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A Novel FPGA-Based Synchronization Signal Sequence Detection Technique for 5G NR Communication Systems

Ashish Singh[1], **Aditya Mishra**[2]
VLSI M. Tech Scholar[1], Assistant Professor [2]
[1,2]Department of Electronics and Communication Engineering *(ECE)*
[1, 2]Vidhyapeeth Institute for Science & Technology, Bhopal. MP INDIA
Email Address: ashishsingh.ec18@gmail.com adivgi023@gmail.com

***Abstract*—The evolution of modern wireless communication systems from 4G LTE to Fifth Generation Wireless Communication has significantly improved mobile connectivity by enabling higher data rates, lower latency, enhanced spectral efficiency, and massive device connectivity for next-generation applications. The overall performance of these advanced cellular networks largely depends on the reliability and quality of the Radio Frequency (RF) interface, which acts as the communication bridge between user equipment and cellular base stations. This study presents a comprehensive evaluation of RF interface performance in both 4G LTE and 5G NR environments using important network quality indicators such as Channel Quality Indicator (CQI), Signal-to-Interference-plus-Noise Ratio (SINR), Reference Signal Received Power (RSRP), and Reference Signal Received Quality (RSRQ). These parameters play a vital role in determining signal coverage, throughput performance, communication reliability, handover efficiency, and latency characteristics in wireless networks. The research incorporates field measurements, drive-test analysis, and simulation-based evaluations across urban, suburban, and rural deployment scenarios to obtain realistic and diverse datasets for comparative analysis. Furthermore, the study investigates the impact of propagation conditions, interference levels, mobility, and network density on RF signal performance in heterogeneous communication environments. The analysis demonstrates that 5G NR achieves superior signal quality, improved spectrum utilization, and higher throughput capability compared to conventional 4G LTE systems, especially in dense network deployments. However, challenges related to interference management, signal attenuation, and coverage consistency in high-frequency 5G bands are also identified. The findings of this research provide valuable insights for researchers, network designers, and telecommunication industries involved in the optimization and deployment of next-generation wireless communication systems..**

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

I. INTRODUCTION

The continuous advancement of wireless communication technologies has transformed modern society by enabling seamless digital connectivity across various applications and services[7][2]. Mobile communication systems have evolved rapidly from conventional voice-centric networks to high-speed intelligent communication infrastructures capable of supporting data-intensive applications such as smart transportation, industrial automation, telemedicine, cloud computing, virtual reality, augmented reality, and Internet of Things (IoT) ecosystems [5][7]. The emergence of Fourth Generation Mobile Communication and Fifth Generation Wireless Communication has significantly improved network capacity, spectral efficiency, reliability, and user experience in modern wireless environments [1] [2]. These technologies are designed to support massive connectivity, ultra-low latency communication, and extremely high data transmission rates required for next-generation digital applications [3] [5].

The Radio Frequency (RF) interface forms the fundamental communication link between user equipment and cellular network infrastructure, including base stations, antennas, and core communication systems [1]. The performance of mobile communication networks is highly dependent on the quality and reliability of the RF interface because it directly affects signal transmission, data throughput, mobility management, and communication stability [3]. A strong RF connection enables uninterrupted voice communication, high-speed internet access, real-time video conferencing, online gaming, and cloud-based services with minimal latency and reduced packet loss [4][6]. However, degradation in RF interface quality can severely affect network performance, leading to poor signal coverage, reduced throughput, increased interference, call drops, and communication delays [8][9].

The deployment of 4G LTE networks introduced a major transformation in wireless communication by shifting network architecture from voice-oriented communication to packet-based high-speed data services [10][11]. The technology improved spectrum utilization, reduced transmission latency, and enabled broadband mobile communication services such as high-definition video streaming, live multimedia communication, and location-based services [13]. Despite these improvements, the rapid growth of smart devices and emerging applications created increasing demands on network capacity and communication reliability [11] [15]. Applications such as autonomous vehicles, remote robotic systems, smart healthcare, machine-to-machine communication, and immersive multimedia services require significantly higher bandwidth, ultra-reliable communication, and real-time responsiveness that exceed the capabilities of conventional cellular systems [12][7].

