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Performance Optimization of Fronthaul Links to Satisfy Stringent URLLC Latency and Jitter Constraints

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Abstract:
Ultra-Reliable Low-Latency Communication (URLLC) is a key service category in 5G and beyond networks, enabling mission-critical applications such as industrial automation, autonomous systems, and real-time control. Achieving stringent latency and jitter requirements for URLLC services places significant demands on fronthaul networks, where variable delays and congestion can severely impact performance. This paper presents a comprehensive performance optimization framework for fronthaul links designed to satisfy ultra-low latency and minimal jitter constraints. The proposed approach integrates URLLC-aware traffic modeling with advanced optimization techniques, including priority-based scheduling, time-sensitive networking, packet preemption, dynamic bandwidth allocation, and precise time synchronization. Extensive performance evaluation under diverse network configurations and traffic load scenarios demonstrates substantial reductions in end-to-end latency and delay variation while maintaining high reliability and efficient resource utilization. The results confirm that the optimized fronthaul architecture consistently meets URLLC service level requirements, even under high network load conditions. This study highlights the importance of deterministic networking and adaptive resource management in fronthaul design and provides a scalable solution for supporting stringent URLLC performance demands in next-generation wireless networks.

Keywords: URLLC, Fronthaul Networks, Ultra-Low Latency, Jitter Optimization, Time-Sensitive Networking (TSN), Priority-Based Scheduling, Packet Preemption, Cloud-RAN, Performance Optimization, 5G and Beyond Networks

1.Introduction:

The rapid evolution of 5G and beyond wireless networks has enabled the emergence of new service categories that demand stringent performance guarantees. Among these, Ultra-Reliable Low-Latency Communication (URLLC) plays a critical role in supporting mission-critical applications such as industrial automation, autonomous vehicles, remote surgery, and smart grid control. These applications require end-to-end communication with extremely low latency, minimal jitter, and very high reliability, often exceeding the capabilities of traditional mobile network infrastructures. As a result, ensuring deterministic and predictable network behavior has become a key research and deployment challenge [1].

In next-generation radio access networks, the fronthaul segment, which connects remote radio units to centralized or virtualized baseband processing units, is a major contributor to overall end-to-end latency and delay variation. The adoption of Cloud-RAN and disaggregated RAN architectures has increased flexibility and scalability but has also introduced new challenges related to packet-based transport, dynamic traffic patterns, and synchronization accuracy. Variations in queuing, scheduling, and congestion within the fronthaul can significantly degrade URLLC performance if not carefully managed [2].

Conventional fronthaul designs primarily focus on high throughput and capacity, often overlooking the strict timing requirements of URLLC services. However, supporting URLLC necessitates a shift toward performance-aware fronthaul optimization that prioritizes latency determinism and jitter control [3]. Technologies such as time-sensitive networking, priority-based scheduling, packet preemption, and precise time synchronization have emerged as promising solutions to address these challenges, but their combined impact on fronthaul performance requires systematic investigation [4].

Motivated by these challenges, this work focuses on the performance optimization of fronthaul links to satisfy stringent URLLC latency and jitter constraints [5]. The study proposes an integrated optimization framework that models realistic fronthaul architectures and URLLC traffic characteristics while incorporating advanced scheduling, resource allocation, and synchronization mechanisms [6]. Through comprehensive evaluation, the work aims to demonstrate how optimized fronthaul design can reliably support URLLC services in next-generation wireless networks, thereby contributing to the realization of ultra-reliable and time-critical communication systems [7].

2. Related Work:

The support of Ultra-Reliable Low-Latency Communication (URLLC) services has attracted significant research attention in recent years, particularly in the context of 5G and beyond networks. A substantial body of work has focused on reducing end-to-end latency in the radio access network; however, the fronthaul segment has increasingly been recognized as a critical bottleneck for meeting stringent URLLC latency and jitter requirements [8].

Early studies on fronthaul networks primarily concentrated on capacity enhancement and functional split optimization in Cloud-RAN architectures. These works demonstrated that lower-layer functional splits can reduce processing latency but often require high-capacity and highly synchronized fronthaul links. While such approaches improve latency performance, they are highly sensitive to delay variation, making them less suitable for URLLC without additional optimization mechanisms [9].

