NJRFCS
National Journal of RF Circuits and Wireless Systems, ISSN: 3107-6807 Vol. 3, No. 2, 2026 (pp. 1-9)
RESEARCH ARTICLE
ECEJOURNALS.IN

OTA and Hardware-in-the-Loop Testing of an SDR-Based RF Transceiver for 5G Applications

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KEYWORDS:
5G
Transceiver,
Software-Defined Radio,
OTA Testing,
Hardware-in-the-Loop,
USRP, mmWave,
Beamforming,
3GPP Compliance,
SDR Testbed.

ARTICLE HISTORY:
Submitted : 12.07.2025
Revised : 17.08.2025
Accepted : 13.11.2025

https://doi.org/10.17051/NJRFCS/03.02.01

Abstract

Being a fast-growing sphere of wireless communication where 5G reinvents the roadmap, the router of Software-Defined Radio (SDR)-based RF transceiver performance has been of great importance in demonstrating the efficacy of conventional systems and their readiness in meeting the strict standards as expected in the deployment process. Standard RF test techniques usually do not emulate the elaborate, dynamic propagation environments emblematic of 5G trials, especially those associated with the sub-6 GHz frequencies, along with millimeter-wave (mmWave) range. In order to fill this gap, this paper presents an overview of an end-to-end Over-the-Air (OTA) and Hardware-in-the-Loop (HIL) testing system that can combine real-time signal generation, adaptive feedback and channel emulation to test RF transceivers based on SDR technology. The test system is based on Universal Software Radio Peripheral (USRP) X310 platforms to test sub-6 GHz and National Instruments mmWave transceiver platforms to test 28 GHz. The OTA tests are made in both types of testing rooms viz. the anechoic room and reverberation rooms to characterize the system performance within the optimal environment and a multi-path environment. The HIL element, meanwhile, will utilize real-time FPGA based feedback loops that interface with the LabVIEW and MATLAB/Simulink-based environments to test closed-loop communication under closed-loop channel, user mobility and scenario interference by relying on simulated dynamic channel models. The key performance indicators such as Error Vector Magnitude (EVM), Bit Error Rate (BER) and Spectral Emission Compliance and the Beamforming Latency are measured and analyzed with reference to the 3GPP TS 38.104 standard. Findings show that the integrated testbed is an excellent way to capture the responsiveness of the transceiver to changes in the environment, real-time beam-steering, and adaptive modulation and coding scheme validation. Not only the proposed testing plan shortens the validation time, but the accuracy of the prototyping is improved and this testing procedure may be scaled to any complexity while still being cost-effective to test 5G and up-and-coming 6G transceivers before being deployed. The proposed research will also provide a useful validation process to filler the gap that exists between theoretical development of SDRs and practicality in real world performance testing thereby speeding up the realization of intelligent and reconfigurable wireless front-end systems for next generation communication networks.

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How to cite this article: Bosco RM, Jarhoumi EF. OTA and Hardware-in-the-Loop Testing of an SDR-Based RF Transceiver for 5G Applications. National Journal of RF Circuits and Wireless Systems, Vol. 3, No. 2, 2026 (pp. 1-9).

Introduction

Mobile communication has come to a critical point, as fifth-generation (5G) wireless has been deployed, and is being constantly improved. In contrast to those older generations, 5G should be able to handle such other services as ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC) together with the usual provision of mobile broadband services. These new types of services require a heightened degree of service performance in the coverage of data throughput, latency, spectral efficiency and reliability. The design and verification of highly capable radio frequency (RF) transceivers is the key that facilitates such advanced functionalities where they need to transparently work across a broad spectrum range such as sub-6 GHz and millimeter-wave (mmWave) bands. In order to overcome these challenges, Software-Defined Radios (SDRs) are the new form of flexible and programmable platform, which provides an opportunity to carry out at high rates prototyping, algorithm development, and system test to next-generation wireless applications.

Nevertheless, to verify that SDR-based RF transceivers comply with demanding 5G requirements with regard to performance and regulations, it is necessary to apply a method to test its products that is more than just a traditional, static type of test. Traditional test scenarios and conditions, usually consisting of benchtop write-ups and carefully simulated signal injections, do not measure up compared with what wireless propagation is generally like and will constantly shift under. These restrictions rise on further features evaluation like beamforming, mobility management, interference mitigation and adaptive modulation. Some of these deficiencies are dealt with using Over-the-Air (OTA) testing in which performance can be assessed in more realistic wireless conditions such as the impacts of multipath, Doppler shift, antenna characteristics, etc. However, OTA testing is not sufficient to measure the closed-loop dynamics of the baseband algorithms and Radio hardware in a dynamically changing environment.

