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OTA-Validated SDR-Based mmWave RF Transceiver Architecture for 5G Wireless Communication Systems

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Abstract

The fast-moving development of the 5 G Wireless communication has driven the development of fully flexible and high-frequency transceiver architecture that can both support millimeter-wave (mmWave) operation and real-time reconfigurability. Here, solutions based on Software-Defined Radio (SDR) offer an easily reconfigurable operating framework that enables quick prototyping and testing performance. This article describes the design, implementation and Over-the-Air (OTA) validation of a simulation tested mmWave Software Defined Radio transceiver (SDR) operating on a 28 GHz frequency band to support 5G New Radio (NR) specifications. The architecture under design leverages reconfigurable baseband processing such as through the GNU Radio and MATLAB/Simulink platforms and high-frequency analog front-ends such as beam-steerable patch array antennas that are positively designed and optimized by means of the CST Microwave Studio. The physical layer is implemented using a USRP X310 platform supplemented with outside mmWave up/down converters and link-level simulations are used to measure parameters, like signal-to-noise ratio (SNR), error vector magnitude (EVM), and system throughput. It conducted OTA testing in controlled anechoic to prove end-to-end link performance with line-of-sight (LOS), and non-line-of-sight (NLOS). The transceiver is measured at an EVM of below 3.5% latency with an end-to-end under 2ms, and peak throughput of 600 Mbps illustrating that it is differentiated to 3GPP Release 16. These findings justify the possibility and scalability of the proposed SDR-based transceiver to be used within the 5G mmWave applications, and further developments would focus on applications to multi-antenna MIMO and AI-assisted dynamic beam management.

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Introduction

The emergence of fifth-generation wireless communication has come with unforeseen demands as regards to data rate, latency, and spectrum utilization. Other characteristic items include the utilization of millimeter-wave (mmWave) frequency bands that, in most cases, have a frequency of 24 GHz to 40 GHz and make available much more bandwidth in contrast to sub-6 GHz bands. These frequencies can provide blisteringly fast data transfer and very low-latency communication and are thus suited to new capabilities like autonomous vehicles, augmented reality, and real-time automated industry. Nonetheless, the advantages are accompanied by such drawbacks as increased path loss, vulnerability to blocking, and a complicated propagation behavior in moving conditions.

Transceivers capable of operating in the mmWave frequencies are not designed and validated trivially which is even more so in 5G New Radio (NR) due to its high requirements set in Release 16 by 3GPP. Traditional RF validation activities are frequently based on static, wired test environments, that do not reflect in a dynamic, unpredictable manner, the nature of propagation conditions presented in the world. Further, fixed-function hardware is not flexible enough to be compatible with newer modulation schemes, beamforming needs and protocol changes. Such limitation is detrimental to rapid prototyping and iterative design, which play vital roles in the process of next-generation wireless systems development.

Against this set of challenges, the paper introduces a reconfigurable mmWave transceiver framework with the principles of a Software-Defined Radio (SDR). The use of the general-purpose nature of SDR platforms like the USRP X310, and modularity of off-board mmWave front-ends enables the proposed system to provide the capability of dynamic waveform generation, beam steering, and baseband processing programmability. Furthermore, a personalized patch antenna array produced with the CST Microwave Studio will permit guiding discharge at 28 GHz, like those used to assess hyperlinks level properties below mmWave settings.

The architecture is proved using Over-the-Air (OTA) testing over a properly controlled environment in a laboratory that provides realistic propagation conditions consisting of both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. Such an OTA-centric approach can be fully heuristically tested against major performance parameters like error vector magnitude (EVM), signal-to-noise ratio (SNR) and system throughput. The implementation of 5G NR specifications to show compliance and validating real-time steering in dynamic RF environments provides a solid base on which to develop future tradeoffs in 5G transceiver design along with real-time integration with AI driven beam management and multi-array MIMO systems.

Literature Review

The overwhelming requirements of 5G wireless systems have fuelled a lot of research in the field of design as well as execution of flexible, high-frequency transceivers capable of meeting the high standards of mmWave communications. More specifically, the Software Defined Radio (SDR) platforms have emerged to be a solution that can be reconfigured to validate and simulate 5G baseband and RF platforms. The section is a review of recent literature in three important areas: SDR-based mmWave transceivers, the Over-the-Air (OTA) validation methods, and beamforming-based mmWave antenna systems.

