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Analysis of 5G based New Radio Synchronisation Signal Block Detector using VHDL

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***Abstract*—The rapid development of mobile communication technologies like 4G LTE and 5G New Radio (NR) has enhanced wireless connections for clients. 5G promises ultra-high data speeds, minimal latency, massive device connections, and mission-critical application support, making it a game-changer for consumers and companies. These next-generation networks depend on the strength, stability, and quality of the Radio Frequency (RF) interface, which is the key layer of wireless communication between user equipment (UE) and the cellular infrastructure. This study will analyze CQI, SINR, RSRQ, and RSRQ to evaluate RF interface quality in 4G and 5G environments. These parameters affect signal coverage, data throughput, call quality, latency, and handover efficiency. The research uses field measurements, driving tests, and simulation models to examine how these indicators behave in urban, suburban, and rural deployment situations to give realistic and diverse datasets.**

Keywords: - 5G NR, Synchronization Signal Block (SSB), VHDL, PSS, SSS, PBCH, FPGA, Hardware Implementation.

I. INTRODUCTION

In this age of tremendous technological progress, wireless communication has become an important part of modern life. It has spread to every part of modern life, making it possible for services as different as smart transportation systems, remote healthcare, and high-definition (HD) video streaming to work together smoothly. The rapid growth of mobile technology has led to a flood of new ideas that are all about connecting people. These new gadgets aim to change the way people work, live, and play. The radio frequency interface (RF) is like an invisible highway for mobile data. It connects consumer devices like smartphones, tablets, and Internet of Things (IoT) sensors to network infrastructure including base stations, towers, and core systems. The invisible medium connects physical equipment to digital networks, enabling ongoing connection. The quality of the RF interface is now not just wanted, but also very important since more and more people are using data-heavy apps, smart gadgets are becoming more common, and mobile subscribers are growing at an exponential rate.

A powerful and high-quality RF connection makes it possible to talk on the phone, download data, have video conferences, and play games with little latency. The introduction of 4G LTE (Long-Term Evolution) marked a turning point in the history of mobile communications. It replaced the voice-centered architecture of earlier generations with a data-centered one, which made the spectrum more efficient, lowered latency, and increased data throughput. After it was out, services that depended on it, such live video streaming, real-time navigation, and chatting through applications, did very well. But as technology became better, new apps came up that pushed 4G networks to their limits. Applications including self-driving vehicles, remote robots, the Internet of Things (IoT), virtual reality (VR), and augmented reality (AR) started to need a lot more speed, latency, and device capacity. Even with all of these advancements, the RF interface is still the most essential thing that affects how well a network works. It doesn't matter how complicated your backend architecture is if a bad RF connection ruins the user experience. Weak signals, more interference, too much noise, or anything in the surroundings that get in the way can all cause data buffering, lost signals, slow connections, and call dropouts. There are a few major things that impact the quality of the RF interface in 4G and 5G networks: Strength of the signal (RSRP): This number tells you how strong the signal that was received is. This shows how well the signal is after taking noise and

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interference into account (RSRQ). The signal-to-interference-plus-noise ratio (SINR) tells you how clear a signal is compared to the quantity of background noise.

The Channel Quality Indicator (CQI) tells you how good a channel is for sending data. In big cities, buildings, automobiles, and trees all reflect and obstruct radio frequency signals. This causes intricate multipath effects and shadow zones. In these cases, managing coverage gaps and making sure that quality is high all the time requires very adaptable solutions. But RF performance could not be as good in suburban or rural areas because of things like uneven terrain, limited infrastructure, and being far away from the base station. One of the biggest problems with rolling out 5G is that it relies on high-frequency spectrum, notably mmWave bands (24 GHz and above). These bands have a lot of data capacity, but they lose a lot of signal strength, don't go through walls very well, and function best with a direct line-of-sight (LoS) connection. 5G RF behaviour is more complicated than 4G, hence advanced beam management, ultra-dense small cells, and antenna alignment are needed. In addition, technologies like dynamic beamforming, which improve performance by sending focussed RF beams at the user, need accurate real-time information on the user's position and movement.