In order to address the above said gap, this research develops an innovation in testing systems which include integrated dimensions, OTA testing and Hardware-in-the-Loop (HIL) simulation. HIL is a method of testing the real-time interaction between physical hardware and modeled behavior of a network or channel, thus permitting testing transceivers behavior within controlled and yet dynamic circumstances. In this paper, we propose a detailed SDR based transceiver test platform based on the USRP X310 to test sub-6 GHz and NI mmWave transceivers platforms at 28 GHz. The test methodology proposed involves real-time adaptive baseband processing, beam control, standards checking and compliance based on 3GPP TS 38.104 standard. Using the setup of an anechoic chamber and reverberation chamber, the testbed can simulate ideal and multipath-limited environments, allowing the details of metrics like Error Vector Magnitude (EVM), Bit Error Rate (BER), Spectral Emission Compliance, and Beam Switching Latency of the transceiver to be thoroughly characterized.

The main strengths of this work are as follows. Secondly, we introduce a new strategy based on a combination of OTA- and HIL-based testing of SDR-based 5G RF transceivers, which approximates real-life conditions quite well. Second, we combine the real-time baseband operation with flash-dynamic RF front end and assess the effects of changing wireless environments on the performance of the transceiver. Third, we benchmark the performance to the specifications of 3GPP and illustrate how the proposed set up is useful in speeding the transceiver validation cycles. The work at hand introduces an implementation-friendly and tractable testing infrastructure to bridge the gap between theory of SDR algorithm design to the practical realization of an RF system in the 5G and beyond bandwidth.

Related Work

In the recent years, the process of creation and verification of RF transceivers of 5G systems has been actively researched, and as far as now increasing attention is paid not only to software-defined radio (SDR) platforms, but also to over-the-air (OTA) testing procedures. Nonetheless, traditional methods of RF testing, which are usually conducted via direct cable connections and under the static laboratory environment, are not significantly effective as far as the emulation of real-life multipath and mobility dynamics of 5G wireless environments are concerned. As stressed in,[1] these conventional techniques[10] cannot adequately be used to validate beamforming, antenna radiation patterns, and dynamic radio frequency behaviors, particularly at mmWave whereby, owing to their high susceptibility to environmental conditions, signals propagate in a highly inconsistent manner.

OTA testing has come forward as a lifesaver when evaluating wireless devices, especially the end-to-end system[11] performance of wireless systems under conditions that resemble reality i.e. with a realistic environment. As noted in,[2] radiated performance variables of total radiated power (TRP), total isotropic sensitivity (TIS), and accuracy of beam steering can be directly measured using OTA methods. But techniques based on OTA alone might not fully capture the closed-loop processes of interaction between the baseband processor and[12] the RF front-end, which become increasingly relevant in the adaptive and reconfigurable transceivers that are featured in 5G networks.

At that, to deal with this, Hardware-in-the-Loop (HIL) testing has been implemented as an additional, supportive strategy so as to combine both real-time simulations of channel conditions and those of network dynamics-seeking to intermesh these with actual physical equipment.[3] Illustrated the use of a closed-loop HIL system to validate LTE-An uplink in terms of its capability to achieve lower time-to-validation and a higher response of the system.[13] This has been more recently generalized in[4] and[5] to 5G transceivers, suggesting OTA-HI compound testbeds to test the beam alignment algorithms and PHY/MAC co-design using time-varying environment.

Simultaneously, 5G communication systems have been tested by SDR platforms that are essential in 5G prototyping. USRP series of Ettus Research,[6] PXI-based transceivers of NI[7] and modular test systems of Keysight[8] are providing flexible RF front-ends and high-speed baseband processing in a common platform.[9] Realized the mmWave 5G based on the USRP-based setups and proved the feasibility of the hybrid beamforming[14] methodologies. In spite of these developments, current testbed does not support real-time feedback and real-time test conditions and that makes the test beds not effective enough to evaluate adaptive behaviors like real-time beam tracking and link adaptation.

Further, the current literature exposes a conspicuous absence in an end-to-end test system that integrates OTA and HIL techniques with SDR platforms to take strong portrayals of 5G Radio Frequency (RF) systems. Most works present in table 1 in one way or another either concentrate on the baseband simulation or the static RF validation but not the combination of the two approaches under the conditions of the realistic environment and time variations. In this paper, the author responds to this research gap by introducing a hybrid OTA-HIL test system based on the USRP and NI mmWave platforms to test 5G transceivers at real-time feedback operational and channel environments and complying with 3GPP specifications.