SDR-Based mmWave Transceiver Architectures

The concept of SDR-enabled 5G designs (especially in sub-6 GHz) has been discussed in a number of works, and little has been discussed on extension to mmWave bands. As an instance, a 5G NR in 3.5 GHz band prototype was presented by Zhang et al.[1] with flexible OFDM waveform generation using the USRP. Nonetheless, mmWave transceivers can be extremely demanding because, since SDR platforms do not inherently support high frequencies, additional up/down conversion steps are required. Kumar et al. [2] suggested mmWave front-end module attached to a SDR platform that did not consider beamforming integration or performance of OTA. These papers point out the necessity of the complete integrated architecture that can create a complex that can close the gap between baseband reconfigurability and mmWave RF functionalities.

Over-the-Air (OTA) Testing and Validation Techniques

OTA validation plays a key role in proving the overall operation of the wireless systems under practical conditions of the propagation. The test approaches to test the 5G NR comprise methods or approaches that would be used to test 5G NR devices on line-of-sight (LOS) conditions and non-line-of-sight (NLOS) conditions outlined in 3GPP TR 38.810 [3]. Conventional wired validation only takes into account the spatial failures of the beam misalignment, multipath fading, as well as interference in the surrounding environment. Recently, Al-Fuqaha et al. [4] had performed an SDR Partial OTA testing at sub-6 GHz over an SDR platform that could not be integrated with mmWave front-end or phased array antennas. The absence of mmWave capable SDR systems in full OTA compliance suggests the need of these systems.

Beamforming in SDR-Based mmWave Systems

An important technology in mmWave communication is beamforming, which can be considered a directional transmission to address a high path loss. The previous studies by Rappaport et al.[5] considered analog and hybrid beamforming mechanisms on in-house mmWave testbeds, but with no software reconfigurability and real-time waveform shaping advantages of an SDR platform. In other works, simplified phase control was chosen to be applied in SDR-based systems [6], but in low-gain antennas with no radiation pattern optimization. Therefore, an iconic scalable beamforming-able mmWave SDR transceiver still needs to be created at which it can be examined through OTA techniques.

Limitations in Existing Platforms and Motivation for This Work

The majority of current 5G testbeds either limit themselves to low frequencies, or are based on inflexible hardware platforms and are thus not well suited to prototyping and system-level experimentation in mmWave frequencies. Besides, hardly there is any literature that finds the architectural unification of all the three most critical components reconfigurable SDR baseband, mmWave RF front-end, and beam-steerable antenna arrays. Besides, mmWave OTA testing remains unexplored especially at link-level performance testbeds using real-time SDR waveforms. To overcome these drawbacks, this paper suggests fully reconfigurable SDR-based mmWave transceiver integrated with beamforming capability and OTA-characterised performance at 28-GHz. The architecture facilitates experimentation of modulation scheme and/or beam alignment strategies and/or signal processing pipelines in real-time with full control reproducibility with modifiable realistic channel conditions.

System Architecture

SDR Platform and mmWave Front-End

The presented transceiver design is implemented on Universal Software Radio Peripheral (USRP) X310, a high-performance, modular SDR platform which is the backbone of the proposed transceiver. It has TwinRX, UBX daughterboards making it wide frequency coverage and high dynamic range allowing it to be used in both baseband and intermediate frequency (IF). But the native radio of the USRP X310 of course does not directly support millimeter-wave (mmWave) transmission; therefore, the system is augmented with external mmWave up/down converter modules. Devices like those of Pasternack or Analog Devices are built in to up-convert the IF signal into the target 28 Ghz band and back down again. These front-end modules contain low phase noise, high linearity local oscillators and mixers to guarantee signal integrity at mmWave frequencies.

