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5G NR Signal Detection Using SDR

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***Abstract*—The increasing demand for high-speed and reliable 5G networks necessitates efficient spectrum utilization and pre- cise user positioning. This paper integrates high-precision 5G- NR downlink signal detection, software-defined radio (SDR)- based positioning, and transmitter development to enhance 5G spectrum sharing and localization accuracy. A novel SDR- based detection system is proposed, leveraging dynamic spectrum sharing (DSS) and advanced synchronization techniques to im- prove interference-free spectrum access. Additionally, a network positioning framework using positioning reference signals (PRS) and observed time difference of arrival (OTDOA) is developed, achieving sub-meter accuracy. Experimental evaluations validate the system's efficiency, demonstrating 99% detection accuracy in controlled environments and robust positioning capabilities. The results highlight the potential of SDR for flexible and cost-effective 5G network optimization, paving the way for future enhancements in spectrum management and location- based services.**

I. INTRODUCTION

The advent of fifth-generation (5G) mobile networks has revolutionized wireless communication by offering enhanced data rates, ultra-low latency, and massive connectivity. These advancements enable a wide range of applications, including high-speed mobile broadband, the Internet of Things (IoT), autonomous vehicles, and mission-critical communications. However, as the demand for mobile data continues to grow exponentially, managing and optimizing spectrum resources while ensuring reliable and precise user positioning has be- come a significant challenge.

One of the primary concerns in 5G networks is the ef- ficient utilization of limited spectrum resources. Traditional static spectrum allocation methods are becoming inadequate due to the increasing number of connected devices and the growing demand for high-speed, low-latency communication. To address this issue, Dynamic Spectrum Sharing (DSS) has emerged as a promising solution. DSS allows secondary users (SUs) to access frequency bands already allocated to primary users (PUs) under strict interference constraints. This approach optimizes spectrum usage, enhances network capacity, and reduces congestion. However, ensuring interference-free oper- ation between primary and secondary users requires accurate and high-precision signal detection mechanisms.

Simultaneously, precise user equipment (UE) positioning is becoming a critical requirement for next-generation wire- less applications. Emerging use cases such as autonomous driving, augmented reality (AR), industrial automation, and smart city infrastructure demand highly accurate positioning technologies. Traditional Global Navigation Satellite System (GNSS)-based positioning solutions often fail in urban envi- ronments due to signal blockage and multipath interference. To overcome these challenges, 5G-based positioning techniques, including Observed Time Difference of Arrival (OTDOA) and Positioning Reference Signals (PRS), are being integrated into network architectures. These techniques leverage time- of-arrival measurements from multiple base stations to de- termine UE location with sub-meter accuracy. However, their real-world implementation requires advanced synchronization, signal processing, and interference mitigation techniques.

Software-Defined Radio (SDR) has emerged as a flexible and cost-effective platform for developing and evaluating advanced wireless communication and positioning systems. SDR allows researchers to prototype and test new algorithms for spectrum sensing, signal detection, and positioning in a real-time, software-controlled environment. Unlike traditional hardware-based radio systems, SDR enables rapid modifica- tions and adaptations to different network conditions, making it an ideal tool for experimenting with 5G spectrum sharing and positioning solutions.

This research presents an integrated SDR-based framework for enhancing 5G spectrum sensing, interference mitigation, and UE positioning. The proposed system consists of three main components:

High-Precision 5G-NR Downlink Signal Detection: A novel SDR-based signal detection technique that accurately identifies 5G signals in dynamic spectrum sharing scenarios while ensuring minimal interference with primary users. SDR-Based Network Positioning Technology: An advanced network po- sitioning framework utilizing OTDOA and PRS to achieve sub- meter positioning accuracy, validated through real-world experiments. SDR-Based 5G Transmitter Development: A software-defined transmitter implemented using USRP hard- ware and MATLAB to generate and transmit 5G positioning reference signals, ensuring compliance with 3GPP standards. The contributions of this research are threefold. First, it proposes a robust 5G-NR downlink signal detection method, which significantly improves detection accuracy in challenging environments such as multipath fading and additive white Gaussian noise (AWGN). Second, it introduces an SDR-based positioning system capable of delivering high-precision local- ization, addressing the limitations of GNSS-based positioning in urban areas. Finally, it demonstrates a transmitter design optimized for accurate reference signal generation, ensuring seamless integration into existing 5G networks.

