# 6G Wireless Systems: Performance Analysis of Hardware Designs Under Non-Ideal Conditions

**Bhargavi K V N A[1], Ravi Chandra M L[2], RAVILLA DILLI[3]**

[1]*Computer Science Engineering, Koneru Lakshmaiah Education Foundation, Telengana, Hyderabad, 500075, India Email: bhargavi@klh.edu.in*

[2]*Professor, Electronics and Communication Engineering, Srinivasa Ramanujan Institute of Technology, Ananthapuramu, Andhra Pradesh, India. ravichandra.ece@srit.ac.in*

[3]*Associate Professor, Electronics and Communication Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Udupi, Karnataka 576 104 India. Email: dilli.ravilla@manipal.edu*

## Abstract.

This paper aims at system level hardware design aspects towards meeting the requirements of 6G use cases in terms of latency and link data rates. It mainly describes the radio frequency (RF) transceiver architectures, hardware components models, channel modelling, and optimization at THz bands (> 100 GHz) under non-ideal conditions. This work aimed at the imperfections of hardware in handling the candidate 6G orthogonal frequency division multiplexin`g (OFDM) signals. The imperfections include non-linearities of power amplifier (PA), phase noise, and filter characteristics that spreads the signal spectrum beyond the channel bandwidth. The impact of various design parameters and deployment options are illustrated by conducting system-level simulations. The system parameters are designed and configured according to international telecommunication union-radio (ITU-R) radio models while quantifying the impairments. The RF hardware imperfections are demonstrated, and the results proved the practical feasibility of such RF systems.

**Keywords**. 6G, Channel model, hardware design, ITU-R, Radio modeling, RF, THz bands

## 1. INTRODUCTION

In this work, the radio transceiver design for above 100 GHz bands is presented by considering the non-ideal characteristics of the hardware, waveform impacts, and channel properties. It mainly aims at the imperfections of hardware designs in handling the candidate 6G OFDM signals. The imperfections include non-linearities of PA, phase noise, and filter characteristics that spreads the signal spectrum beyond the channel bandwidth. The hardware imperfections are demonstrated using adjacent channel power ratio (ACPR) and error vector magnitude (EVM) as metrics. ACPR measurements help to study spectral regrowth due to nonlinearity of PA.

## 2. EXISTING WORKS

The nascent research [1-4] has proved that the 6G connectivity can operate at sub-1 GHz range, 3.5-6 GHz mid-band range, 7-15 GHz centimetric range, 26 -72 GHz millimeter-wave range, and 90-300 GHz sub-THz range. The initial deployments of 6G are expected at lower edge of sub-THz range due to their favourable propagation characteristics and availability in the commercial RF equipment ecosystem. In this context, W and D bands at sub-THz range looks interesting [5-8]. Artificial intelligence (AI) supported air interfaces in 6G systems enhance the beamforming and channel state information (CSI) compression. To maintain linearity over huge bandwidths at sub-THz and THz bands, digital pre-distortion plays a crucial role. AI techniques can optimize the digital pre-distortion through the collection of real data from PA and train and test the neural network [9-10].

## 3. METHODS

This section mainly focuses on modelling the imperfections in non-linear characteristics of PA, spectral characteristics of filter, and phase noise as shown in Figure 1. RF modelling is presented mainly in three stages: signal generation, introducing non-ideal conditions in the RF hardware, and measure the performance deviations.

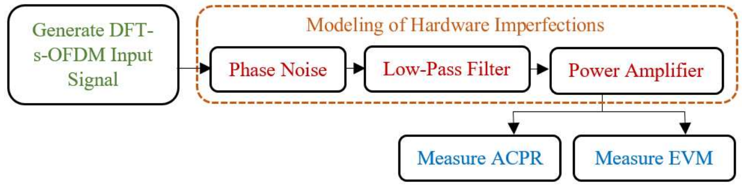



Figure 1: Modelling of RF hardware imperfections for 6G candidate waveform generation.