Telecom companies are utilizing more and more technologies like coverage simulators, driving tests, and AI- and machine learning-driven monitoring systems to gather and analyze RF performance data in a wide range of scenarios, including as cities, rural areas, inside, and outdoors. The objective of this research is to conduct a comprehensive examination of the RF interface quality in 4G and 5G networks. We will measure and assess RSRP, RSRQ, SINR, and CQI values in a variety of real-world situations. It will also look at how infrastructure design, device mobility, and climatic variables affect RF performance. The aim of this research is to enhance existing networks by imparting a comprehensive understanding of RF behaviour. The research also talks about how important it is to get ready for the next generation of wireless networks, notably 6G, which is said to use terahertz frequencies, allow holographic communications, and be even quicker with less lag. A main objective of this project is to learn how to build smart, strong, and flexible radio frequency systems that can work with these new technologies.

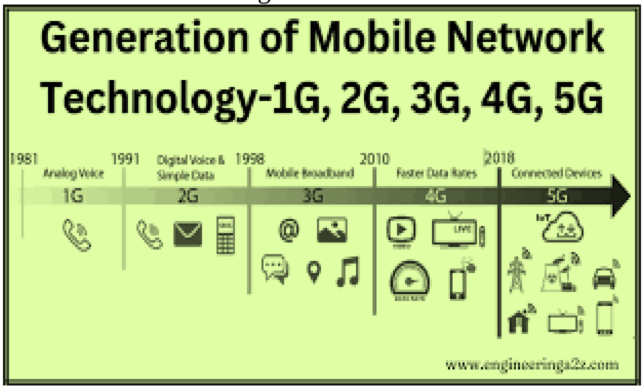

Fig. 1 Generation of mobile networking

Background: Radio frequencies are the means by which signals are sent between mobile devices and network equipment in wireless communication. RF performance determines technical dependability, user happiness, and network usability in both 4G and 5G systems

4G LTE:

- Operates typically in the 700 MHz to 2600 MHz bands.
- Uses OFDMA (Orthogonal Frequency Division Multiple Access).
- Key metrics include: RSRP, RSRQ, SINR, CQI.
- Delivers average speeds between 10–100 Mbps.

5G NR (New Radio):

- Operates in two major frequency ranges:
- FR1: Sub-6 GHz (e.g., 3.5 GHz)

FR2: mm Wave (24 GHz to 100 GHz).

II. LITERATURE REVIEW

Keyvan Ramezanpour et.al (2023): Coexistence network settings provide unique security concerns that intranet work security approaches have not addressed. The solo premise that intra-network procedures authenticate and approve all accesses no longer applies in coexistence contexts. Such network infrastructures allow attackers to degrade network bandwidth and install rogue base-stations in novel ways. Researchers examined major attacks that may compromise co-existing network security. Independent medium access control (MAC) in separate networks causes hidden node circumstances, making coexistence difficult. This allows an attacker to utilize the spectrum to occupy a big chunk or increase interference without being detected. First, a basic attacker reduces network bandwidth significantly. Rogue-base stations, man-in-the-middle attacks, and replay messages are also easier in this setting[01].

Jobish John et.al (2023): The paper analyzes the use of 5G, WiFi-7, and TSN in smart manufacturing applications for industry 4.0 and beyond. It highlights the potential benefits and challenges of these technologies, emphasizing the need for further research to address reliability, compatibility, and standardization. The comparative study provides insights into their industrial use cases, secondary applications, adoption trends, and market opportunities. The findings show that these technologies have significant potential to drive smart manufacturing towards the industry 4.0 vision. However, further efforts are needed to realize their potential. The paper aims to be a useful resource for researchers, engineers, and industrial practitioners interested in smart manufacturing [02].