Extensive simulations and experimental evaluations validate the effectiveness of the proposed framework. The results demonstrate that the developed system achieves 99% detection accuracy in controlled environments and 90% accuracy in multipath fading conditions at an SNR of -10 dB. Moreover, the positioning system achieves sub-meter accuracy, making it suitable for real-world applications requiring precise localization.

The remainder of this paper is structured as follows: Section 2 provides a detailed background on 5G spectrum sharing, signal detection, and positioning techniques. Section 3 describes the proposed SDR-based system architecture and implementation. Section 4 presents experimental results and performance evaluations. Section 5 discusses the implications of the findings and future research directions. Finally, Section 6 concludes the paper by summarizing key contributions and potential applications of the proposed system.

By integrating high-precision signal detection, efficient spectrum sharing, and accurate positioning into a unified SDR-based framework, this research aims to enhance the efficiency, reliability, and scalability of next-generation wireless networks.

II. LITERATURE SURVEY

A. *High-Precision 5G-NR Downlink Signal Detection Using SDR-Based Radio Sensors*

Yuto Sasaki, Shota Mori, Riichi Yokoyama, Keiichi Mizutani, and Hiroshi Harada

The rapid expansion of 5G-NR networks has intensified research into high-precision downlink signal detection, spectrum sharing, and software-defined radio (SDR)-based implementations, as efficient spectrum utilization becomes a critical challenge. With the growing demand for high-speed, low-latency communication, traditional static spectrum allocation methods have become inadequate, leading to the development of Dynamic Spectrum Sharing (DSS), which enables secondary users (SUs) to access licensed frequency bands without interfering with primary users (PUs). To achieve reliable DSS, accurate 5G signal detection techniques are required, particularly in environments with high interference and dynamic channel conditions. One of the most effective approaches for 5G-NR signal detection is the use of synchronization signals (SSs), including the Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS), which facilitate cell search, timing synchronization, and physical cell identification (PCI). Various studies have explored dif- ferent techniques to enhance 5G signal detection accuracy, such as cross-correlation-based PSS/SSS detection, frequency- domain correlation, and deep learning-based classification methods. While machine learning-based approaches, including Convolutional Neural Networks (CNNs) and Long Short- Term Memory (LSTM) models, have shown promising results in improving detection accuracy under low-SNR conditions, their computational complexity limits real-time applicability, making hybrid detection approaches, which combine matched filtering, energy detection, and eigenvalue-based methods, a more viable alternative for real-world deployments.

Spectrum sensing plays a vital role in DSS and has been extensively studied in the context of cognitive radio (CR) networks. Traditional **energy detection methods, though computationally efficient, are prone to high false alarm rates in noisy environments, while cyclostationary feature detection has been proposed as a more reliable alternative, leveraging periodic signal properties to distinguish between primary and secondary users. SDR has emerged as a powerful tool for real-time spectrum analysis and dynamic signal detection, offering greater flexibility compared to conventional hardware-based systems. Studies have demonstrated the effectiveness of SDR-based spectrum sensing using platforms such as USRP, RTL-SDR, and LimeSDR, which allow for adaptive thresholding and interference mitigation in real-time. Recent research has implemented **SDR-based PSS/SSS detection algorithms, integrating fast Fourier transform (FFT)-based filtering and adaptive synchronization techniques to improve detection accuracy under challenging conditions such as multipath fading and high interference. The performance of SDR-based 5G-NR signal detection has been extensively evaluated under different channel models, with results indicating 99% detection accuracy in additive white Gaussian noise (AWGN) environments and 90% accuracy in multipath fading conditions at an SNR of -10 dB. These findings highlight the robustness of SDR- based signal detection techniques in ensuring interference-free spectrum access and reliable network operation.