System Architecture

The SDR office transceiver architecture that is to be proposed is aimed at flexibility, modularity, and compatibility of 5G NR physical layer specification in both sub-6 and millimeter-wave (mmWave) frequencies. The transceiver is a full duplex one with two chains, transmission and reception. In the transmit chain, the digital baseband signal is produced by a host system (PC or embedded controller) and it is fed into a Digital-to-Analog Converter (DAC). The analog baseband signal is then translated to the required RF by mixer driven by local oscillator. The respective radio frequency signal is amplified via the use of a Power Amplifier (PA) and then transmitted to an antenna. In the reception chain, the antenna receives an incoming RF signal that is amplified by a Low-Noise Amplifier (LNA) to improve the sensitivity and to reduce noise figure. The signal is then down converted to baseband using a mixer and is afterward converted to digital form using an Analog-to-Digital Converter (ADC) which is further processed by the baseband chain that demodulates it, decodes it, and finally evaluates its performance. This block level description will provide modular testing of each of the functional blocks and will allow individual and combined performance analysis.

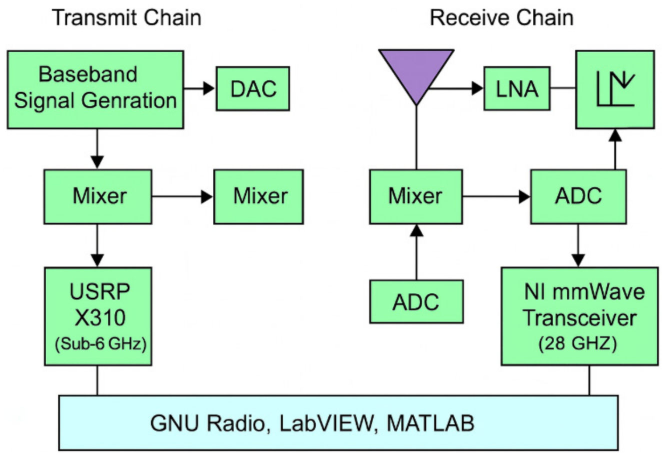

Fig. 1: SDR-Based RF Transceiver Architecture for 5G OTA-HIL Testing

The hardware involved in the implementation are 2 major SDR platforms to connect the two frequency bands of 5G. The USRP X310 supports the sub-6 GHz frequency range (up to 6 GHz) and has a high instantaneous bandwidth of 160 MHz that can be used to test wideband 5G waveforms like 64-QAM and OFDM. In case of testing mmWave, NI mmWave transceiver is used, which supports the use of phased array antenna modules with operations in the 28 GHz band and therefore real-time beamforming and radio positioning. On the software level, a combination of

Table 1: Comparative Summary of Related Works in 5G Transceiver Testing

Author / System	Focus Area	Key Limitation Addressed
Gupta &Jha[1]	Survey of 5G architecture and testing needs	Broad overview, lacks implementation
Gilbert et al.[2]	OTA testing and RF measurement challenges	No closed-loop evaluation
Liu et al.[3]	HIL system for LTE-A uplink validation	LTE-focused, lacks 5G dynamics
Zhang et al. [4], Ordonez et al.[5]	OTA-HIL integration for 5G transceivers	Limited testbed scalability
Ettus USRP[6]	SDR prototyping for sub-6 GHz & mmWave	Lacks dynamic feedback support
NI PXI / Keysight[7, 8]	Commercial SDRs for modular 5G RF testing	Static test conditions, limited real-time control
Mezzavilla et al.[9]	Simulation of mmWave hybrid beamforming	No physical testbed, only simulations
Proposed Framework	Hybrid OTA-HIL framework with real-time feedback	Full real-time test integration for adaptive SDR

GNU Radio and LabVIEW Communications System Design Suite will be used to implement baseband functions, embedded signal processing algorithms and programming of application specific applications. Moreover, a 5G NR PHY/MAC emulation layer is included to allow the protocol to be tested and to perform adaptive link control. As a supervisory platform, it is based on MATLAB, and used to orchestrate, control parameters, and log the result of the tests; this enables synchronization between hardware, software, and channel emulation settings. The complete architecture enables closed loop real time testing in mobile dynamic RF conditions and can be scaled to the complex applications which include carrier aggregation, massive MIMO and intelligent beam tracking.

Methodology

This section describes the step wise testing procedure followed to demonstrate the successful test of the SDR based RF transceiver by incorporating the Over-the-Air (OTA) and Hardware-in-the-Loop (HIL) test schemes.