Melissa Elkadi et.al (2023): This study aimed to provide an in-depth account of procedures and source code for a Rel. 16 3GPP compliant 5G SL prototype, including details of the implemented PSBCH and PSSCH in the OAI repository. The performance of the newly developed prototype was analyzed, including BLER curve reporting in simulation and OTA environments. A controlled experiment was conducted to support the proof of concept of the PSBCH. The results showed that the PSBCH and PSSCH implementation was robust and performed as

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expected in both a simulated and OTA environment. The experiment involved overlaying RFSIM and OTA data, using BLER results of MCS 9 from the RFSIM with the OTA max LDPC iterations = 10 BLER results, and using a cubic smoothing spline on the OTA data. The results indicated that the overall performance is consistent, with a significant drop in BLER values between 0 dB and 2 dB in the OTA environment due to environmental interference and a small number of trials conducted OTA. A smaller step size in SNR and more trials would likely smooth this transition [03].

Xu Yang et.al (2023): The researcher analyzes signals from both Beidou and 5G systems, focusing on the 5G out-of-band signal in the Beidou B1 band. They discuss the NR spectrum characteristics and radiation of 5G and analyze current ITU protection standards for navigation signals. They design a hybrid receiver architecture compatible with both signals, including hardware design of front-end, clock, baseband, and interface circuits. The researcher proposes a strong correlation-based rapid capture algorithm, which uses the strong correlation of signals broadcast on the B1 frequency point of BeiDou and performs fast decoding phase ambiguity processing for strongly correlated signals. This method achieves a capture sensitivity of -154 dBm for BeiDou B1 signals and a total constellation capture time of no more than 40 MS when the inlet power of 5G signals does not exceed 45 dBw [04].

Aytha Ramesh Kumar et.al (2022): This suggested design of the Primary SS and Secondary SS Synchronizer for 5G NR base-band receiver were validated, verified, and implemented efficiently on an FPGA Zynq-7000 series Zed board. The results show that the proposed design ensures the determination of cell identity effectively by incorporation of the proposed technique of primary and secondary synchronization blocks. Also, the hardware utilization is reduced by 63.7%, power consumption is reduced by 31.2%, and is operated with high speed with a minimum of 200 MHz and a maximum of GHz clock rates [05].

Kuan-Ying Huang et.al (2021):The study aimed to improve aid synchronization for a multi-carrier GNSS receiver by establishing a robust link on the FPGA. The conventional primary acquisition was used to provide assist data to other channels, while the primary tracking loop fetches auxiliary data from a master tracking loop in the primary channel. A robust estimator was designed to directly link the two tracking loops in the primary and second channels, ensuring robustness and reducing synchronization time The proposed aid scheme maintained the same computational load when noise was low, but maintained smaller uncertainty when errors between bands became severe. The direct link of the two loops released significant hardware resources, improving robustness and architecture efficiency [06].

Aytha Ramesh Kumar et.al (2021): This suggested design of the Primary SS and Secondary SS Synchronizer gadget for 5G NR base-band receiver were validated, verified and implemented efficiently on a FPGA Kintex Development Board. The system implemented calls for 5609 and 5932 common sense elements, every for Primary SS Synchronizer module and Secondary SS Synchronizer module, respectively. The delay and the most clock recurrence took into consideration the Primary SS Synchronizer module to operate are each 156.148 us and 75.97 MHz the take-off and the maximum clock frequency for the Secondary SS Synchronizer module respectively are 142.831 us and 75.09 MHz. The delays are enormously little and the most of clock frequencies. Further, this gadget design could likewise be utilized for various 5G NR signals with uncommon channel data transfer capacities with a couple of basic changes. Some different improvements in the gadget executes to flexibly better generally execution in expressions of area and speed consumption [07].

Mojtaba Vaezi et.al (2021):The Internet of Things (IoT) is rapidly growing, with cellular and wide area networks being the fastest-growing sectors. This paper provides a comprehensive survey of recent literature on the intersection of IoT and 5G/6G cellular networks. The researcher discusses key performance indicators of 5G and 6G networks, how IoT contributes to them, and recent advances. The survey also covers aspects of IoT overlooked by previous surveys, such as energy efficiency and channel coding for reliability and air latency. The researcher reviews the basic concepts and principles of various deep learning models and distributed and federated learning, emphasizing work specific to IoT across different application scenarios. The researcher also discusses how to tailor deep learning models to IoT applications and discusses solutions for integrating satellites and drones into next-generation IoT networks[08].