To address these limitations, 5G New Radio technology was introduced with advanced communication features including massive Multiple Input Multiple Output (MIMO), millimeter-wave communication, beamforming, network slicing, and ultra-dense small-cell deployment. These technologies provide improved spectral efficiency and support large-scale connectivity for future intelligent communication systems. However, the use of high-frequency spectrum bands, particularly millimeter-wave frequencies above 24 GHz, introduces several challenges related to signal propagation, path loss, penetration capability, and interference management [18]. Unlike lower-frequency communication systems, high-frequency 5G signals experience significant attenuation and require accurate beam alignment and line-of-sight communication for efficient transmission. Therefore, maintaining high RF interface quality becomes increasingly important in 5G communication environments[19] [20].

Several important performance metrics are commonly used to evaluate RF interface quality in modern cellular networks. Reference Signal Received Power (RSRP) is used to measure the strength of the received reference signal and indicates the coverage capability of the network [21][22]. Reference Signal Received Quality (RSRQ) evaluates overall signal quality by considering signal power, interference, and noise conditions. Signal-to-Interference-plus-Noise Ratio (SINR) represents signal clarity and communication reliability under noisy environments, while the Channel Quality Indicator (CQI) provides information regarding channel conditions and achievable data transmission quality [23]. These parameters collectively determine network efficiency, user experience, handover performance, and communication reliability in both 4G and 5G systems [9][11].

RF performance is strongly influenced by environmental and deployment conditions. In dense urban areas, buildings, vehicles, and other obstacles cause multipath fading, signal reflection, diffraction, and shadowing effects that complicate wireless signal propagation. In suburban and rural environments, large distances between users and base stations, irregular terrain, and limited communication infrastructure can reduce network coverage and signal stability. Furthermore, user mobility, weather conditions, interference from neighboring cells, and network congestion also affect RF communication quality. As a result, efficient RF optimization techniques and intelligent network management strategies are necessary to maintain stable and reliable wireless communication across different deployment scenarios [16].

Modern telecommunication systems increasingly utilize advanced monitoring and optimization techniques such as drive testing, propagation modeling, coverage prediction tools, and artificial intelligence-based network analysis to evaluate RF performance under practical operating conditions. These techniques help network operators identify coverage gaps, optimize antenna placement, improve beamforming efficiency, and enhance overall network reliability. In addition, machine learning algorithms are being integrated into wireless systems to support adaptive resource allocation, interference mitigation, and predictive network optimization for future communication networks.

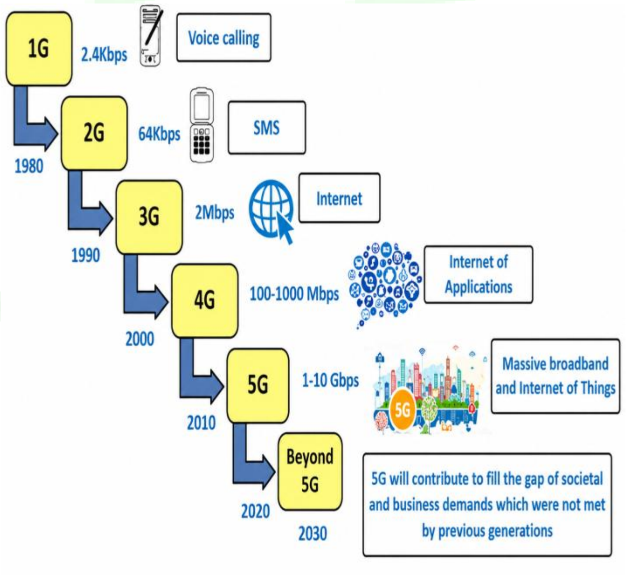

Fig. 1 Generation of mobile networking [24]

II. 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.

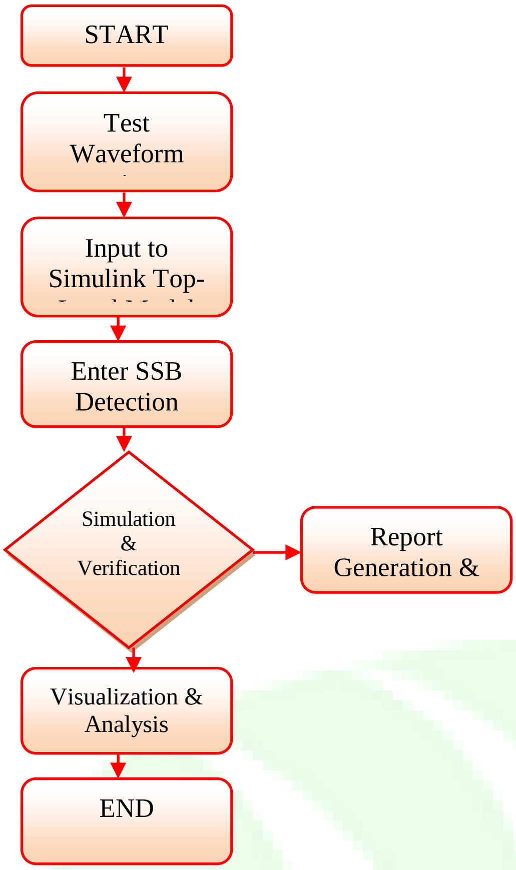

Fig. 2: Flow Diagram

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.