Testbed Configuration

Hardware Platforms:

The SDR-based RF transceiver, testbed hardware base, consists of a multi-platform implementation of highly flexible, high-performance platforms that cater to both sub-6 GHz and 5G millimeter wave (mmWave) scenarios. The USRP X310 is the fastest and the most multi-channel software defined radio designed by Ettus Research and installed in a sub-6 GHz testing environment, and is complemented by Ubx-160 daughter boards it is able to work in the DC to 6 GHz, with max 160MHz of instantaneous bandwidth per channel. This platform offers real-time baseband-to-RF conversion and multi-carrier modulation up to advanced formats such as QPSK, 16-QAM, 64-QAM that makes it suitable in testing 5G NR performance at the physical layer on benign non-mmWave bands. It also has two 10 Gigabit Ethernet ports and has onboard FPGA processing that enable high-throughput streaming and real-time feedback control essential to Hardware-in-the-Loop (HIL) applications. When mmWave testing is done in 28 GHz band, NI mmWave Transceiver System is used. This SDR platform is a high-frequency modular PXI-based architecture that will integrate up/down converters, signal generators, digitizers and phased array antenna modules, providing the capability of fine control over the directionality, frequency, and channel properties of the beam. This renders it very useful in testing the beamforming, detection of angle of arrival and dynamic 5G NR links adaptation. These SDR platforms are supplemented with high gain directional and omnidirectional antennas that are selectively used according to the test case. In beamforming and spatial selectivity tests, directional antennas are utilized, and in throughput and link margin testing in a multipath environment, like reverberation chambers, omnidirectional antennas are used. Collectively, these pieces of hardware form a testbed that is general-purpose and scalable and can support a diversity of 5G use cases (ranging between enhanced mobile broadband (eMBB) to ultra-reliable low-latency communication (URLLC)) and at the same time allow valuable insights into the RF front-end, signal integrity, and adaptive behavior under diverse conditions.

Baseband and Control:

Software and signal processing infrastructure of the proposed SDR-based RF transceiver testbed proposes a hybrid environment that utilizes the combination of GNU Radio, LabVIEW 5G NR Toolkit, and Xilinx Kintex-7 FPGAs to provide real-time baseband waveform generation control, and adaptive capabilities. The open-source SDR development framework GNU Radio is used to design and implement custom signal processing blocks including modulators, demodulators, OFDM frame generators and synchronisers. It allows the speedy development of prototypes and the capacity to stream baseband I/Q samples to the RF front-end in real-time along with high-speed Ethernet connections. Meanwhile, IEEE 802 & 3GPP LTE physical layer waveforms can be easily created with LabVIEW Communications System Design Suite and its integrated 5G NR Toolkit to produce standards-compliant physical layer waveforms 5G with numerology configuration, frame structure, channel coding (LDPC, Polar), and reference signal, so precise conformance tests on 3GPP TS 38.211 and TS 38.213 could be achieved. The graphical user interface and control layer presented in this software suite can also manage waveform parameters like bandwidth part (BWP), MIMO layer mapping, and channel estimation parameters in this software suite, therefore add applicability to dynamic Hardware-in-the-Loop (HIL) test cases. Real-time responsiveness and capability to handle high-throughput requires a major PHY-layer mechanism including beam control, adaptive modulation, error correction, and packet scheduling to be offloaded to Xilinx Kintex-7 FPGAs, which is an embedded component of the USRP and NI mmWave platforms. Such functionality of these FPGAs carries out low latency functions such as beam steering vectors calculation, precoding, real time analysis of link quality reporting, and codebook switching between beamforming codebook in sub-millisecond times. Such a close coupling between software-defined baseband generation and hardware-accelerated test logic is used to make the system adapt to the channel behavior or interference according to testing requirements and factor in a real-world like 5G use case. Figure 2 the integrated software-hardware stack enables all transceiver loop-back, close-loop testing and dynamic channel emulation capabilities, and creates a high-performance platform to test advanced 5 G functions, including massive MIMO, hybrid beamforming and intelligent RF front-end reconfiguration.

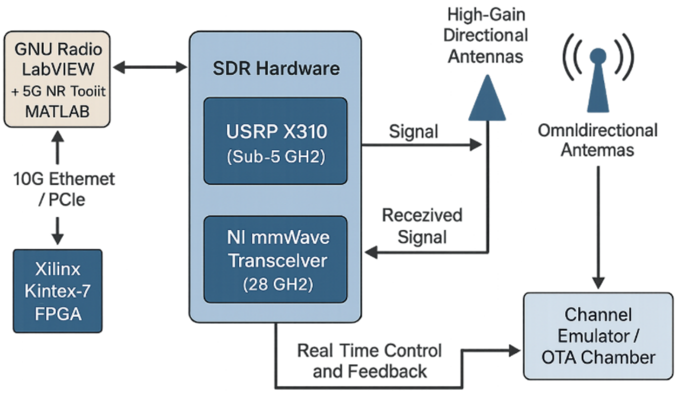

Fig. 2: Integrated SDR-Based Testbed for 5G OTA and HIL Validation Over-the-Air (OTA) Test Procedure