The 6G waveform is generated with appropriate configuration parameters as follows: ***Step 1:*** Configure the OFDM signal. ***Step 2:*** Define bandwidth occupancy (transmission bandwidth to channel bandwidth ratio). Minimal values of bandwidth occupancy cause poor spectral efficiencies. ***Step 3:*** Generate the carrier configuration. As per the values of bandwidth occupancy, define the sub-carrier spacing (SCS), compute number of resource blocks, and transmission bandwidth to configure the carrier signal. ***Step 4:*** Define the length of time division duplexing (TDD) frame and optimally configure slots for uplink and downlink. ***Step 5:*** Configure physical downlink shared channel (PDSCH) for the allotted resource block and enable phase tracking reference signal (PT-RS). ***Step 6:*** Generate a resource grid that contains a PDSCH transmission, demodulation reference signal (DM-RS), and PT-RS. ***Step 7:*** Oversample the OFDM signal with a specified oversampling factor to compute the spectral emission beyond channel bandwidth.

Finally, conduct measurements on error performance of RF systems to demonstrate sub-THz signal transmissions, estimations with different modulation schemes. Phase noise is one of the key hardware impairments at sub-THz bands and the adequate output powers of PA demands less peak-to-average-power ratio (PAPR) signal design [11-15]. For efficient utilization of the waveform, a low back-off in the PA is required. Discrete Fourier Transform Spread OFDM (DFT-S-OFDM) is a suitable waveform as it provides a low PAPR and a good power efficiency for the PA. According to 3GPP, a memoryless polynomial model of Gallium Nitride (GaN) PA presented in [16] is considered for analysing the imperfections. ACPR is measured to analyse the spectral regrowth due to nonlinear PA model as shown in Figure 2. Set the model back-off to minimize the input signal amplitude and minimize the distortion. Based on the results shown in Figure 3, ACPR characteristics with respect to output power of PA shifts at higher frequencies. EVM measurements were conducted for the signal received at receiver (Rx) as: 1. Perform timing synchronization for Rx signal. 2. Demodulate the OFDM signal. 3. Perform PDSCH channel estimation. 4. Equalization of PDSCH symbols for each slot. 5. Estimation and correction of phase errors. 6. Calculate the RMS and peak EVM values for PDSCH symbols. 7. Plot the EVM per subcarrier, averaged over OFDM symbols. 8. Plot EVM per symbol, averaged over subcarriers.

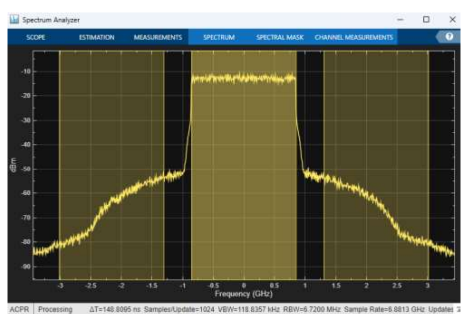


Figure 2: ACPR measurements due to nonlinearities of PA.

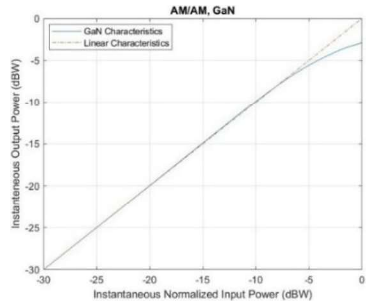
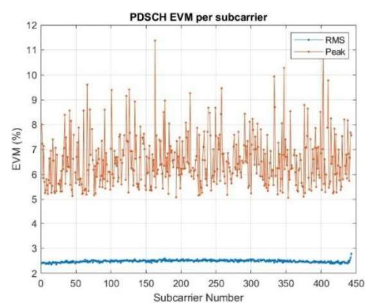



Figure 3: Nonlinear characteristics of PA imperfections at 140 GHz.