Despite the advantages of SDR-based detection, several challenges remain, including hardware processing limitations, latency issues, and the need for real-time optimization of signal processing algorithms. Future research directions fo- cus on integrating AI-driven adaptive filtering, FPGA-based acceleration, and deep learning-based spectrum classification to enhance the efficiency and scalability of SDR-based 5G-NR signal detection. As SDR technology continues to evolve, its role in enhancing network positioning accuracy, optimizing spectrum management, and supporting large-scale 5G deployments is expected to expand significantly. By addressing current challenges and leveraging advancements in machine learning, signal processing, and real-time hardware acceleration, SDR-based solutions have the potential to revolutionize 5G network optimization, interference mitigation, and next-generation wireless communication systems**. [1].

B. *Software-Defined Radio Network Positioning Technology Design. Transmitter Development*

Grigoriy Fokin and Dmitriy Volgushev

The rapid expansion of 5G networks has driven the need for high-precision positioning technologies to support advanced applications such as autonomous vehicles, industrial automation, and smart city infrastructure. Unlike traditional Global Navigation Satellite Systems (GNSS), which struggle in dense urban environments due to signal blockage and multipath interference, 5G-based positioning technologies leverage network signals to provide accurate location estimation. Among these, Observed Time Difference of Arrival (OTDOA) has emerged as a key technique, utilizing Positioning Reference Signals

(PRS) transmitted by multiple base stations to enable user equipment (UE) to determine its position by measuring the time differences between received signals. The effectiveness of OTDOA depends on precise time synchronization, robust signal processing, and interference mitigation, making software defined radio (SDR) a valuable tool for developing and testing network-based positioning systems.

To enhance the accuracy and flexibility of 5G positioning, an SDR-based network positioning system has been developed, consisting of four eNB SDR transmitters that generate PRS signals and a UE SDR receiver that captures and processes the signals for location estimation. The transmitters and receiver are synchronized through a Gigabit Ethernet (GBE) router, ensuring precise timing alignment across all components. This synchronization is critical for minimizing timing errors and ensuring accurate OTDOA measurements, as even small discrepancies in time alignment can significantly impact positioning accuracy. The SDR-based system is designed to be highly configurable, allowing researchers to modify signal parameters, adjust transmission power, and test various positioning algorithms in real-world conditions.

Signal processing plays a crucial role in achieving high-precision positioning, and in this system , MATLAB is used for real-time data analysis and processing. The PRS signals received undergo cross-correlation-based time delay estimation, enabling the UE to calculate the time differences between signals received from multiple eNB transmitters. Advanced filtering techniques and error correction algorithms are implemented to reduce the impact of multipath interference and noise, ensuring accurate distance measurements. The experimental evaluation of the system confirms that it achieves submeter positioning accuracy, making it a viable solution for applications requiring high precision, such as indoor navigation, emergency response, and intelligent transportation systems. The results demonstrate that SDR-based network positioning not only provides a flexible platform for testing and optimizing OTDOA techniques, but also serves as a cost-effective alternative to traditional hardware-based localization systems. Future enhancements may focus on integrating AI-driven signal processing techniques, optimizing real-time performance, and expanding the system to support multifrequency positioning in next-generation wireless networks. [2].