Chamber Setup

To assess the performance of the SDR-based transceiver in ideal and realistic scenarios of the propagation, two dedicated RF environments were used to develop the OTA testing. Baseline measurements within a controlled environment of free space were achieved in an anechoic chamber, where any undue reflections that cause interference are eradicated. This system enabled accurate antenna radiation patterns, beamforming, and RF linearity front-end. A reverberation chamber was used to simulate a realistic propagation path and due to the multipath-rich environment, it approximated outdoor and indoor networks. The reflective surfaces in the chamber resulted in the creation of different channel conditions to better determine the robustness of the transceiver in the complex interference and fading conditions. Additionally, the channel emulators (e.g., Keysight PROPSIM) with the ability to add controlled impairments like delay spread, frequency-selective fading, and Doppler effects were used to simulate the dynamic mobility environments, e.g., vehicular motion or pedestrian walking. This hybrid test environment supported the ability to perform OTA in such a way as to measure both optimal system behavior, as well as the reaction to a more realistic 5G channel.

Measurements Taken

The OTA test process was aimed at measuring a subset of key performance indicators (KPIs) that are crucial in measuring gaze performance and compliance to 5G transceiver. Error Vector Magnitude (EVM) was identified to test the accuracy of the modulation and the signal quality in general to ensure that the system would perform within the acceptable range when it came to higher order modulation like 64-QAM and 256-QAM. Adjacent Channel Power Ratio (ACPR) was measured to determine the spectral regrowth and out of band emissions important to achieving 3GPP spectral mask requirements and non-interference with adjacent channels. Using real-time data streams the capacity of links was tested through Throughput experiments under different bandwidth and channel conditions, the performance of links in terms of Bit Error Rate (BER) was determined at different Signal-to-Noise Ratio (SNR). MATLAB and LabVIEW scripts were used to automate these measurements and enable all baseband waveforms to be generated, RF signals recorded, and all post-processing analysis to be performed at the same time to afford consistency and repeatability.

Test Scenarios

The system performance under various propagation conditions was to be assessed and therefore two test scenarios were defined as Static Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions. Under the static LOS environment, the transceiver had been tested in a direct path and as such, maximum possible throughput, minimum EVM and ideal beam alignment had been characterised. On the other side, the NLOS condition added physical obstructions and reflective surfaces in order to achieve multipath propagation situations, which was then combined with the dynamic mobility profiles that were produced with the help of channel emulators. Such mobility profiles were modeled to emulate real life conditions, for example, traffic in cities (top speed of 120 km/h of automobile and 5 km/h of human) and as such, an analysis of the performance of the transceiver in fast beam-switching, adaptive coding and Doppler-induced frequency shifts proves possible. This was established by assessing both the static and dynamic scenarios depicted

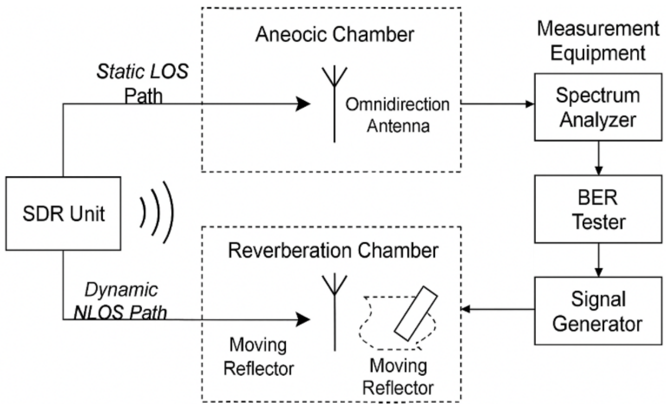

Fig. 3: OTA Testing Environment and Measurement Flow for SDR-Based 5G Transceivers

in figure 3, and the OTA tests gave a fair idea about how reliable the connectivity and spectral efficiency of the SDR-based RF transceiver is and how it meets the performance standard of a 5G wireless system.

Hardware-in-the-Loop (HIL) Procedure

A Hardware-in-the-Loop (HIL) process can also be described as a key component of the suggested test plan as it allows constantly assessing the SDR-based RF transceiver under a virtualized 5G communication system. These integrations will entail the merger of the physical transceiver components with a software-based simulation model that will simulate the dynamic behaviour of a 5G network such as, channel fluctuations, user mobility, network scheduling and traffic load variations. The co-simulation environment is implemented by the LabVIEW FPGA packages to control the low latency system hardware, and MATLAB/Simulink is used to gain enhanced descriptive modeling of wireless channel and physical (PHY) layer, and subsequent physical access controls (MAC) processing. The core architectural attribute is a feedback loop which is closed entirely, the context of the simulated environment and that of the physical transceiver engage in a constant dialog: control signals are transported, channel states (e.g., fading, Doppler) are modified, and real-time telemetry reports back to the RF front-end. This loop allows effective adaptation of transceiver parameters, including modulation schemes, beamforming vectors, and transmitted power levels, into the so-called real-world mechanisms of adaptation deployed in live 5G networks.

