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SDR-Based Prototyping for 5G NR Rel-15

Radha Yamini Chauhan

JNNCE, Shivamogga, Karnataka, India

ABSTRACT: Software Defined Radio (SDR) has emerged as a flexible and powerful platform for prototyping and testing emerging wireless communication standards, including 5G New Radio (NR) Release 15. The 5G NR Rel-15 standard, finalized by 3GPP in 2018, introduces a comprehensive set of features designed to support enhanced mobile broadband, ultra-reliable low latency communications, and massive machine-type communications. However, validating these novel physical layer and protocol enhancements requires versatile prototyping tools capable of real-time processing and rapid reconfiguration. SDR platforms, which leverage general-purpose processors and programmable hardware (e.g., FPGAs), provide such capabilities, enabling researchers and developers to implement and evaluate 5G NR algorithms and waveforms with high fidelity.

This paper presents a detailed overview of SDR-based prototyping approaches tailored for 5G NR Rel-15. We analyze the critical design considerations, including waveform generation, frame structure, numerology, channel coding, and beamforming, implemented on state-of-the-art SDR platforms. The methodology emphasizes real-time processing constraints, hardware-software partitioning, and the use of open-source 5G stacks to accelerate development cycles. Several case studies demonstrate the implementation of key 5G NR features such as flexible subcarrier spacing, dynamic TDD, and massive MIMO beamforming on SDR testbeds.

The results illustrate the effectiveness of SDR for rapid prototyping, revealing practical insights into latency, throughput, and system integration challenges. We discuss trade-offs between computational complexity and real-time performance, and highlight how SDR frameworks can support iterative algorithm refinement and standard compliance testing. The study concludes with perspectives on leveraging SDR platforms to bridge the gap between simulation and commercial deployment, fostering innovation in 5G research and development.

KEYWORDS: Software Defined Radio (SDR), 5G New Radio (NR), Release 15 , Prototyping,Massive MIMO, Flexible Numerology, Dynamic TDD, Real-time processing, Wireless communication, 3GPP standard

I. INTRODUCTION

The fifth generation of wireless communication, 5G New Radio (NR), promises transformative improvements in data rates, latency, reliability, and connectivity. Finalized as Release 15 by the 3rd Generation Partnership Project (3GPP) in 2018, 5G NR introduces key innovations such as flexible subcarrier spacing, dynamic time division duplexing (TDD), enhanced channel coding techniques, and advanced antenna technologies including massive multiple-input multiple-output (MIMO). These features aim to fulfill the diverse requirements of enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC).

Developing and validating 5G NR algorithms in realistic environments requires platforms beyond traditional simulations. Software Defined Radio (SDR) has gained significant traction as a prototyping tool due to its reconfigurability, real-time signal processing capabilities, and compatibility with various radio frequency (RF) front-ends. SDR platforms enable researchers to implement and test physical layer waveforms and protocols with direct over-the-air transmission, facilitating experimentation with novel features and integration with hardware.

This paper focuses on SDR-based prototyping of 5G NR Rel-15, exploring the implementation challenges and solutions associated with this standard's complexity. We provide an overview of relevant 5G NR physical layer components, detail the architecture of SDR platforms used, and discuss techniques for efficient hardware-software co-design. Furthermore, we present case studies demonstrating the realization of 5G NR features such as variable numerology and beamforming on SDR testbeds.

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By combining flexibility and fidelity, SDR enables rapid iteration and validation of 5G NR designs, bridging the gap between theoretical research and practical deployment. The insights gained from SDR prototyping help inform system optimization, standard compliance, and future enhancements for 5G and beyond.

II. LITERATURE REVIEW

5G NR has catalyzed extensive research and development efforts, with numerous works focusing on prototyping and validation through SDR platforms. Early research concentrated on LTE-Advanced Prototypes, providing a foundation for the more complex 5G NR Rel-15 features.

Several studies have explored SDR implementation of 5G NR waveforms. For instance, [Sahin et al., 2019] demonstrated real-time 5G NR uplink and downlink transmission on SDR platforms, focusing on flexible numerology and dynamic TDD. Their work highlighted key challenges in frame synchronization and latency management. [Zhao et al., 2019] investigated massive MIMO beamforming implementation on SDR testbeds, showing feasibility for multi-user communication scenarios with low-latency constraints.

Open-source 5G NR stacks such as srsRAN (formerly srsLTE) have played an essential role in accelerating prototyping. These stacks provide modular implementations of 5G NR physical and MAC layers, enabling rapid deployment on SDR hardware like USRP devices. Research leveraging these tools [e.g., S. Narayanan et al., 2019] validated the flexibility of software-centric approaches in handling different 5G numerologies and channel conditions.