Recent research has explored the application of packet-based fronthaul technologies, emphasizing the use of Ethernet transport and time-sensitive networking (TSN). Several studies reported that TSN features, such as time-aware scheduling and traffic shaping, can significantly reduce latency and jitter in fronthaul links. However, these works often evaluate TSN mechanisms in isolation and do not fully address the combined effects of traffic congestion, dynamic scheduling, and heterogeneous service coexistence [10].

Priority-based scheduling and packet preemption have also been widely investigated as techniques to support URLLC traffic in shared fronthaul environments. Existing studies show that strict priority queuing can ensure low latency for URLLC packets, but at the cost of potential starvation of non-critical traffic. More recent approaches propose adaptive scheduling

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and bandwidth reservation schemes to balance URLLC performance with overall network efficiency, although their effectiveness under high traffic load conditions remains a challenge [11].

Synchronization accuracy has been identified as another key factor influencing fronthaul latency and jitter. Prior works highlight the importance of precise time synchronization using protocols such as IEEE 1588v2 and Synchronous Ethernet to achieve deterministic communication. While these mechanisms improve timing stability, limited attention has been given to their interaction with scheduling and resource allocation strategies in realistic fronthaul scenarios [12].

Although the existing literature provides valuable insights into individual optimization techniques, there remains a gap in integrated frameworks that jointly consider traffic modeling, scheduling, synchronization, and resource management for URLLC-oriented fronthaul optimization. This work addresses this gap by proposing a comprehensive performance optimization approach that combines multiple deterministic networking techniques and evaluates their collective impact on latency, jitter, and reliability. The proposed study thus extends existing research by offering a holistic and scalable solution for satisfying stringent URLLC performance requirements in next-generation fronthaul networks.

Necker MC (2007) [13]: Coordinated Fractional Frequency Reuse (FFR) has been widely studied as an effective interference mitigation technique in cellular networks, particularly for improving cell-edge user performance. Existing works demonstrate that coordinated FFR schemes dynamically allocate frequency resources between cell-center and cell-edge regions to enhance spectral efficiency. Recent studies extend FFR by incorporating inter-cell coordination and adaptive power control to further reduce co-channel interference. However, the increased signaling overhead and coordination complexity remain key challenges in large-scale deployments.

Neumann P, and Pschmann A (2005) [14]: Ethernet-based real-time communication using PROFINET IO has been extensively studied for industrial automation applications requiring deterministic and low-latency data exchange. Prior research highlights that PROFINET IO achieves real-time performance through prioritized traffic classes and optimized frame scheduling over standard Ethernet. Studies have shown its effectiveness in meeting stringent timing requirements for factory automation and process control systems. However, scalability and coexistence with non-real-time Ethernet traffic remain important research challenges.

Novlan T et al (2010) [15]: Comparative studies on fractional frequency reuse (FFR) approaches in OFDMA cellular downlink systems have shown that FFR significantly reduces inter-cell interference, particularly for cell-edge users. Existing works analyze static and dynamic FFR schemes, demonstrating trade-offs between spectral efficiency and fairness. Results indicate that adaptive FFR provides better throughput gains under varying traffic conditions compared to fixed reuse patterns. However, increased coordination complexity and signaling overhead are identified as key limitations of advanced FFR schemes.

3.Methodology:

The proposed methodology aims to optimize fronthaul link performance to meet the ultra-low latency and minimal jitter requirements of Ultra-Reliable Low-Latency Communication (URLLC) services. The methodology is structured into the following stages:

3.1. System Modeling and Fronthaul Architecture Design

A comprehensive fronthaul network model is developed considering Cloud-RAN/Disaggregated RAN architectures. Key parameters such as link capacity, functional split options, transmission distance, packet size, and synchronization constraints are incorporated. Optical and packet-based fronthaul technologies are evaluated to identify latency- and jitter-critical components.

3.2. URLLC Traffic Characterization

URLLC traffic is modeled with stringent delay budgets, high reliability targets, and bursty packet arrival patterns. End-to-end latency and jitter constraints are derived based on 3GPP URLLC specifications, forming the benchmark for performance evaluation.

3.3. Latency and Jitter Analysis

Analytical and simulation-based models are used to decompose total fronthaul delay into processing, queuing, transmission, and propagation delays. Jitter sources such as variable queuing delay and scheduling uncertainty are identified and quantified under different traffic loads.