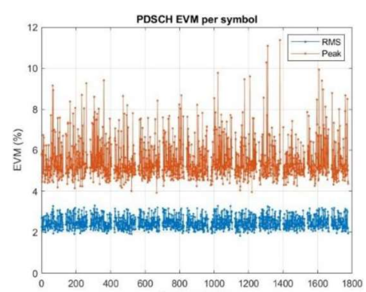
Table 1: Error performance of PDSCH.

| Modulation scheme | EVM values | |
|---|---|---|
| | RMS value (%) | Peak value (%) |
| QPSK | 2.795 | 13.119 |
| 16 QAM | 2.735 | 13.748 |
| 64 QAM | 2.816 | 14.531 |
| 256 QAM | 2.775 | 13.034 |
| 1024 QAM | 2.487 | 11.373 |

As the higher order modulation schemes are more sensitive to interference and noise, they expect higher powers and SNR for reliable communication. But the error performance results were very interesting as the error values are still minimal even when the order of modulation is increased to 1024 as presented in Table 1. This allows data transmissions with robustness to noise and interference while providing the higher data rates in the given bandwidth. In Figure 4, the RMS and peak values of PDSCH EVM per symbol and per subcarrier are drawn for 1024 QAM scheme.




(a) per subcarrier




(b) per symbol

Figure 4: EVM values of PDSCH with 1024 QAM.

To take advantage of high processing speed and lower memory requirements, infinite impulse response (IIR) filters are selected in designing current RF systems. We have optimally selected the IIR filter cut-off frequencies, stop band attenuation, and pass band ripple to achieve lower EVM values. Figure 5 presents the magnitude and phase responses of the LPF, output proves more optimal for smaller stopband attenuation.

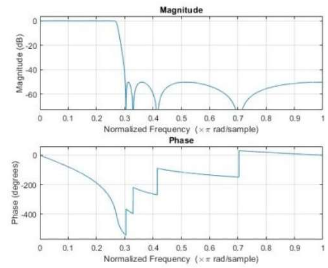



Figure 5: IIR LPF output with passband ripple=0.01 & stopband attenuation=50

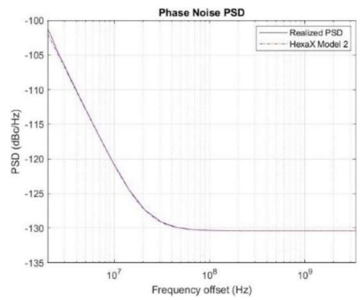



Figure 6: Phase Noise Filter Characteristics at 2 MHz minimum offset frequency.

Phase noise measurements were conducted to quantify the timing fluctuations of received signal's phase that can affect the performance of the Rx. In this work, phase-noise is calculated using the power spectral density (PSD) of phase deviations. Hexa-X model [16] is used to characterize the phase noise distortion at 140 GHz. Define the minimum frequency offset to calculate phase noise spectrum mask. From the phase noise filter characteristics shown in Figure 6, the lower values of minimum frequency offset model the

low frequency phase noise more accurately at the cost of longer design time for phase noise filter.

## 4. CONCLUSIONS AND FUTURE SCOPE

Design of 6G systems operate at sub-THz bands enables performance gains in terms of latency, data rates, transmission bandwidth, signal interference, and network capacity. But the main challenges at such higher frequency bands are to have resilient waveforms, and capability in handling hardware limitations such as phase noise. This work mainly aimed at the imperfections of hardware designs in handling the candidate 6G OFDM signals. The imperfections include non-linearities of PA, phase noise, and filter characteristics that spreads the signal spectrum beyond the channel bandwidth. The system parameters are designed and configured according to ITU-R radio models while quantifying the imperfections. The hardware design imperfections are demonstrated by exploring various specifications of RF modules using ACPR and EVM as metrics.