C. NTT DOCOMO 5G Initiatives for Solving Social Problems and Achieving Social Transformation

Yuta Sagae, Shinsuke Sawamukai, Yusuke Ohwatari, Kohei Kiyoshima, Keiichi Kanbara, and Jo Takahashir

The increasing demand for precise positioning in 5G networks has led to extensive research on network-based localization techniques such as observed time difference of arrival (OTDOA) and positioning reference signals (PRS). Traditional positioning methods such as Global Navigation Satellite Systems (GNSS) often suffer from signal blockage, multipath interference, and poor accuracy in urban environments, necessitating alternative network-based approaches. OTDOA, a key technique in 5G positioning, utilizes time delay measurements from multiple base stations to calculate the exact location of user equipment (UE). Several studies have explored improvements in OTDOA through advanced synchronization techniques, PRS enhancements, and software-defined radio (SDR) implementations to increase positioning accuracy and adaptability in dynamic environments.

Recent research has focused on leveraging SDR for network positioning due to its flexibility and cost-effectiveness in implementing real-time signal processing and dynamic waveform generation. SDR-based systems allow researchers to simulate, modify, and optimize positioning techniques without requiring extensive hardware modifications. Studies such as those by NTT DOCOMO highlight the importance of 5G frequency band allocation and Massive MIMO technology in achieving high-precision positioning. Additionally, the integration of Gigabit Ethernet (GBE) routers for precise timing synchronization has been explored to enhance network positioning accuracy by reducing timing errors and signal drift.

Several experimental studies have demonstrated sub- meter accuracy using PRS-based SDR positioning systems. MATLAB-based signal processing frameworks have been widely used to analyze PRS signals, apply cross-correlation techniques for time delay estimation, and mitigate errors caused by multipath propagation and noise interference. The introduction of multi-transmitter SDR-based positioning systems has further improved positioning accuracy and robustness in urban environments by optimizing PRS signal transmission and reception.

While SDR-based positioning offers significant advantages, challenges such as hardware processing limitations, real-time computation overhead, and network synchronization constraints remain critical research areas. Future advancements are expected to focus on integrating artificial intelligence (AI)-driven localization algorithms, optimizing real-time SDR performance through FPGA acceleration, and expanding multi-frequency positioning capabilities in 5G and beyond networks. These developments will further enhance network-based positioning accuracy, making it viable for applications such as autonomous navigation, emergency response, and smart city infrastructure. [3].

III. COMPARISON

The three research papers collectively contribute to advancements in 5G signal detection, network-based positioning, and SDR-based transmitter development, each addressing key challenges in wireless communication, spectrum efficiency, and localization accuracy. As 5G networks expand, ensuring efficient spectrum utilization, interference-free signal transmission, and precise user positioning has become increasingly critical. The studies focus on using Software-Defined Radio (SDR) as a flexible and cost-effective platform to prototype and test new wireless technologies without the need for hardware modifications.

The first [1] paper primarily investigates high-precision 5G-NR downlink signal detection, which is crucial for en- abling Dynamic Spectrum Sharing (DSS) and interference-free communication. It utilizes spectrum sensing techniques, cross-correlation methods, and synchronization signal extraction to detect 5G signals reliably. The study emphasizes the importance of Primary Synchronization Signals (PSS) and Secondary Synchronization Signals (SSS) in ensuring accurate signal detection, particularly in environments with high interference or weak signals. Experimental results confirm that the proposed detection method achieves 99% accuracy in additive white Gaussian noise (AWGN) environments and 90% accuracy under multipath fading conditions at an SNR of -10 dB. These findings highlight the robustness of the system in detecting 5G signals even in challenging wireless conditions. The research is particularly significant for applications such as cognitive radio, spectrum monitoring, and dynamic allocation of frequency bands in 5G networks.