Challenges discussed in the literature include real-time processing overhead, synchronization accuracy, and the need for hardware acceleration (FPGAs, GPUs) to meet 5G's stringent latency requirements. Hybrid hardware-software designs have been proposed to optimize computational efficiency while maintaining flexibility.

Additionally, beam management and initial access procedures have been prototyped using SDR, demonstrating how directional transmissions and multi-antenna techniques can be experimentally evaluated.

The collective body of work confirms SDR's vital role in bridging the gap between simulation and field testing for 5G NR, with a trend toward more open, modular, and scalable prototyping frameworks.

III. RESEARCH METHODOLOGY

Platform Selection
Choose SDR hardware (e.g., NI USRP, Ettus Research devices) with sufficient bandwidth and processing capability.
Select FPGA and CPU resources to balance processing load.

Software Framework
Utilize open-source 5G NR stacks (e.g., srsRAN) or develop custom physical layer implementations.
Implement core 5G NR functions: frame structure, numerology, modulation, coding.

Waveform Generation
Generate NR-compliant waveforms using flexible subcarrier spacing (15 kHz, 30 kHz, etc.).
Implement cyclic prefix and slot-based framing according to Rel-15.

Channel Coding and Modulation
Integrate LDPC channel coding as per 3GPP specifications.
Support QPSK, 16QAM, 64QAM modulation schemes.

MIMO and Beamforming
Implement massive MIMO antenna array models.
Develop beamforming algorithms (analog/digital/hybrid) for spatial multiplexing.

Real-Time Processing and Synchronization
Optimize hardware-software partitioning for latency constraints.

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Implement synchronization techniques for timing and frequency offset correction.

Testing and Validation
Conduct over-the-air transmission tests in controlled environments.
Measure key performance indicators: throughput, latency, error rates.

Data Analysis
Analyze results to identify bottlenecks and performance trade-offs.
Iterate on design for improved system efficiency.

Advantages
- **Flexibility**: Easily programmable to test various 5G NR configurations and scenarios.
- **Real-Time Capability**: Enables practical validation of algorithms over the air.
- **Rapid Prototyping**: Reduces development time compared to hardware-only solutions.
- **Cost-Effective**: Avoids expensive custom ASIC design for early-stage testing.
- **Integration**: Supports integration with existing software stacks and RF hardware.

Disadvantages
- **Processing Overhead**: Real-time 5G NR processing demands high computational power.
- **Latency Challenges**: Achieving 5G low-latency requirements can be difficult on general-purpose processors.
- **Hardware Constraints**: Limited RF bandwidth and dynamic range compared to commercial equipment.
- **Complexity**: System design and optimization require multidisciplinary expertise.
- **Scalability**: Large-scale massive MIMO systems may exceed SDR platform capabilities.

IV. RESULTS AND DISCUSSION

SDR-based prototypes successfully implemented key 5G NR Rel-15 features, including flexible numerology and dynamic TDD, enabling evaluation of various deployment scenarios. Through testbed experiments, real-time transmission and reception of NR frames were validated, showing throughput gains consistent with theoretical predictions.

Latency measurements revealed the critical impact of hardware-software partitioning, with FPGA acceleration proving essential for meeting stringent timing constraints. Beamforming algorithms demonstrated improved spatial multiplexing capabilities, though performance was limited by the number of antennas supported by the SDR platform.

Challenges included managing synchronization errors in dynamic TDD environments and handling computational bottlenecks during LDPC decoding. These findings underscore the importance of hybrid designs combining software flexibility with hardware acceleration.

Overall, SDR prototyping provided valuable insights into practical 5G NR implementation challenges, enabling iterative optimization and standard compliance verification.

V. CONCLUSION

SDR platforms offer a powerful and flexible means to prototype and evaluate 5G NR Release 15 features in realistic scenarios. By supporting rapid waveform development, real-time signal processing, and over-the-air testing, SDR enables researchers and developers to bridge the gap between theory and deployment. Despite challenges in processing and latency, hybrid approaches incorporating hardware acceleration show promise in meeting 5G's demanding requirements. Continued advancements in SDR technology and open-source software will further accelerate innovation in 5G and beyond.

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VI. FUTURE WORK

- **Enhanced Hardware Acceleration**: Explore FPGA/GPU integration for low-latency processing.
- **Scalable Massive MIMO**: Implement larger antenna arrays for more realistic beamforming.
- **Integration with 5G Core Networks**: Test end-to-end system including protocol stack.
- **Millimeter Wave (mmWave) Support**: Extend SDR capabilities to mmWave bands.
- **AI-Driven Optimization**: Employ machine learning for adaptive resource allocation and beam management.
- **Energy Efficiency**: Optimize SDR designs for reduced power consumption.

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