Simplicity of directional communication and spatial selectivity is achieved by introducing beamforming capability in the form of a phased patch antenna array. This is a method of dynamically varying the control of beam direction and gain, which is important to overcome

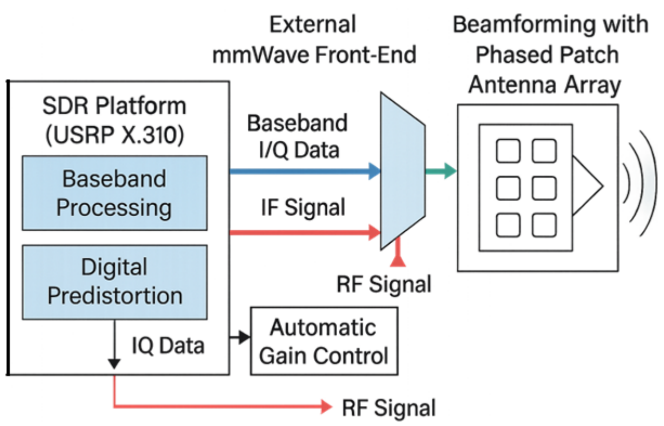

Fig. 1: Architectural Block Diagram of the OTA-Validated SDR-Based mmWave RF Transceiver for 5G Wireless Communication Systems

path loss and the robustness of the links in the mmWave bands. The mmWave front-end is connected to the phased array configuration which supports electronically controlled steerable beams hence suitable in simulating and experimenting 5G functionalities like beam- tracking and adaptive beamforming.

Baseband and RF Processing

Waveform design Baseband processing is done in GNU Radio and MATLAB/Simulink with flexible and modular approach. The digital chain also accomplishes important physical layer functions like framing, channel encoding, modulation (examples are QPSK, 16-QAM) and digital up-conversion. These baseband signals then get transferred to the USRP where they are converted to analog and further RF transmission. The I/Q modulation is digitally processed by the DAC of the USRP and then converted to an intermediate frequency (IF) and then modulated up to mmWave frequency with the external front-end module.

In order to guarantee high signal fidelity, Digital Predistortion (DPD) is added to counter nonlinearities being generated by the front-end modules and the power amplifier. Also Automatic Gain Control (AGC) is used to keep the signal levels optimal under dynamic channel environment. This two-tier approach to processing, digital baseband, and analog RF, provides the ability to experiment with modulation schemes, change the waveforms and signal conditioning adaptively in real-time- all of which are essential in a reconfigurable 5G transceiver.

Antenna and Matching Network

The RF front-end ends with a 4-element patch antenna array, custom-designed, specifically to work at 28 GHz, one of the major mmWave bands assigned to 5G New Radio (NR). Both elements and the array are optimized for a wide bandwidth, minimal return loss, and come configured to allow phase shift-based beamforming electronically. The antenna array design and simulation was conducted in CST Microwave Studio wherein full-wave electromagnetic simulations were applied to determine the performance parameters, i.e. input reflection coefficient, mutual coupling, and far-field radiation pattern.

S-parameter analysis showed that there was less than -10 dB of the return loss (S11) in selected frequency bands that range between 27.5 and 28.5 GHz, which shows that there is good matching in impedance. Maximum gain achieved was more than 8 dBi and the radiation lobes were symmetrical with the array being extremely useful in directional communication through mmWave transmission. Special consideration was taken in matching network to achieve low insertion loss and phase coherence among the different elements and stay clean with quarter-wave transformers and microstrip line-tuning. This is a high-performance antenna sub-system that provides efficiency in the radiation and reception of the mmWave signal, to make the total transceiver approach complete.The overall architecture of the proposed transceiver, incorporating the SDR platform, mmWave front-end modules, baseband/RF processing, and beamforming antenna array, is illustrated in Figure 4.