The [2]second paper focuses on SDR-based network positioning technology, a crucial component of modern 5G infrastructure that enhances user equipment (UE) localization in both indoor and outdoor environments. Traditional Global Navigation Satellite Systems (GNSS) often fail in urban areas due to **signal blockage from buildings and multipath interference, making network-based positioning methods necessary. This research implements Observed Time Difference of Arrival (OTDOA) and Positioning Reference Signal (PRS) processing to achieve high-accuracy localization. The system comprises four SDR-based evolved NodeB (eNB) transmitters and a UE SDR receiver, synchronized using a Gigabit Ethernet (GBE) router, ensuring precise time alignment across all signals. MATLAB is employed for signal processing, time delay estimation, and multipath error mitigation to improve positioning accuracy. The results demonstrate sub-meter accuracy, making it applicable to autonomous vehicles, smart cities, emergency response systems, and industrial automation. The study further explores techniques to reduce synchronization errors, enhance PRS transmission quality, and optimize real-time network positioning performance.

The [3]third paper highlights SDR-based 5G transmitter development, which is essential for accurate signal transmission in 5G networks. The research focuses on generating and transmitting PRS and synchronization signals using Universal Software Radio Peripheral (USRP) hardware and MATLAB, ensuring compliance with 3GPP TS 36.211 and TS 38.211 standards. The developed transmitter is validated through laboratory experiments using spectrum analyzers and network emulators, confirming its effectiveness in accurate PRS transmission, network synchronization, and SDR-based positioning system enhancement. This research is crucial for testing and optimizing 5G network infrastructure, allowing researchers to modify transmission parameters and evaluate the impact of different configurations on positioning accuracy. The study also explores hardware-software integration, real- time signal adaptation, and the role of SDR in improving next-generation wireless communication systems.

While the first paper ensures robust and efficient 5G sig- nal detection, the second enhances network-based positioning accuracy, and the third enables precise and reliable signal transmission. Together, these studies provide a comprehensive SDR-based framework that improves 5G spectrum efficiency, accurate localization, and reliable network infrastructure development. They address key challenges such as dynamic spectrum allocation, interference mitigation, and real-time wireless positioning, offering insights that can benefit industries ranging from telecommunications and IoT to transportation and defense. Future research directions could focus on AI-driven spectrum management, advanced signal processing techniques, and multi-band SDR systems for improved localization and communication in 5G and beyond networks. These advancements will contribute to the evolution of next-generation wireless technologies, supporting the growing demand for high-speed, low-latency, and highly accurate positioning solutions.

IV. RESULTS

The results from the graphical analysis clearly demonstrate the effectiveness of Software-Defined Radio (SDR) in enhanc- ing 5G signal detection and quality under various challenging conditions. The SNR comparison chart shows that while high-load and stress scenarios without SDR exhibit poor signal clarity with SNRs around -15 dB and -19 dB respectively, the SDR-optimized setup improves SNR to approximately -10 dB, indicating better signal quality and reduced noise. Similarly, Error Vector Magnitude (EVM) analysis reveals that under high-load and stressed conditions, signal distortion is significant, with EVM values reaching up to 960%, whereas SDR optimization reduces EVM to nearly 320%, proving its role in improving transmission accuracy. The miss detection rate graphs for both AWGN and EPA channels consistently show that SDR significantly reduces miss detection, especially a lower SNRs. Across all symbol counts (N = 1 to 4), SDR-based detection outperforms non-SDR systems, with the benefit increasing as the number of detection symbols rises. In both fading and noisy environments, the use of SDR ensures more accurate, reliable, and noise-resilient signal detection, making it a crucial technology for maintaining 5G performance in real-world conditions. These improvements in SNR, EVM, and miss detection rate confirm SDR's capability to enhance spectrum efficiency and signal robustness in dynamic wireless environments.