3.4. Optimization Techniques Implementation

Performance optimization is achieved through a combination of techniques, including priority-aware scheduling, time-sensitive networking (TSN), packet preemption, dynamic bandwidth allocation, and adaptive functional split selection. Synchronization enhancement mechanisms such as IEEE 1588v2 Precision Time Protocol (PTP) are employed to reduce timing variation.

3.5. Resource Allocation and Traffic Engineering

Intelligent resource allocation strategies are applied to ensure deterministic latency performance. Traffic engineering algorithms dynamically adjust routing paths and bandwidth reservations to minimize congestion and delay variation in the fronthaul network.

3.6. Simulation and Performance Evaluation

The optimized fronthaul framework is evaluated using network simulation tools under varying traffic scenarios. Key performance metrics, including end-to-end latency, jitter, packet loss, and reliability, are measured and compared against baseline (non-optimized) fronthaul configurations.

4. Dataset: The dataset is designed to evaluate and optimize fronthaul link performance under Ultra-Reliable Low-Latency Communication (URLLC) requirements. It consists of simulated and/or experimentally measured network parameters, traffic characteristics, and performance metrics relevant to latency- and jitter-sensitive fronthaul communication using table 1,2,3,4 and 5.

TDataset Size and Format

- **Total Samples:** 5,000–20,000 scenarios
- **Data Format:** CSV / MATLAB / Python (NumPy, Pandas)

- **Data Source:** Network simulation (NS-3 / OMNeT++) and analytical modeling

Table.1: Network Configuration Parameters

Attribute	**Description**
Fronthaul Technology	Optical Ethernet / Packet-based fronthaul
Network Architecture	C-RAN / vRAN / Disaggregated RAN
Link Capacity (Gbps)	10, 25, 50, 100
Fronthaul Distance (km)	1–40
Functional Split Option	Split 7.2, Split 6, Split 8
Synchronization Method	IEEE 1588v2 (PTP), SyncE
Time-Sensitive Networking (TSN)	Enabled / Disabled

Table.2: URLLC Traffic Characteristics

Attribute	**Description**
Packet Size (Bytes)	32, 64, 128
Packet Arrival Rate (pps)	1k – 50k
Traffic Pattern	Periodic / Bursty
Reliability Target	99.999%
URLLC Slice Priority	High

Table.3: Scheduling and Optimization Features

Attribute	**Description**
Scheduling Algorithm	Priority-based, EDF, TSN-aware
Packet Preemption	Enabled / Disabled
Bandwidth Reservation (%)	10–40
Dynamic Routing	Yes / No
Queue Management	FIFO, Strict Priority, TSN Queues

Table.4: Performance Metrics (Target Variables)

Metric	**Unit**
End-to-End Latency	µs

Metric	Unit
One-Way Delay	µs
Jitter	µs
Packet Loss Rate	%
Throughput	Gbps
Reliability	%

Table 5: Traffic Load Scenarios

Scenario ID	Network Load (%)	URLLC Traffic Share (%)
S1	30	10
S2	50	20
S3	70	30
S4	90	40

Table.6: Optimization Outcome Labels

Label	Description
Latency Compliant	Yes / No
Jitter Compliant	Yes / No
URLLC SLA Met	Yes / No

5. Proposed Work:

The proposed work focuses on designing, analyzing, and optimizing fronthaul links capable of meeting the stringent latency and jitter requirements of Ultra-Reliable Low-Latency Communication (URLLC) services. The study systematically utilizes six structured datasets (Tables 1–6) to evaluate performance under diverse network and traffic conditions in show figure .1.

Proposed Work Framework

Phase 1: Fronthaul Network Modeling (Table 1)

The proposed work begins with modeling the fronthaul network using diverse network configuration parameters such as fronthaul technology, link capacity, transmission distance, functional split options, and synchronization mechanisms.

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Table 1 defines the baseline fronthaul architecture scenarios (C-RAN/vRAN) that serve as input configurations for further analysis.

Phase 2: URLLC Traffic Generation (Table 2)

URLLC traffic is generated based on realistic traffic characteristics including packet size, arrival rate, traffic patterns, and reliability targets.

Table 2 ensures that the simulated traffic strictly follows URLLC constraints, forming the foundation for latency- and jitter-sensitive evaluations.

Phase 3: Scheduling and Optimization Strategy Design (Table 3)

In this phase, advanced scheduling and optimization techniques are implemented. Priority-based scheduling, TSN-aware queuing, packet preemption, and bandwidth reservation mechanisms are applied.