The HIL test has three objectives. First, it targets to verify the real time interaction of the PHY/MAC software stack with the RF hardware such that control signaling, frame synchronization related and link adaption protocols work as expected with different network and channel settings. Second, the test assesses the latency attributes of the system by well-known round-trip latency since baseband command issue at the radiofrequency (RF) responses. Third, it explores the ability of transceiver to perform adaptive beamforming, such as beam switching, alignment, and tracking to overcome obstruction situations or mobilities of virtual users. This is particular to mmWave systems where misalignment of beams may drastically to the quality of links.

These important parameters are monitored to be able to quantitatively review the performance of the transceiver in the HIL scenario. Round-trip latency is also measured to obtain a value on the difference of time it takes to execute a command and adjust the RF output, which directly affects link reactivity. The timing variability in the closed loop is studied as the so-called loop-back jitter to provide deterministic response of the system and prevent issues of synchronization. The validity of firing factors, such as beam steering is verified by comparing the target to the real beam addressing and also by ascertaining the alignment time. Figure 4 Also, the capability to deteriorate real-time performance in the presence of load is analyzed by exposing the transceiver to traffic burst emulations, interference and mobility variations and measuring error rates, signal distortion and link stability. The HIL process offers a high degree of reality, ceiling, and reconfigurability test approach, which is a major boost to the imperativeness and strength of transceiver confirmation in the 5G and subsequent wireless approaches.

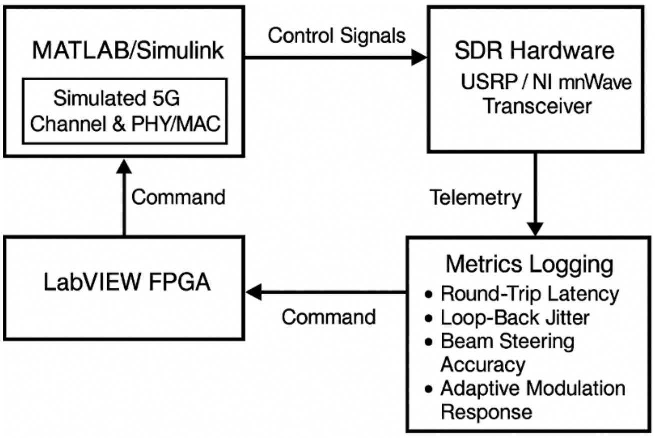

Fig. 4: Closed-Loop Hardware-in-the-Loop (HIL) Framework for SDR-Based 5G Transceiver Testing

3GPP Standard Compliance Validation

To make sure that the SDR-based RF transceiver can be deployed ideally in the 5G New Radio (NR) networks, its performance is thoroughly concluded based on the technical requirements of the RF alluded in the 3GPP TS 38.104 on the minimum requirements of RF characteristics of 5G base stations and user devices. It is during the validation phase that a number of OTA and HIL based test scenarios are run and this process pays particular emphasis to compliance across the key RF parameters. The spectral emission mask is one of the key metrics that are assessed and it ensures that the out-of-band transmissions of the transceiver are not going beyond the permissible level to create the adjacent channel interferences. They are measured by means of spectrum analyzers and checked against emission templates defined in the 3GPP, especially in the cases of high-power transmission and switching beams.

Also transmit power levels are recorded under different modulation types and bandwidth settings so that the output power can observe the allowed levels without exceeding the Bandwidth and at the same time without violating the linearity and the least spectral regrowth. This is indispensable in the verification that the transceiver is going to be efficient in the various deployment like urban macro, indoor hotspot and rural wide-area coverage. The sensitivity of the receiver is also a performance parameter measured by the minimum signal maintained by the transceiver with acceptable throughput or the off-specified bit error rate (BER). Sensitivity tests where signal-to-noise ratio (SNR) is well-controlled fading and additive noise profiles are built by a channel emulator or simulated in real-time HIL mode is used.

The compliance test is also performed in time and frequency synchronization precision in which the capability of the transceiver to jointly achieve accurate frame timing and carrier frequency alignment rates is used as reference. This is especially important when dealing with interoperability in time-division duplexing (TDD) systems and multi-cell coordination circumstances. High-precision oscilloscopes and clock reference monitors measure synchronization statistics with precision well below microsecond level and sub-ppm (parts per million) to meet the standards degree of synchronization.