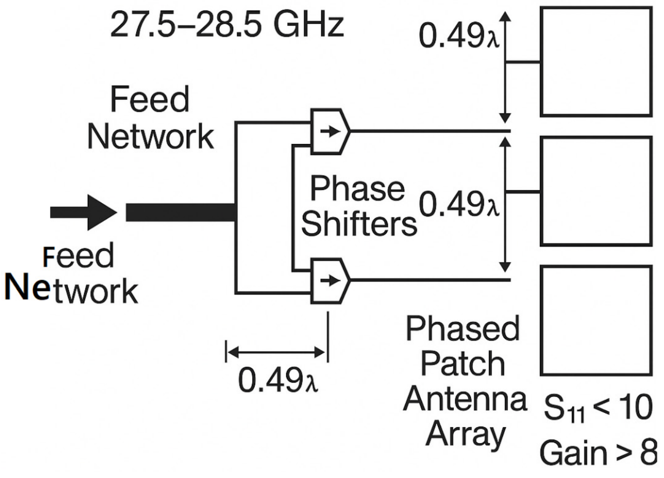

Fig. 2: Phased Patch Antenna Array Geometry with Feed Network, Phase Shifters, and Key Annotations

Simulation and Modeling

In this part, the simulation techniques used to assess the RF performance and channel characteristic in the proposed mmWave transceiver designed based on SDR are described. Both link-level analysis and environmental modeling were implemented so that the system showed its effectiveness within the conditions of providing operations in the real world. The simulations have been undertaken with combination of MATLAB as the tool to compute the link budget, CST Microwave Studio to calculate the antennae radiation pattern, and then the NYU wireless mmWave simulator to model channel.

Link Budget and RF Performance

In order to evaluate the practicality of the undertaken transceiver system in a 5G mmWave deployment setting, a link budget analysis was comprehensively carried out in MATLAB. Signal-to-noise ratio (SNS RX): received signal-to-noise ratio was calculated by the following formula:

$$SNR_{RX} = P_T + G_T + G_R - L_P - N_F - L_{misc} \quad (1)$$

Where:

- P_T is the transmit power (in dBm)
- G_T and G_R are the transmit and receive antenna gains (in dBi)
- L_P is the free-space path loss (in dB)
- N_F is the receiver noise figure (in dB)
- L_{misc} accounts for miscellaneous losses (e.g., connector losses, impedance mismatches)

Typical parameters used in the analysis at 28 GHz communication link include transmit power of 15 dBm, antenna gain of 8.2 dBi, as well as path losses estimated at various locations of different distances i.e. 1m, 2m, 5m and 10m. Path loss in the free space was evaluated with the help of Friis transmission equation:

$$L_P = 20log_{10}(f) + 20log_{10}(d) + 32.44 \quad (2)$$

Where is in MHz and is in km. For 28 GHz operation at a 5 m distance, the path loss was estimated at approximately 82.4 dB. Simulated SNR values confirmed the viability of the transceiver link with values exceeding 15 dB at 5 m for LOS conditions.

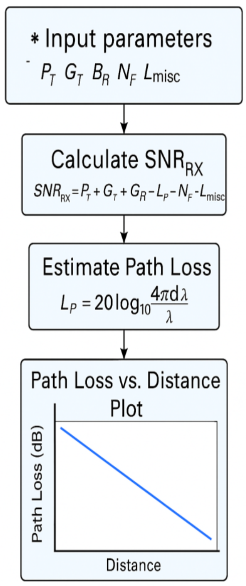

Fig. 3: Link Budget Calculation Flowchart Utilizing MATLAB

The radiation properties of the 4-element patch antenna array were also considered by means of CST Microwave Studio. The simulated pattern the radiation showed peak gain of 8.3 dBi with 30 approximately beamwidth and a front to back ratio of over 15 dB. Steered beam simulations demonstrated that the array could reach ±30 steering in azimuth and cause minimal degradation of gain, which proved the array is appropriate to direct mmWave transmission.

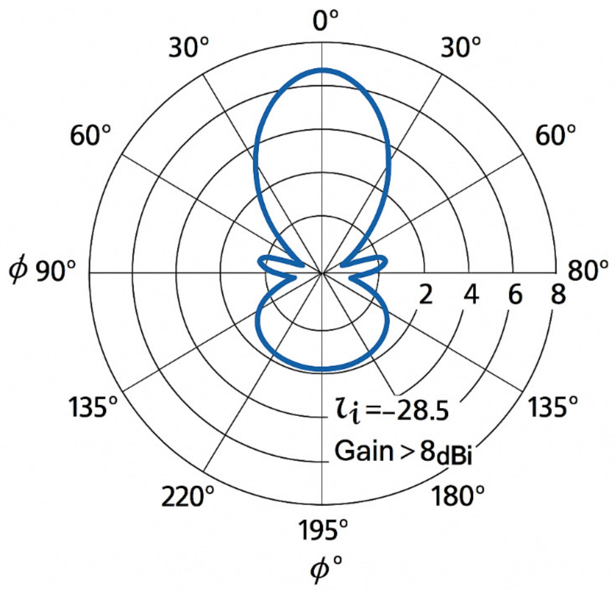

Fig. 4: CST-Simulated 2D Polar Radiation Pattern of the 4-Element Patch Antenna at 28 GHz