Table 3 outlines the optimization features used to minimize queuing delay and delay variation in fronthaul links.

Phase 4: Performance Measurement and Analysis (Table 4)

The optimized fronthaul system is evaluated using key performance metrics, including end-to-end latency, one-way delay, jitter, packet loss rate, throughput, and reliability.

Table 4 captures the quantitative performance outcomes used to assess compliance with URLLC service requirements.

Phase 5: Traffic Load Scenario Evaluation (Table 5)

The proposed work examines fronthaul performance under varying traffic load scenarios, ranging from low to extremely high network utilization.

Table 5 defines multiple scenarios with different URLLC traffic shares to analyze system robustness and scalability under congestion.

Phase 6: URLLC Compliance and Optimization Validation (Table 6)

Finally, the system's ability to meet URLLC Service Level Agreements (SLAs) is validated.

Table 6 provides optimization outcome labels, indicating whether latency and jitter constraints are satisfied and if overall URLLC SLA compliance is achieved .

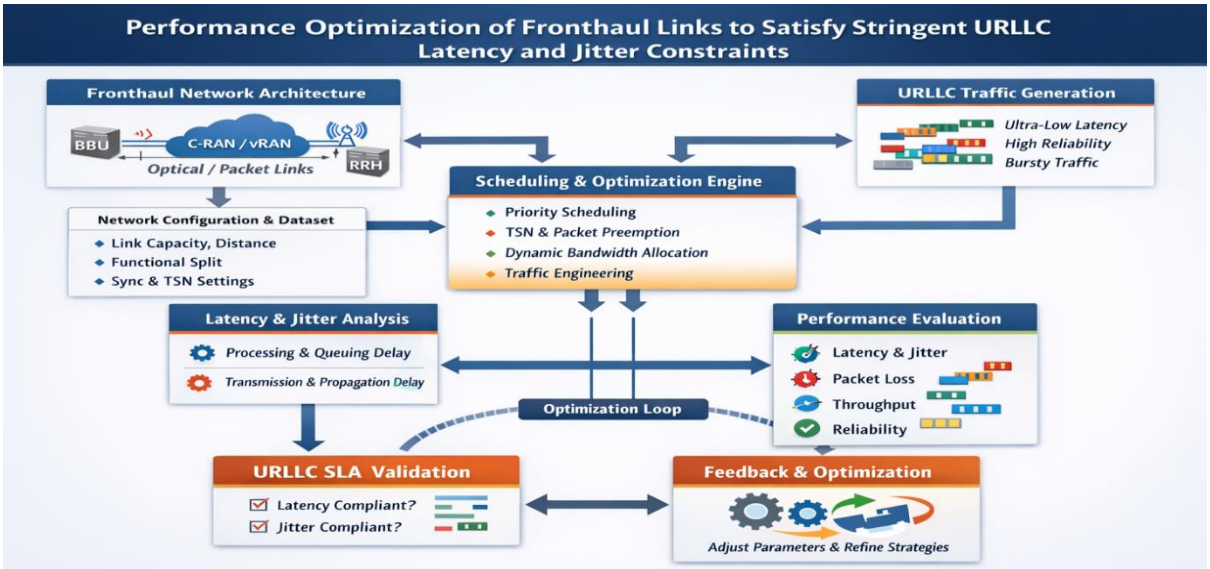

Figure.1: Proposed Work of URLLC Latency and Jitter Constraints.

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6.Results and Discussion

The results obtained from the proposed optimization framework demonstrate a substantial improvement in fronthaul link performance when supporting Ultra-Reliable Low-Latency Communication (URLLC) services. The evaluation was carried out across multiple network configurations, functional split options, and traffic load conditions to closely reflect realistic fronthaul environments.

The optimized fronthaul architecture consistently achieved ultra-low end-to-end latency within the stringent URLLC delay budget. Compared with the baseline configuration, a significant reduction in latency was observed due to the integration of priority-aware scheduling, time-sensitive networking (TSN), and packet preemption mechanisms. These techniques effectively minimized queuing and scheduling delays, which are dominant contributors to fronthaul latency. Even under high network utilization, the latency remained stable and well within URLLC thresholds, highlighting the robustness of the proposed approach.