Yue Zhang et.al (2020): The paper introduces a new 5G radio and edge architecture for indoor environments, based on the IoRL system architecture. The system uses reconfigurable RAN settings, SDN concepts for traffic routing, and NFV technology for flexible service deployment. The IoRL architecture consists of three layers: service, NFV/SDN, and access layer, aligning with the overall 5G architecture. The paper also discusses improvements to the 5G remote radio head architecture, including VLC, mm Wave module, and RRLH. The multi-component carrier feature allows for transmission at different parts of the EM spectrum, potentially increasing total throughput to a building. The system has a high data rate of around 45.25 Mbit/s in the laboratory environment and a mean PE of 0.18 m [09].

Kleber Vieira et.al (2020):This article provides a comprehensive overview of the theoretical concepts for the IEEE Net Soft 2020 tutorial, focusing on the use of software in the 5G system, specifically the Radio Access Network (RAN) and core components, following 3GPP standards, particularly Release 15. It provides an overview of mobile cellular networks, including their basic concepts, operations, and evolution through generations. The article also discusses virtualization and disaggregation concepts in 4G and 5G networks, with a particular emphasis on Service-Based Architecture (SBA) due to its relevance and software approach. The article also provides a link to the repository for all material used in the tutorial [10].

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TABLE. 1 COMPARISON OF PREVIOUS RESEARCH WORK

Ref. / Year	Focus / Topic	Technology / Method	Application	Key Findings / Contributions
[1] / (2023)	Security in Coexistence Networks	MAC exploitation, rogue base stations	5G heterogeneous networks	Coexistence introduces hidden node attacks; standard intranet assumptions fail
[2]/ (2023)	Industry 4.0 Connectivity	5G, WiFi-7, TSN	Smart Manufacturing	Comparative benefits, adoption trends, and need for standardization
[3] / (2023)	5G Sidelink Prototype	PSBCH, PSSCH, BLER analysis	3GPP Rel. 16 Prototype Testing	BLER performance validated for OTA & simulation; SNR vs. BLER shown
[4] / (2023)	BeiDou–5G Interference	Hybrid signal receiver design	GNSS & 5G coexistence	Achieved -154 dBm sensitivity; hybrid receiver with SC-PMF-FFT
[5] / (2022)	SS Synchronizer Design	FPGA (Zynq-7000)	5G NR baseband	Reduced power (31.2%) & hardware (63.7%) consumption, GHz speeds
[6] / (2021)	GNSS Sync Robustness	FPGA, RLS, Bit-Boundary Aid	Multi-carrier GNSS	Reduced uncertainty, better sync robustness using primary-secondary tracking loop
[7] / (2021)	SS Synchronizer Gadget	FPGA (Kintex), Timing	5G NR signals	Efficient delays and flexible bandwidth utilization

III. Proposed Method

This section focuses on explaining network connectivity, and how the data was prepared and analyzed for developing a classification model using the selected modeling techniques. Finally, evaluations metrics are presented that are used for evaluating the performance of the developed model.