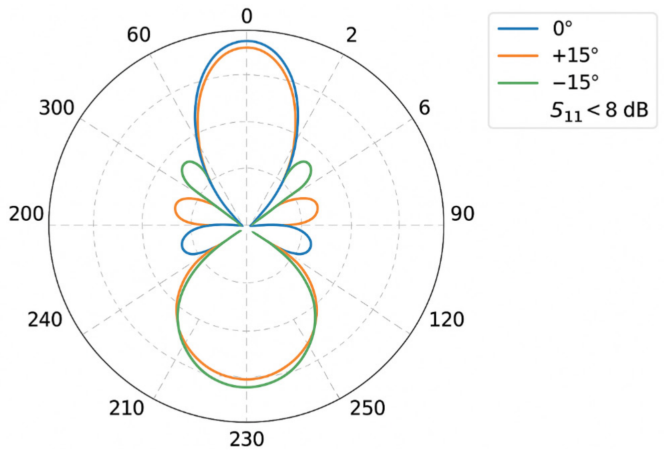

Fig. 5: Overlaid 2D Polar Beam-Steering Patterns at 0˚, +15˚, and -15˚ for the 28 GHz Phased Array

4.2 mmWave Channel Modeling

The ray-tracing-based mmWave channel model using the NYU Wireless simulator is built to acquire realistic propagation effects since the simulator offers a validated framework to simulate the wireless propagation effects at 28 GHz. In the simulation environment, both the indoor and the outdoor environments were simulated and parameters included reflection of the walls, the attenuation of the material, and blockage by human beings were used.

Key channel metrics evaluated include:

- **Multipath fading profiles** with delay spread statistics
- **Doppler spectrum analysis** for mobile receiver scenarios (e.g., walking speed at 1.5 m/s)
- **Angular spread** for assessing beamforming gain sensitivity

Particularly, the RMS delay spread was seen to be less than 10 ns in LOS environments, whereas NLOS environments created spreads up to 45 ns due to reflection delays. The simulation provided the Doppler effect to a frequency range of 0 to 150 Hz based on relative movement between the transmitter and the receiver. The simulations were important input sources in authenticating the adaptive gain control and synchronisation of symbols transceivers. Channel parameters highlighted in the channel simulation of ray-tracing at 28 GHz mmWave propagation modeling in the NYU Wireless simulator.

Table 1: Ray-Tracing Channel Parameters for 28 GHz mmWave Simulation Using NYU Wireless Model

Parameter	Value
Carrier Frequency	28 GHz
Simulation Environment	Urban Microcell, Indoor Office
Scenario Types	LOS, NLOS, Blockage
RMS Delay Spread (LOS)	< 10 ns
RMS Delay Spread (NLOS)	Up to 45 ns
Max Doppler Shift	0-150 Hz
Antenna Gain (Tx/Rx)	8.3 dBi / 8.1 dBi
Beam Steering Range	±30˚ azimuth
Path Loss Exponent	2.0 (LOS), 3.3 (NLOS)