## 5. REFERENCES

1. W. Jiang, et. al., 'Terahertz Communications and Sensing for 6G and Beyond: A Comprehensive Review', In-press, IEEE Commun. Surveys & Tutorials, 2024. DOI:10.1109/COMST.2024.3385908
2. ITU Recommendation ITU-R M.2160-0. 'Framework and overall objectives of the future development of IMT for 2030 and beyond' 2023.
3. Hexa-X Deliverable D2.2 - Initial radio models and analysis towards ultra-high data rate links in 6G.
4. J. M. Jornet, et. al., 'The Evolution of Applications, Hardware Design, and Channel Modelling for Terahertz (THz) Band Communications and Sensing: Ready for 6G?', Proc. of the IEEE, In-press, 2024. DOI:10.1109/JPROC.2024.3412828

5. https://www.ericsson.com/en/6g/spectrum/sub-thz
6. ITU-R, Report M.2516-0. 'Future technology trends of terrestrial International Mobile Telecommunications systems towards 2030 and beyond', 2022.
7. 3GPP TS 38.211 'NR; Physical channels and modulation' 3GPP; Technical Specification Group Radio Access Network. version 16.2.0 Release 16.
8. 3GPP TS 38.331 'NR; Radio Resource Control (RRC); Protocol specification' 3GPP; Technical Specification Group Radio Access Network.
9. Y. Xing and T. S. Rappaport. 'Millimeter Wave and Terahertz Urban Microcell Propagation Measurements and Models', IEEE Communications Letters, vol. 25, no. 12, pp. 3755–3759, 2021. DOI:10.1109/LCOMM.2021.3117900
10. J.F. Smith, Y. Gui, I. Fatadin. 'Measuring the peak performance of a 6G THz communication testbed, Frontiers in Antennas and Propagation', Article ID: 2:1471091, Vol. 24, pp. 1–9, 2024. DOI:10.3389/fanpr.2024.1471091
11. Abdo, et. al., '64 QAM wireless link with 300 GHz InP-CMOS hybrid transceiver', IEICE Electronics Express, Vol. 18, Issue. 17, 20210314–4, pp. 1–4, 2021. DOI:10.1587/elex.18.20210314
12. Bodet, et. al., 'Sub-terahertz near field channel measurements and analysis with beamforming and Bessel beams', Sci Rep., Vol. 14, Article ID: 19675, pp. 1–13, 2024. DOI:10.1038/s41598-024-70542-z
13. H. Hamada, et. al., '300-GHz-Band 120-Gb/s wireless front-end based on InP-HEMT PAs and mixers', IEEE J. Solid-State Circuits, Vol. 55, Issue. 9, pp. 2316–2335, 2020. DOI:10.1109/jssc.2020.3005818
14. Fatadin, et. al., 'Demonstration of 120 Gbit/s 64-QAM wireless link operating in the 300 GHz band', IEEE Access, Vol. 12, pp. 31159–31167, 2024. DOI:10.1109/access.2024.3368884
15. D. Marasinghe, et. al., 'Waveform Learning under Phase Noise Impairment for Sub-THz Communications', IEEE Trans. Commun., In-press, 2024. DOI: 10.1109/TCOMM.2024.3430982
16. Hexa-X Deliverable D2.3 - Radio models and enabling techniques towards ultra-high data rate links and capacity in 6G.


## Biographies

Prof. Bhargavi KVNA, is currently working as Head of KLH Global Business School and Assistant Professor in Computer Science Engineering Department. She holds good academic record and received a Gold Medal for her academic excellence.

**M. L. Ravi Chandra** currently working as a Professor and Head of ECE at Srinivasa Ramanujan Institute of Technology, Ananthapuramu, Andhra Pradesh, India since 2015. He has 22 technical publications in Journals and Conferences. His Research areas are Wireless Communications and IoT.

**Ravilla Dilli** is currently working at Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India. He holds 4 best research paper awards to his credit and received Excellence award for internship as part of SAMSUNG PRISM. He has published 40 research papers in International Journals and Conference Proceedings. His research expertise includes Network Security, MANETs, WSNs, 5G and 6G Wireless Technologies, and IoT.