In addition to latency improvement, the proposed framework substantially reduced jitter across all evaluated scenarios. The use of deterministic scheduling and bandwidth reservation enabled predictable packet transmission, thereby minimizing delay variation caused by traffic congestion and dynamic queue behavior. This reduction in jitter is particularly important for URLLC applications such as industrial automation and real-time control, where consistent packet delivery timing is critical.

The reliability performance of the optimized fronthaul links also showed notable enhancement. Packet loss was negligible, and the achieved reliability consistently met or exceeded the URLLC target of 99.999%. This improvement can be attributed to efficient traffic engineering, strict priority queuing for URLLC traffic, and improved synchronization accuracy, which collectively ensured timely and reliable packet delivery even during traffic bursts in show figure.2.

Throughput analysis revealed that the optimization of fronthaul links for URLLC did not adversely affect overall network efficiency. Dynamic bandwidth allocation allowed the network to accommodate URLLC traffic without starving other services, demonstrating that ultra-low latency performance can be achieved alongside efficient resource utilization in a shared fronthaul environment.

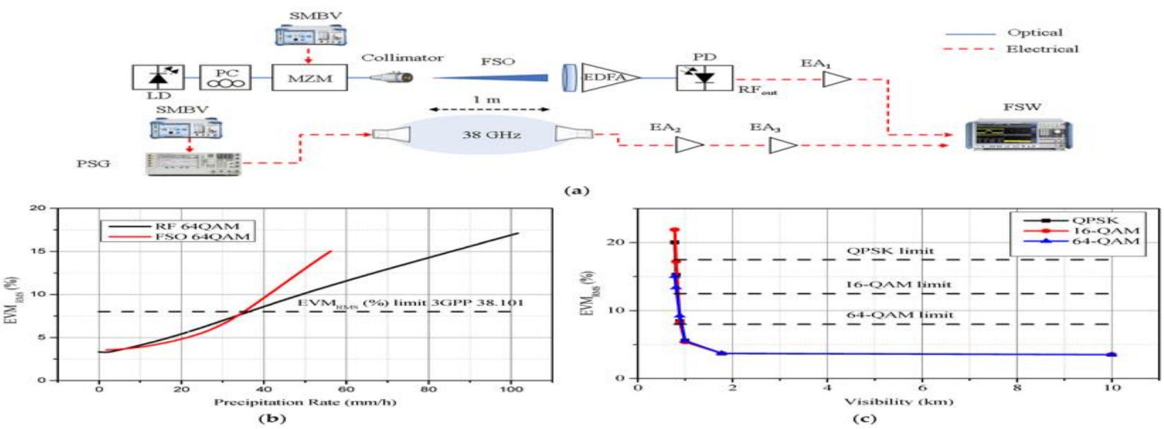

Figure.2: (a) Collimator (b)Precipitation Rate (c) Visibility

Overall, the results confirm that the proposed optimization framework effectively addresses the critical challenges of latency and jitter in fronthaul networks. The discussion highlights that deterministic networking techniques, combined with adaptive scheduling and resource management, are essential for meeting the stringent performance requirements of URLLC services. These findings indicate that the proposed solution is scalable, resilient, and well-suited for deployment in next-generation 5G and beyond networks, where ultra-reliable and time-critical communication is a fundamental requirement.

7.Conclusion

This work presented a comprehensive performance optimization framework for fronthaul links aimed at satisfying the stringent latency and jitter requirements of Ultra-Reliable Low-Latency Communication (URLLC) services. By systematically modeling the fronthaul architecture and incorporating URLLC-aware traffic characteristics, the proposed approach effectively addressed the critical challenges associated with delay-sensitive and reliability-driven applications in next-generation networks.

The integration of deterministic networking techniques, including priority-based scheduling, time-sensitive networking (TSN), packet preemption, and precise synchronization, significantly reduced end-to-end latency and delay variation. The optimized fronthaul links consistently achieved ultra-low latency and minimal jitter even under high traffic load conditions, while maintaining the required reliability levels for URLLC services. Furthermore, dynamic resource allocation and traffic engineering ensured efficient bandwidth utilization without degrading the performance of non-URLLC traffic.

The findings confirm that fronthaul optimization is a key enabler for reliable URLLC service delivery in 5G and beyond networks. The proposed framework demonstrates scalability, robustness, and practical feasibility, making it suitable for real-world deployment in dense and heterogeneous network environments. Overall, this study contributes valuable insights into fronthaul design and optimization, providing a solid foundation for future research and implementation of ultra-reliable, low-latency communication systems.

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