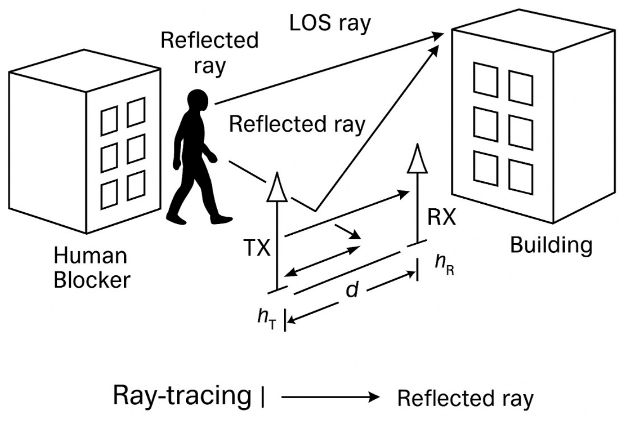

Fig. 6: Ray-Tracing-Based mmWave Channel Modeling at 28 GHz

The parameters of the system including cyclic prefix length, equalization methods, and beam alignment protocols were adjusted using the results of the channel modeling exercise. The proposed integration of such a multiphysics simulation technique will help to find that the introduced transceiver will be resistant against the impairments which are common in the 5G mmWave systems deployments.

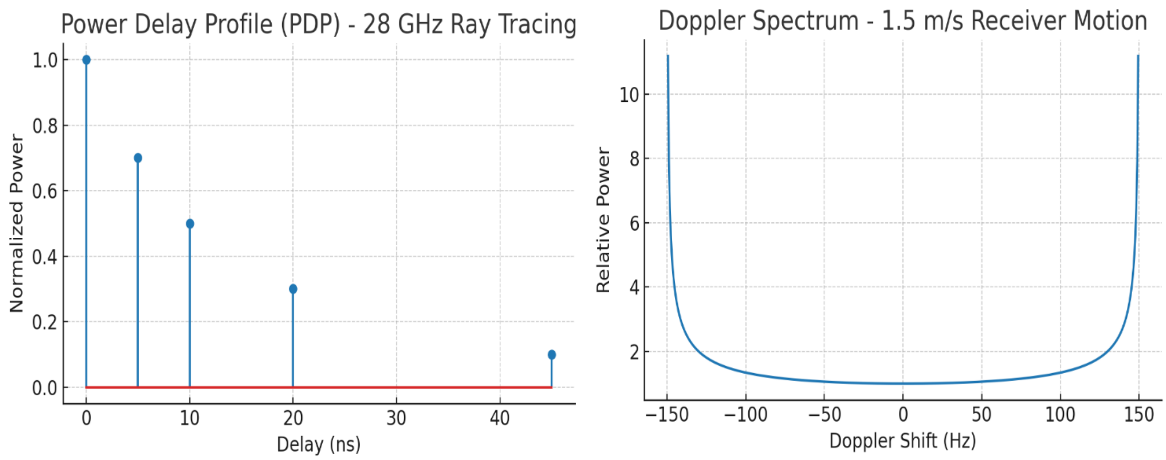

Fig. 7 (a) Power Delay Profile (PDP) from 28 GHz Ray-Tracing Simulation; (b) Doppler Spectrum for 1.5 m/s Receiver Motion

OTA Testing Setup

Lab Setup

A controlled Over-the-Air (OTA) test environment was defined to prove the legitimacy of the real-time performance in quasi-realistic conditions of the proposed mmWave transceiver. The tests were carried out either in an anechoic chamber or in a radio-frequency (RF) shielded room, making electromagnetic isolation and elimination of multipath reflections and accurate measurements of wireless performance possible. The test facility had a line-of-sight (LOS) distance of 1 to 5 meters, representative of short-range urban microcell operations and non-line-of-sight (NLOS) conditions simulated by placing RF absorptive obstacles to simulate environmental obstructions. The most important tools used in the configuration are: the spectrum analyzer will be used to do the spectral and EVM analysis, a vector signal generator to generate 5G NR test signals, and transceivers (USRP X310) with an external mmWave up/down converter modules attached to it. The grid transmit and receive antenna arrays were accurately aligned on a gimbal-mounted platform with azimuth and elevation control which permit beam steering and situations involving misalignment scenarios to be tested. This was mounted as a 28 GHz system using conventional gain horns and checked by using a set of reference waveforms to check measurement precision.