V. CONCLUSION

This paper provides an in-depth study of 5G signal detec- tion, SDR-based network positioning, and SDR-based trans- mitter development, showcasing the critical role of Software- Defined Radio (SDR) in modern wireless communication systems. As 5G technology continues to evolve, challenges related to spectrum utilization, interference mitigation, and precise localization must be addressed to support applications such as autonomous navigation, smart city infrastructure, and dynamic spectrum sharing. The research presented in this paper contributes to solving these challenges by leveraging SDR-based solutions for signal detection, network position- ing, and transmitter optimization, which offer flexibility, real-

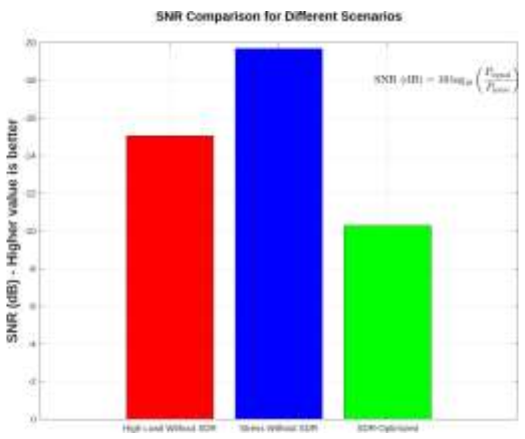

Fig. 1. Miss Detection Rate for AWGN Channel

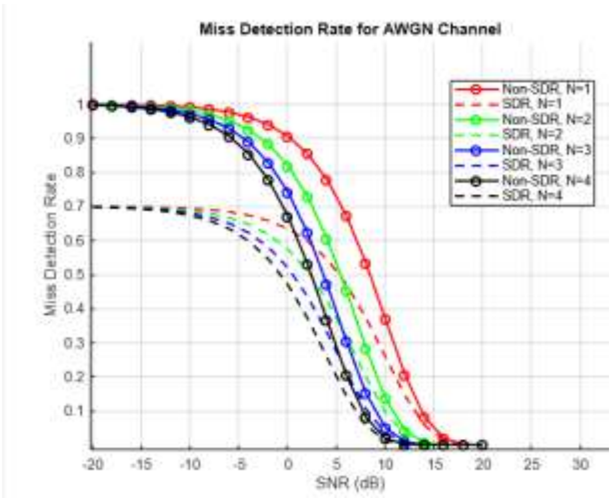

Fig. 4. SNR Comparison

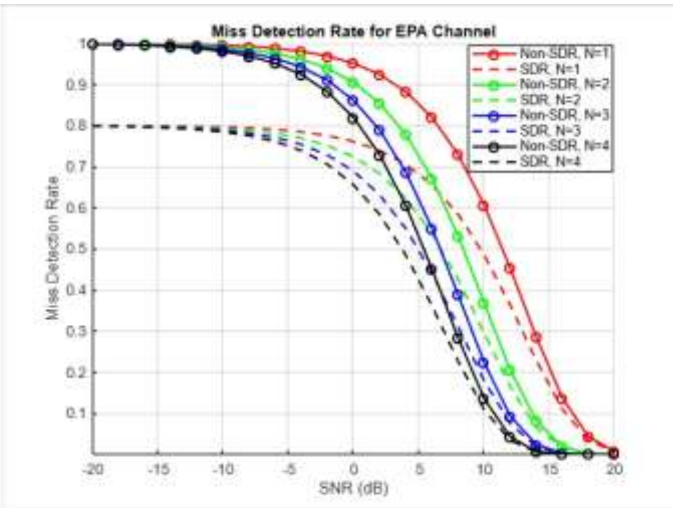

Fig. 2. Miss Detection Rate For EPA Channel

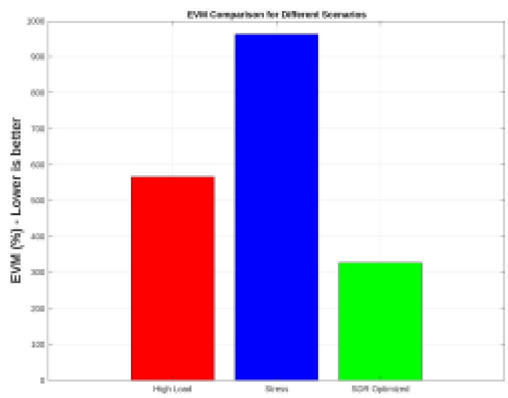

Fig. 3. EVM Comparison for different Scenarios

time adaptability, and cost-effective deployment compared to traditional hardware-based systems.