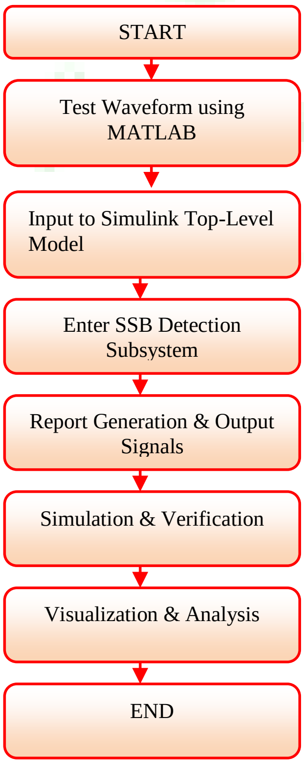

Fig. 2 Flow Diagram

The SSB detector performs primary synchronization sequence (PSS) search, orthogonal frequency division multiplexing (OFDM) demodulation, and secondary synchronization sequence (SSS) search. It also includes a digital down converter (DDC) for correcting frequency offsets in the received signal. The SSB detector has two modes of operation, search and demodulation, which are demonstrated in this example. In search mode, the detector searches for SSBs and returns their parameters. In demodulation mode, the detector recovers a specified SSB OFDM-demodulates its resource grid and searches for SSS within the appropriate resource elements.

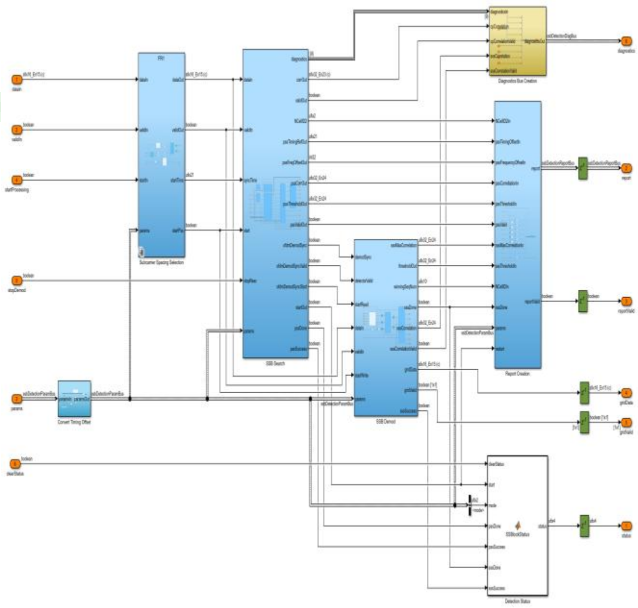

Fig. 3 SSB detection model

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Structure
The example uses these files.
Simulink models

- nrhdlSSBDetection.slx: This Simulink model uses the simulates the behavior of SSB detection.
- nrhdlSSBDetectionFR1Core.slx: This model implements the SSB detection algorithm.
- nrhdlDDCFR1Core.slx: This model implements a DDC to create sample streams for SIB1 and SSBs.

Simulink data dictionary

- nrhdl Receiver Data.sldd: This Simulink data dictionary contains bus objects that define the buses contained in the example models.

MATLAB code

- Run NRSSB Detection Model Search.m: Script for running and verifying the nrhdlSSB Detection model in search mode.
- Run NRSSB Detection Model Demod.m: Script for running and verifying the nrhdlSSB Detection model in demodulation mode.

Nrhdlexamples: Namespace containing the MATLAB reference code and utility functions for verifying the implementation models.

IV. SIMULATION AND RESULT

Simulation Setup The block diagram shows the simulation setup of this example, which is implemented in the run NRSSB Detection Model Search and run NRSSB Detection Model Demod scripts. 5G Toolbox™ functions are used to generate a test waveform which is applied to the MATLAB and Simulink implementations of the SSB detector in search mode and then in demodulation mode. Key diagnostic signals from each detector are compared in terms of their relative mean-squared error (MSE) and the final outputs are compared. Finally, the resource grid output of the Simulink model is decoded to show that the MIB contents are as expected.