SSB Detection Model

This diagram shows the top level of the nrhdlSSBDetectionFR1Core model. The model performs SSB detection and demodulation. Its internal sampling rate varies depending on the subcarrier spacing (SCS). The model uses 7.68 Msps for 30kHz SCS and 3.84 Msps for 15kHz SCS. The Subcarrier Spacing Selection subsystem on the left is responsible for changing the sampling rate. The rate can change only when a new operation is triggered by the *startProcessing* input.

The receiver has an internal timing reference system that keeps track of time by using counters at key points in the datapath. Time is measured in samples at 61.44 Msps modulo 1228800. Therefore the timing reference wraps around every 20ms - the assumed SSB periodicity for cell search as defined by the 5G NR standard. Since the actual sampling rate is either 7.84 Msps or 3.84 Msps, the timing reference counters increment by either 8 or 16, respectively, for each sample. The timing reference is relative to the first valid sample at the input and runs continuously. When a new operation is triggered by the *start* input, the timing reference is not restarted. Instead, the start time is recorded at the input timing reference.

The other timing references wait until reaching the start time before changing their increment, when a new subcarrier spacing and corresponding sampling rate applies. This architecture enables the receiver to keep track of time consistently, even when a sampling rate change occurs. Due to hardware latency, the other timing references lag behind the input timing reference. The timing update process relies on this latency.

The nrhdlSSBDetectionFR1Core model contains these main subsystems.

- *Subcarrier Spacing Selection*: Converts the input to two synchronized sample streams, one at 7.68 Msps and one at 3.84 Msps, and selects which stream to pass to subsequent processing stages according to the subcarrier spacing.
- *SSB Search*: Performs PSS correlation to search for SSBs.
- *SSB Demod*: Performs OFDM demodulation and SSS correlation.
- *Report Creation*: Aligns all of the parameters corresponding to one SSB detection, so that they are all valid at the same time.

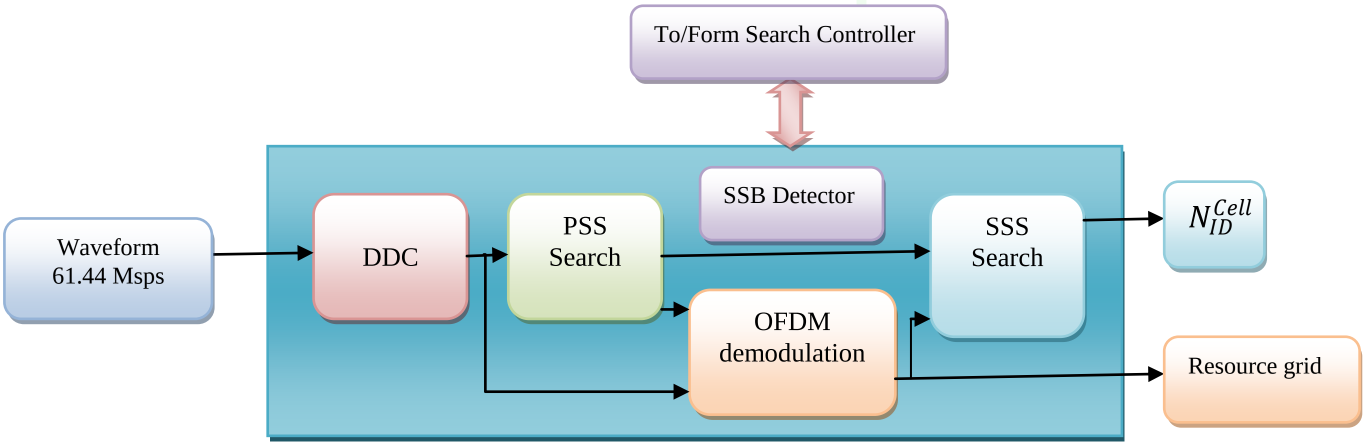

Fig. 3: SSB detection model

III. 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.

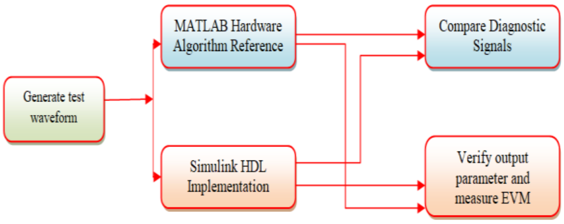

Fig. 4 Simulation Setup

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:

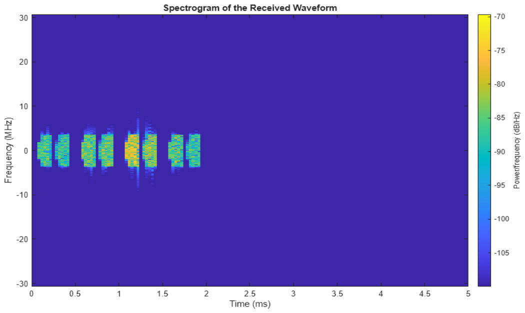

Fig. 5 spectrogram of received waveform

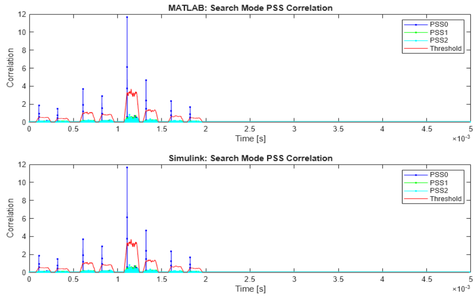

Fig. 6 Correlation Graph

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.

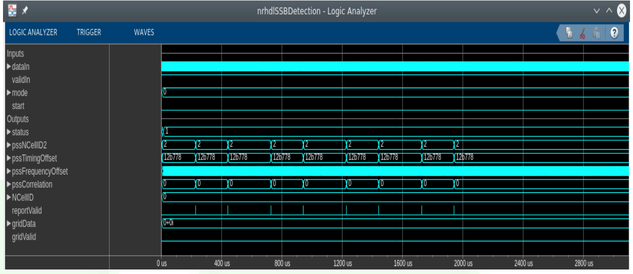

Fig. 7 Logic Analyzer

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 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.

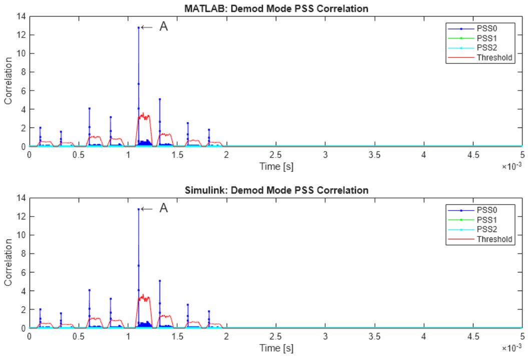

Fig. 8 Correlation Graph

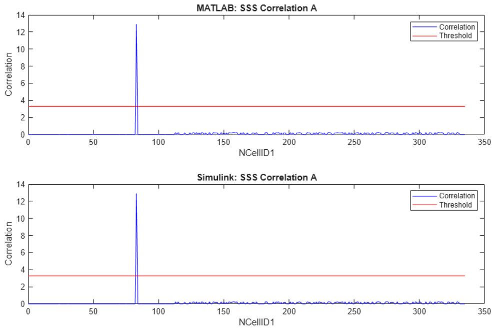

Fig. 9 Correlation Graph

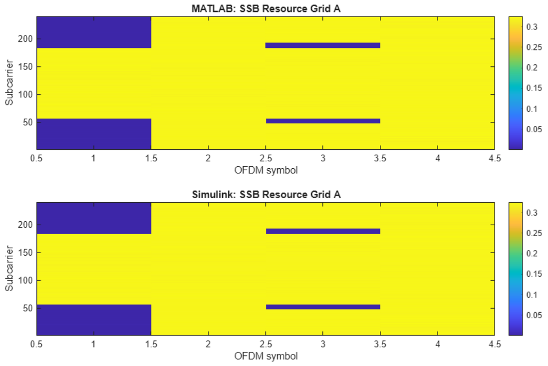

Fig. 10 Correlation Graph

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

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 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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