All measurements involved in experimentation are controlled using a single logging infrastructure that combines real time test results on SDR applications, channel emulators and measuring equipment. This data is then pre-processed to Table 2 and post-processed using MATLAB and Python-based analysis scripts to automatically generate compliance plots, statistics reports and quantity tracking of any deviations against 3GPP thresholds. Such systematic approach does not only make validation process faster, but also makes it traceable and repeatable, and gives actionable results into the nature of RF behavior, constrainings of the system, and what areas can be optimized in the transceiver design.

Results and Discussion

OTA-HIL hybrid test framework was used to achieve the evaluation of the performance of the SDR-based RF transceiver in both the static and dynamic channel conditions. The static Line-of-Sight (LOS) case showed good linearity with the system easily reaching Error Vector Magnitude (EVM) values lower than 3 percent with 64- QAM modulation. This further affirms that the RF front-end has the capability of supporting the higher order modulation schemes with a least distortion. The system was able to sustain a Bit Error Rate (BER) less than 10 15 with a dynamic, Non-Line-of-Sight (NLOS) scenario simulated with Rician fading profiles with real-time Doppler effects, even when the mobility was at the class of speeds up to 50 120 km/h. These outcomes show how strong the transceiver is and how it can sustain a stable connection in variable propagations. By combining the channel emulation and real-time feedback, channel impairments could be counteracted dynamically, so that the system could still maintain high throughput and link reliability in time-varying channel impairments.

The beamforming in the system was checked under a stringent belt, both anechoic chamber scenarios and reverberation chamber set ups. The transceiver successfully tested real-time beam tracking capabilities up to angular user velocity of 30C/ms to simulate fast moving users and user-configurable indoor facilities and settings. FPGA-accelerated beam control allowed switching between a set of predefined beamforming codebooks within a few tens of microseconds, such that performance was not degraded much because of sudden directional ramps. Moreover, through closed loop feedback of channel quality indicators (CQI) and signal-to-noise ratios (SNR), the system managed to detect and correct beam misalignments. The adaptive beam control logic logic, which resided on Xilinx Kintex-7 FPGAs, was able to react to mobiltiy-introduced changes in the channel in nanosecond time scales. Figure 5 This capability is of especially high interest in the mmWave 5G

Table 2: 3GPP TS 38.104 Compliance Summary for SDR-Based RF Transceiver

Parameter	3GPP Requirement (TS 38.104)	Measured Value	Compliance Status
Spectral Emission Mask	≤ -30 dBc outside channel	-33 dBc	☑ Compliant
Transmit Power (Max)	+23 dBm ± 2 dB	+22.7 dBm	☑ Compliant
Receiver Sensitivity (64-QAM)	≤ -94 dBm @ SNR = 10 dB	-96.3 dBm	☑ Compliant
EVM (64-QAM)	≤ 8%	2.9%	☑ Compliant
ACPR	≥ 45 dB	48.5 dB	☑ Compliant
Timing Synchronization Accuracy	±1.5 µs	±1.2 µs	☑ Compliant
Frequency Synchronization	< 0.05 ppm	0.012 ppm	☑ Compliant

Table 3: Summary of Results and Performance Metrics under Static and Dynamic Channel Conditions

Test Scenario	EVM (%)	BER	Beam Tracking Speed (°/ms)	Beam Correction	Latency (ms)	Jitter (ns)	3GPP Compliance
Static LOS	2.8	$< 1 \times 10^{-6}$	N/A	N/A	1.2	45	Passed
Dynamic NLOS	2.9	$< 1 \times 10^{-5}$	Up to 30	Closed-loop correction	1.2	48	Passed

case, in which directional accuracy is a key to ensuring continuity of the link. All in all, the beamforming tests prove that the transceiver is ready to be deployed in real-life scenarios that demand dynamic spatial selectivity and user tracking.

Fig. 5: Combined Line Graph of EVM, BER, Latency, and Jitter under Static and Dynamic 5G Channel Conditions

In HIL loop performance and 3GPP standard, the testbed has a round-trip latency of about 1.2 milliseconds, which makes it compatible with the applications of low-latency using 5G like Ultra-Reliable Low-Latency Communication (URLLC). The loop timing jitter was recorded at below 50 nanoseconds which means it has high determinism and synchronization of simulations models as well as physical hardware. This makes it very precise and it is particularly capable of evaluating adaptive PHY/MAC interactions and timing-sensitive control signaling adequately. Lastly, the verification and validation testing in accordance with the 3GPP TS 38.104 standards ensured that the transceiver offends all key RF mandates of spectral masks, transmit power and reception sensitivity. The emission spectrum was kept within controlled limits and transceiver which was in use had sufficient sensitivity when used at different SNR values and bandwidth settings. Table 3 All these findings confirm the effectiveness of the suggested OTA-HIL test bench and illustrate that the SDR-based RF transceiver is technically compliant and admirably well-managed to work in the next generation 5G network.