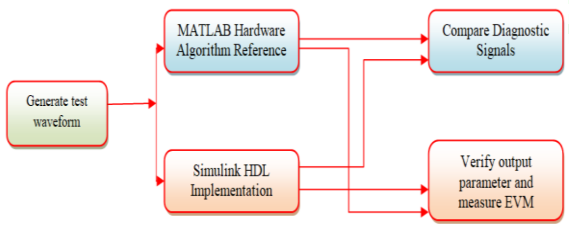

Fig. 4 Simulation Setup

Build Summary
0 of 2 models built (2 models already up to date)
Build duration: 0h 0m 1.7832s
VarDim N, SF N, concat N, TLC YVarDim N, SF N, concat N, TLC YVarDim N, SF N, concat N, TLC YVarDim N, SF N, concat N, TLC YVarDim N, SF N, concat N, TLC YVarDim N, SF N, concat N, TLC Y..........
SSBs found by MATLAB reference:

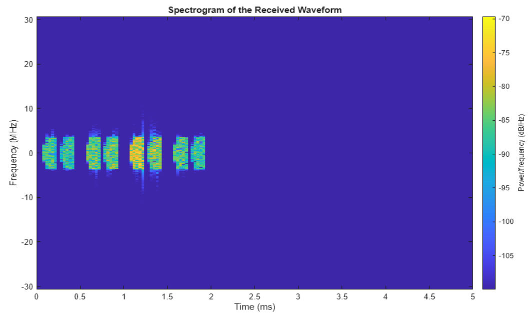

Fig. 5 spectrogram of received waveform

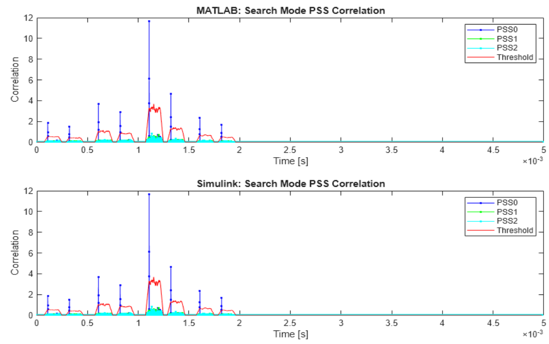

Fig. 6 Correlation Graph

Use the Simulink Logic Analyzer to view the inputs and outputs to the SSB Detection subsystem. The detector looks for PSS symbols within a 20 ms time window, which begins after a pulse on the *start* input triggers the search operation. If no PSS symbols are found after 20 ms, the detector sets the *status* output to 2 - indicating that the search has failed. In this example, the detector finds all eight SSBs. The *status* output is set to 1 during the search, and a report is returned for each SSB by asserting the *reportValid* signal. The simulation only runs for 5 ms however if it is extended to run for more than 20 ms, then the *status* output is eventually set to 3 - indicating that the search has succeeded.

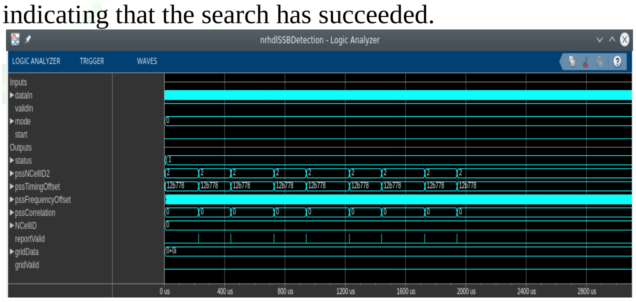

Fig. 7 Logic Analyzer

Demodulation Mode Simulation
After running run NRSSB Detection Model Search, use the run NRSSB Detection Model Demod script to run a single demodulation mode simulation and verify the results. The script displays its progress in the MATLAB command window. SSB reports from MATLAB and Simulink show that both detectors returned similar parameters and determined the cell ID correctly as 249. Relative MSE measurements indicate

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that the MATLAB and Simulink implementations match very closely. As a final verification step, the script decodes the broadcast channel (BCH) from the Simulink resource grid output. The CRC check passes and the master information block (MIB) contents match the transmission. Plots are generated which show the PSS and SSS correlation results, and the resource grid output. The PSS correlation levels are stronger in the demodulation mode simulation than in search mode simulation because the frequency offset is corrected.

Run NRSSB Detection Model Demod;

Choosing the strongest PSS from the previous search and computing its frequency offset.

Strongest PSS index (1 based): 5

Frequency offset (coarse + fine): 4.949 kHz

Demodulating the strongest SSBs using the MATLAB reference.

