, for all measured viewing angles, the BLER remains at 0 for the bits examined in the proposed mmWave phased array-aided 5G communication system.

V. CONCLUSIONS

This paper outlines a proposed mmWave phased array-aided 5G communication testbed operating in the 27 GHz band. The testbed incorporates real FR2 5G signal implementations adhering to 3GPP standards, coupled with RF front-end integration. The testbed is evaluated in a real indoor environment, and a comparative analysis with 5G-CS without a phased array antenna is introduced. The experimental findings demonstrate that the proposed communication system testbed, featuring a phased array antenna, is a 5G/6G enabler. The results obtained were validated using commercial equipment and showed a consistent agreement between them. In addition, when the proposed phased array-aided 5G communication system testbed is evaluated, the throughput for each receiver point reaches the maximum with a 0% error rate. Finally, our efforts in this article represent a starting point in showing the practical feasibility and potential of a phased array-aided 5G communication system built upon a real FR2 5G signal.

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