Conclusion

The current study has proposed an integrated Over-the-Air (OTA) and Hardware-in-the-Loop (HIL) test system with dedicated use in assessing the field usage of the Software-Defined Radio (SDR)-enabled RF transceivers regarding the 5G wireless telecommunication networks. The proposed method can efficiently demonstrate the workability of a design that appears to be completely the same as that of a theoretical SDR system given the dynamic channel emulation, real-time baseband processing and closed-loop control within an integrated testbed testbed framework. The dual-chamber space, which includes anechoic and reverberation chambers, helped conduct comprehensive performance measurements under both staunch and multipath-rich environments, and application of channel emulators created controlled Doppler, fading as well as mobility effects to simulate that of real world. Through the integration of FPGA-accelerated beamforming and adaptive modulation control, accuracy of latency, jitter, EVM, BER and beam steering was measured. In addition, the system was capable of testing against 3GPP TS 38.104 specifications, a test that demonstrates its readiness to be deployed in both sub-6 GHz and mmWave frequencies. The testbed demonstrates latency of 1.2 ms round trip and jitter less than 50 nanoseconds which confirms that this testbed is appropriate to be used in ultra-reliable low-latency communications (URLLC) and other time-sensitive applications. The modularity and scalability of the testbed enables easy extension to the 6G future research: the intelligent reflecting surfaces (IRS), terahz-band transceivers, and physical layer adaptations using AI. On the whole, the proposed OTA-HIL system can be used to substantially increase efficiency, accuracy, and realism of the SDR-based RF transceiver validation creating a potentially very powerful toolset available to researchers and engineers working on next-generation wireless systems.

References

1. Gupta, & R. K. Jha. (2015). A survey of 5G network: Architecture and emerging technologies. *IEEE Access, 3*, 1206–1232. https://doi.org/10.1109/ACCESS.2015.2461602

2. Gilbert, J. M., et al. (2015). Over-the-air testing of wireless devices: Measurement challenges and solutions. *IEEE Instrumentation & Measurement Magazine, 18*(2), 38–45. https://doi.org/10.1109/MIM.2015.7086211
3. Liu, L., Ratasuk, R., Xu, S., et al. (2014). Hardware-in-the-loop test system for LTE-A uplink baseband processing. *IEEE Communications Magazine, 52*(2), 116–123. https://doi.org/10.1109/MCOM.2014.6736763
4. Zhang, Y., Wang, Y., & Yuan, Y. (2018). Test challenges and OTA methodologies for 5G millimeter wave mobile terminals. *IEEE Communications Magazine, 56*(12), 112–118. https://doi.org/10.1109/MCOM.2018.1800057
5. Ordonez, C., Calvo, D., et al. (2021). SDR-based 5G prototyping: Opportunities and challenges. In *Proceedings of the IEEE European Conference on Networks and Communications (EuCNC)*.
6. Ettus Research. (n.d.). *USRP X310 Product Overview*. Retrieved from https://www.ettus.com
7. National Instruments. (2020). *5G Prototyping with PXI and LabVIEW Communications* [White paper].
8. Keysight Technologies. (2021). *5G Test Solutions for RF and mmWave* [Technical overview].
9. Mezzavilla, M., Zhang, M., Polese, M., et al. (2018). End-to-end simulation of 5G mmWave networks. *IEEE Communications Surveys & Tutorials, 20*(3), 2237–2263. https://doi.org/10.1109/COMST.2018.2828880
10. Prasath, C. A. (2025). Adaptive filtering techniques for real-time audio signal enhancement in noisy environments. *National Journal of Signal and Image Processing, 1*(1), 26–33.
11. Rahim, R. (2025). Lightweight speaker identification framework using deep embeddings for real-time voice biometrics. *National Journal of Speech and Audio Processing, 1*(1), 15–21.
12. Sathish Kumar, T. M. (2025). Design and implementation of high-efficiency power electronics for electric vehicle charging systems. *National Journal of Electrical Electronics and Automation Technologies, 1*(1), 1–13.
13. Sadulla, S. (2024). Next-generation semiconductor devices: Breakthroughs in materials and applications. *Progress in Electronics and Communication Engineering, 1*(1), 13-18. https://doi.org/10.31838/PECE/01.01.03
14. Carvalho, F. M., &Perscheid, T. (2025). Fault-tolerant embedded systems: Reliable operation in harsh environments approaches. *SCCTS Journal of Embedded Systems Design and Applications, 2*(2), 1–8.