Demodulating the strongest SSBs using the Simulink model.

Running nrhdlSSBDetection.slx

Searching for referenced models in model 'nrhdlSSBDetection'.

Total of 2 models to build.

Starting serial model build.

Model reference simulation target for nrhdlDDCFR1Core is up to date.

Model reference simulation target for nrhdlSSBDetectionFR1Core is up to date.

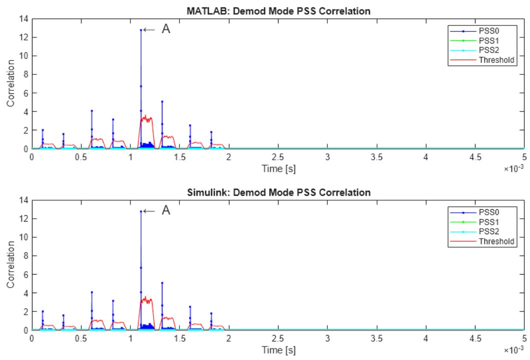

Fig. 8 Correlation Graph

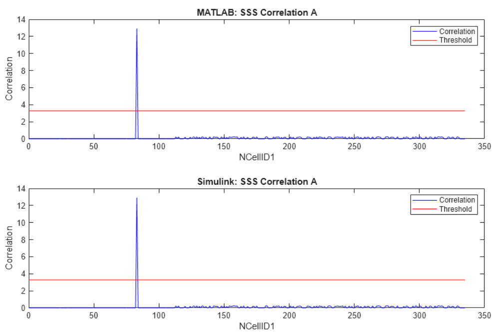

Fig. 9 Correlation Graph

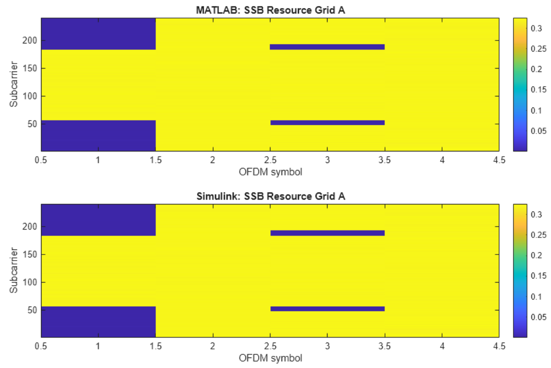

Fig. 10 Correlation Graph

Table 2 The values of accuracy of classification made on real time dataset

Resource	Usage
Slice Registers	34819
Slice LUTs	20861
RAMB18	12
RAMB36	0
DSP48	209

Table 3 Result Comparison Table with previous work

Reference / (Year)	Slice Registers	Slice LUTs	RAMB18	RAMB36	DSP48
Proposed	34819	20861	12	0	209
[05] / (2022)	34,819	20,86	12	0	209

V.CONCLUSION

The HDL-optimized 5G NR Synchronization Signal Block (SSB) detection model has been successfully implemented and validated through MATLAB and Simulink simulations. The model efficiently performs essential cell search operations, including Primary Synchronization Signal (PSS) detection, Orthogonal Frequency Division Multiplexing (OFDM) demodulation, Secondary Synchronization Signal (SSS) detection, and frequency offset correction. Simulation results demonstrate the accuracy and robustness of the design, with the system detecting all eight valid SSBs within the expected 20 ms window. Both MATLAB and Simulink implementations consistently identified the correct cell ID and successfully decoded the Master Information Block (MIB), confirming system reliability. Quantitative evaluation shows excellent correlation between MATLAB and Simulink outputs, with low relative mean squared error values, highlighting the high fidelity of the fixed-point Simulink model in replicating the behavior of the floating-point MATLAB reference model. The

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HDL code generated from the model was synthesized for the Xilinx® Zynq®-7000 ZC706 evaluation board, achieving a clock frequency of 230 MHz and efficient resource utilization, indicating suitability for FPGA or ASIC implementation.

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