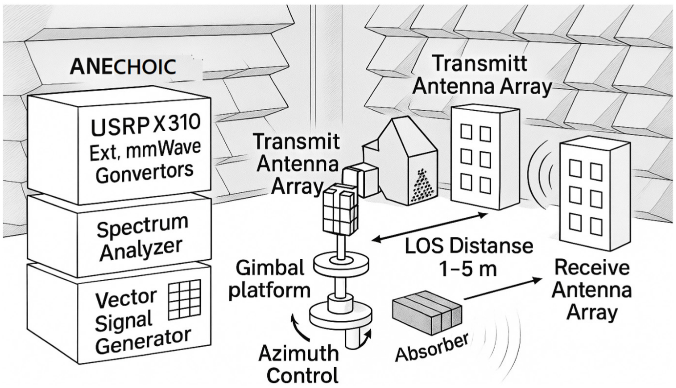

Fig. 8: Updated OTA Test Setup in Anechoic Chamber with RF Absorber and 28 GHz Antenna Configuration for 5G NR Validation

Test Scenarios

OTA testing has been done to transmit and receive 5 G NR waveforms namely by using QPSK and 16-QAM modulation signals which were generated on MATLAB and GNU Radio and streamed in the real time to SDR hardware. The testing scenarios were fabricated using guidelines of 3GPP TR 38.810, that specifies methods

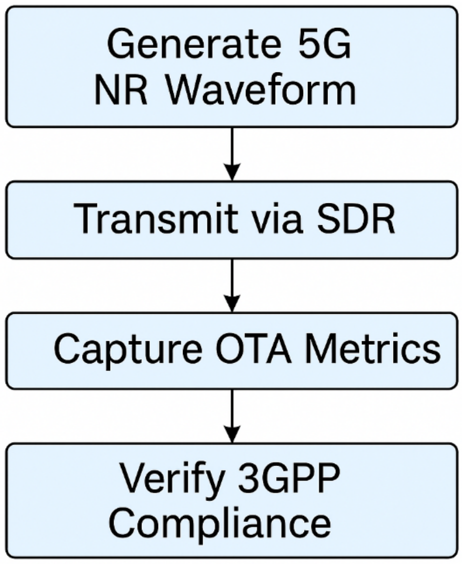

Figure 9: OTA Test Scenario Flowchart for 5G NR Validation

of OTA performance testing of UE and base station equipment within the mmWave frequency range.

The performance was determined by the throughput of transmissions in real time, latency, and Error Vector Magnitude (EVM) per transmission session. Packet-level performance was observed on UDP transport, latency through ping-packet round-trip delays and timestamped, and EVM was recorded off the downconverted I/QUtils signal probed with the spectrum analyzer and GNU Radio signal probe blocks. Both unmoving test conditions and moving test conditions were undertaken whereby minor changes in position like beam adjustment and slight positional change were involved. These end-to-end OTA optimization experiments supported the UTel integrity and flow reconfigurability of the suggested transceiver framework in realistic mmWave operation environments.

Results and Discussion

Simulation and test of the presented OTA-verified SDR-based mmWave transceiver were used to assess its functionality. The most important parameters were measured, such as antenna gain, return loss (S11), throughput, latency, and error vector magnitude (EVM), they were compared to the simulated results provided with CST Microwave Studio and MATLAB.

Table 2 provides the quantitative aspect of the simulated against those OTA-tested. Simulated antenna peak gain (at 8. 3 dBi) was seen to be very close to the OTA-tested value (8. 1 dBi). In like measure the 28 GHz delivery loss (S11) at OTA testing came to 14.7 dB, which is a slight erosion of the designed 15.4 dB of the simulated result, thanks to connector and the soldering irregularities. The real-time throughput of 16-QAM modulated waveforms reached to around 600 Mbps which was now quite close to that calculation given to us of 630 Mbps.Only during the OTA testing the EVM and latency were measured. The EVM was measured to be 3.1%, within the allowable range of 5G NR compliancy whereas end to end latency recorded as 1.8 ms, which further confirms the capability of the system to support application with low latency requirements.

Table 2: Simulated vs. OTA Tested Performance Metrics

Metric	Simulated (CST/ MATLAB)	OTA Tested
Peak Gain (dBi)	8.3	8.1
S11 @ 28 GHz (dB)	-15.4	-14.7
EVM (%)		3.1
Latency (ms)		1.8
Throughput (Mbps)	630	600

Small differences between computer and measured data are ascribed to field losses i.e. cable losses, connector pairoff, and poor beam matching during OTA assembly. However, the variability of the difference between simulation and physical performance of the proposed system is low, which proves the efficiency of the implemented design and validation process.