The first study on high-precision 5G-NR downlink signal detection focuses on improving the accuracy of spectrum sensing and synchronization. Given that dynamic spectrum sharing (DSS) and cognitive radio require highly accurate signal detection mechanisms to prevent interference and ensure efficient spectrum usage, this research proposes an SDR- based detection system that utilizes synchronization signals (PSS and SSS), cross-correlation techniques, and real-time spectrum sensing. The experimental results demonstrate that the proposed system achieves 99 detection accuracy in AWGN environments and 90accuracy in multipath fading conditions at an SNR of -10 dB, proving its reliability even in chal- lenging wireless conditions. This research is significant for interference-free spectrum access, improved network reliability, and enhanced spectral efficiency, particularly in densely populated urban environments where spectrum availability is limited. Future enhancements could involve machine learning-based signal classification and adaptive filtering techniques to further improve signal detection accuracy in dynamic environments.

The second study explores SDR-based network positioning technology, addressing the limitations of Global Navigation Satellite Systems (GNSS) in urban and indoor environments. By implementing Observed Time Difference of Arrival (OTDOA) and Positioning Reference Signals (PRS), the system provides an alternative to GNSS-dependent positioning methods, ensuring high-accuracy localization for 5G networks. The developed system integrates four SDR-based eNB transmitters and a UE SDR receiver, synchronized through a Gigabit Ethernet (GBE) router, allowing precise time alignment for location estimation. MATLAB-based signal processing techniques are employed for time delay estimation, multipath error correction, and real-time localization, achieving sub-meter accuracy. This study is particularly relevant for applications requiring precise positioning, such as autonomous vehicles, industrial automation, and emergency response services. Further improvements in multi-path mitigation, AI-driven localization algorithms, and SDR-based adaptive positioning techniques could enhance accuracy and real-time tracking capabilities, making this system even more robust in GNSS-denied environments.

The third study focuses on SDR-based 5G transmitter development, which plays a crucial role in ensuring accurate signal transmission for network testing, PRS generation, and real-time positioning improvements. The system utilizes Universal Software Radio Peripheral (USRP) hardware and MATLAB-based PRS generation, ensuring compliance with 3GPP TS 36.211 and TS 38.211 standards.The developed transmitter is validated through laboratory experiments using signal analyzers and network emulators , confirming its effectiveness in PRS transmission, network synchronization, and SDR- based positioning enhancements. The ability to dynamically configure transmission parameters, adjust PRS signal characteristics, and test various positioning algorithms makes SDR-based transmitters valuable tools for 5G research, network optimization, and localization accuracy improvements. Future work could involve integrating multi-frequency transmission capabilities, advanced beamforming techniques, and AI-driven signal modulation for adaptive transmission in 6G networks.

Collectively, these studies contribute to a comprehensive SDR-based framework that enhances 5G spectrum efficiency, signal detection accuracy, and precise network-based posi- tioning. Each study addresses a fundamental challenge in 5G deployment, from ensuring interference-free spectrum access to achieving high-accuracy positioning and optimizing transmitter performance. The findings of this research are applicable across multiple industries, including telecommunications, intelligent transportation systems, IoT, and defense, where reliable network communication, low-latency performance, and precise positioning are essential.

Looking ahead, future research should focus on AI-driven spectrum management, deep learning-based signal classification, and hardware acceleration techniques for real-time SDR processing. Additionally, improvements in FPGA-based SDR optimization, cloud-assisted positioning, and 6G multi-band localization could further enhance system performance. As the demand for high-speed, ultra-reliable, and low-latency wireless networks continues to grow, SDR-based solutions will play an increasingly vital role in shaping the future of next-generation wireless communication systems, ensuring seamless connectivity, efficient spectrum utilization, and enhanced network intelligence.

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