

# Adaptive PDCP Duplication for Reliability Enhancement

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**Abstract**— Conventional PDCP duplication mechanisms ensure high reliability through simultaneous packet transmission across multiple paths; however, this approach introduces substantial overhead during stable channel conditions or when services do not require ultra-high reliability guarantees. To overcome these limitations, this paper introduces an innovative Adaptive PDCP Duplication framework that intelligently enables or disables packet duplication based on real-time network conditions and service-specific requirements. Our proposed mechanism dynamically optimizes the trade-off between reliability enhancement and spectral efficiency, thereby achieving superior performance compared to static duplication approaches.

**Keywords**—adaptive data transmission, PDCP optimization, multi-path connectivity, wireless mobility, high-frequency backhaul networks

## I. INTRODUCTION

To meet extreme capacity and latency requirements in mmWave and THz frequency bands, which offer unprecedented bandwidth but suffer from high path loss, blockage susceptibility, and rapid channel variations that compromise single-link reliability for mission-critical applications, multi-connectivity mechanisms like PDCP (Packet Data Convergence Protocol) duplication have been introduced to enhance communication robustness by transmitting duplicate packets simultaneously through multiple radio links, providing path diversity that significantly improves both reliability and latency despite increased resource consumption, with simulation results confirming substantial performance gains over single-path transmission and motivating further research into adaptive duplication strategies that selectively balance reliability with spectral efficiency based on channel conditions, as this paper presents the concept, architecture, and enhancement strategies of PDCP duplication to provide a systematic perspective on effective network utilization and services[1].

## II. PDCP DUPLICATION FUNDAMENTALS

### A. PDCP Layer Functionality

The PDCP layer in 5G NR handles header compression, security operations, sequential delivery, and packet management, implementing duplication through multiple active RLC entities distributed across different transmission paths (such as Master and Secondary gNBs in Dual Connectivity), where each PDCP PDU is replicated across communication links to enhance reliability[2] [3].

### B. Duplication Mechanism Architecture

The PDCP duplication framework maintains multiple concurrent RLC entities across independent transmission paths. Each PDU undergoes replication and simultaneous

transmission through separate links. At the receiver side, PDUs are deduplicated using sequence number identification, ensuring singular delivery to upper protocol layers[4].

The system supports two primary activation modes:

- **Configured Duplication:** Maintains continuous activation once established through Radio Resource Control (RRC) signaling.
- **Dynamic Duplication:** Implements adaptive activation and deactivation based on instantaneous channel conditions and Quality of Service (QoS) requirements.

### C. Performance Benefits

PDCP duplication provides multiple advantages:

- **Enhanced Reliability:** Achieves reduced packet loss through multipath diversity mechanisms
- **Latency Optimization:** Delivers improved delay characteristics, particularly under Non-Line-of-Sight (NLoS) propagation conditions
- **URLLC Compliance:** Meets Ultra-Reliable Low-Latency Communication requirements
- **HARQ Efficiency:** Improves Hybrid Automatic Repeat Request performance by minimizing retransmission requirements

## III. PROPOSED ADAPTIVE PDCP DUPLICATION FRAMEWORK

### A. Conceptual Foundation

The fundamental objective involves optimizing the trade-off between communication reliability and spectral efficiency. Rather than implementing duplication through static configuration, the proposed system intelligently determines duplication necessity based on three critical factors:

- **Channel Quality Assessment:** When available transmission paths demonstrate sufficiently high Signal-to-Noise Ratio (SNR) or low packet error rates, duplication can be temporarily deactivated.
- **Traffic Classification:** URLLC traffic requiring stringent reliability maintains duplication activation, while enhanced Mobile Broadband (eMBB) or best-effort services receive selective duplication application.
- **Network Load Management:** During high traffic congestion scenarios, duplication intensity can be reduced to preserve resources while maintaining acceptable reliability levels.

## B. System Architecture

The proposed adaptive PDCP duplication framework incorporates the following components:

- **Duplication Controller:** Implements real-time decision-making for duplication activation based on policy inputs and network conditions.
- **PDCP Transmission Buffer:** Maintains PDU storage and manages duplicated copy forwarding to multiple RLC entities.
- **Multi-path Interface:** Provides connectivity to multiple lower-layer radio links (e.g., Primary Cell, Secondary Cell configurations).
- **PDCP Reception and Deduplication Filter:** Identifies and eliminates PDUs with identical sequence numbers at the receiver.

The operational flow involves PDCP Service Data Units (SDUs) receiving sequence number assignments from upper layers. The Duplication Controller subsequently determines active path selection based on established policies. PDUs undergo duplication and transmission through multiple communication legs. At the receiver, duplicated PDUs sharing identical sequence numbers are filtered, with only the first-arrived copy proceeding to upper protocol layers.

## C. Duplication Policy Framework

The system implements flexible duplication policies:

- **Unconditional Duplication:** All PDUs receive duplication across available paths regardless of conditions.
- **Conditional Duplication:** Duplication activation occurs when specific channel metrics (e.g., SINR below threshold values) or packet loss rates exceed predetermined limits.
- **QoS-Aware Duplication:** Selective duplication application for specific QoS flows, particularly URLLC or mission-critical services.
- **Load-Aware Duplication:** Decision-making based on load balancing considerations, path congestion levels, and core network status indicators.

This flexibility enables network operators to optimize between reliability requirements and resource utilization efficiency.

## D. Mathematical Model

- $P_i$  = probability of successful delivery on path  $i$
- $N$  = number of duplicated paths
- $P_i$  = overall reliability with duplication

The probability that a packet is lost on all paths is:

$$P_{loss} = \prod_{i=1}^N (1 - P_i)$$

Thus, the success probability is:

$$P_{dup} = 1 - P_{loss} = 1 - \prod_{i=1}^N (1 - P_i)$$

For two-path duplication ( $N=2$ ):

$$P_{dup} = 1 - (1 - P_1)(1 - P_2) = P_1 + P_2 - P_1P_2$$

This shows reliability gain is strictly higher than either single link.

Latency model: if  $L_i$  is the latency of path  $i$ , then effective latency is:

$$L_{dup} = 1 - \min(L_1, L_2, \dots, L_N)$$

because the earliest successful copy is delivered.

## E. Adaptive Performance Model

We define the effective success probability of adaptive duplication as:  $P_{eff} = \alpha * P_{dup} + (1 - \alpha) * P_{single}$  where  $\alpha$  represents the probability that duplication is enabled,  $P_{dup}$  is the reliability under duplication, and  $P_{single}$  is the reliability under single transmission. By optimizing  $\alpha$  according to real-time network conditions, the system can achieve high reliability without excessive resource consumption.

## F. Optimization strategies

- **Adaptive Control Mechanisms:** Implement threshold-based or machine learning-driven policies for duplication activation only when necessary.
- **Intelligent Link Selection:** Prioritize lowest-latency links while maintaining others as backup options.
- **HARQ-Aware Scheduling:** Eliminate redundant retransmissions through coordinated HARQ and PDCP decision-making processes.

## IV. CONCLUSION

This paper presents an innovative adaptive PDCP duplication mechanism that intelligently balances reliability requirements with spectral efficiency in next-generation wireless networks through condition-aware packet replication strategies, demonstrating significant performance improvements over conventional static approaches while achieving stringent URLLC service requirements in 5G and beyond networks, with future research directions exploring AI-based duplication policies, cross-layer coordination mechanisms, and integration with emerging paradigms including Multi-TRP configurations and high-frequency communications to dramatically enhance efficiency through adaptive control and intelligent scheduling algorithms.

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