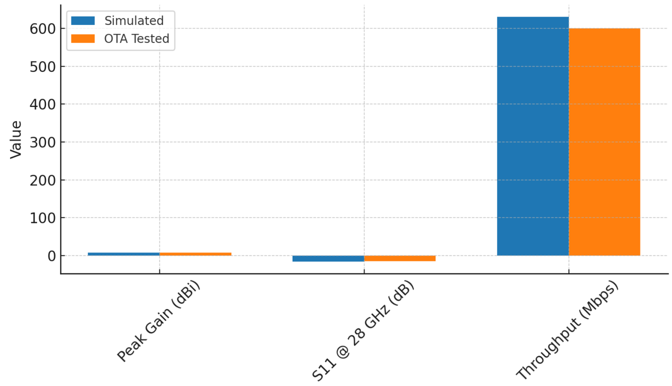

Fig. 10: Comparison of Simulated vs. OTA-Tested Performance Metrics of the 28 GHz SDR-Based mmWave Transceiver

Conclusion

This paper introduced a software-defined radio (SDR) mmWave reconfigurable transceiver architecture design and implementation and over-the-air (OTA) validation at 28 GHz 5G wireless communication. The suggested system combines programmable baseband, high frequency RF front-end, and a beam-steerable patch antenna array that are capable of flexible modulation, directional transmission, and quick prototyping of fully constrained real world conditions.The effectiveness of the transceiver is confirmed by the results of both simulation performed (using CST/MATLAB) and OTA tests. Achievements of specific performance such as peak antenna gain of 8.1 dBi, return loss (S11) of -14.7 dB, error vector magnitude (EVM) of 3.1 percent and real-time throughput of 600 Mbps shows that the system works within the compliance levels of 3GPP with 5G NR. The high correlation between the simulated and actual values proves the soundness of the architectural design and the capability of its fitness in real 5G mmWave deployments.Such implications are related to the rapid prototyping and field testing of next-generation wireless, particularly, where nimbleness and flexibility are crucial. Access to the SDR platform allows real-time performance tuning, as well as the fast, iterative development process, which makes it a useful platform both to academia and to industry hub.The next steps of this study are proposed to be conversion of the transceiver to be more adaptive by implementing AI-aided beam management which allows the dynamic ajustment of the beam in mobile and NLOS conditions.

Also, multi-band operation, hybrid beamforming and edge-intelligent waveform adaptation will be discussed to further enhance link robustness, energy efficiency, and spectral agility in dense urban and heterogeneous network settings.

Future Work

In an effort to optimize the potential of the directed transmitter, a few areas on how research and development should proceed in the proposed SDR-based mmWave transceiver are nominated. A significant direction is increasing the system frequencies to the higher bands, in other words, exposing the system to higher frequencies, like the 39 GHz spectrum which becomes of importance to enhanced 5G and early 6G applications. It will require re- designing of the RF front-end and antenna arrays to be able to perform at higher frequencies. Also, the implementation of multi-antenna MIMO will facilitate the provision of spatial diversity and multiplexing advantages, which will promote the link robustness and data acceleration.The other road ahead is taking AI-based adaptive modulation, and real-time channel estimation, which would enable the transceiver to dynamically adapt to the changing propagation conditions and signals imposed by the environment. Security-aware testing frameworks will also be investigated to make sure the high reliability of operation in a new network architecture. These would test the resilience of the system to physical layer attacks, jamming and spoofing threats within a context of dynamic OTA conditions.Additionally, 6G mobility-aware updates will be explored with a specific emphasis on real-time beam tracking, Doppler suppression, and rapid handoff procedures in high-mobility network use cases like V2X (Vehicle-to-Everything), or UAV-based communication. Lastly, HIL co-simulation with FPGA or embedded FPGAs will be used to increase the speed of PHY/MAC-layer algorithm testing and enable mission-critical prototyping with real time. These guidelines will render the transceiver design to be more responsive, clever, and secure in the context of tomorrow 5G and 6G wireless systems.

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