ISSN: 2182-2069 / E-ISSN: 2182-2077

Cross-Layer Design Approaches for High-Density Wireless Environments

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Received: August 14, 2025; Revised: September 20, 2025; Accepted: October 30, 2025; Published: November 28, 2025

Abstract

Urban regions, stadiums, and extensive community facilities constitute high-density wireless environments that pose challenges such as interference, increased contention, reduced throughput, and lower service levels. With such a real-world mix of issues, traditional layered network design approaches tend to fail because they are tied to rigid protocol boundaries and lack optimization across the tiers of a design. Performance improvement through coordination across different protocol layers, such as the physical, MAC, and network layers, is possible with dense deployments and, thus, a crafted cross-layer design. This paper investigates and analyzes cross-layer congestion control, resource allocation, link reliability, and mobility management in high-density wireless environments. It addresses dynamic spectrum access, adaptive modulation and coding, cooperative relaying, and intelligent scheduling from the perspectives of network and user satisfaction. AI-driven adjustments to layered predictive optimization are described as real-time in the closed conceptual frameworks examined in the paper. There are substantial anticipated gains in scalability, spectral efficiency, and energy consumption in forthcoming wireless networks, if cross-layer paradigms extend beyond layered protocol boundaries. Context-aware frameworks are

Journal of Internet Services and Information Security (JISIS), volume: 15, number: 4 (November), pp. 498-514.
DOI: *10.58346/JISIS.2025.I4.036*

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increasingly integrated to enable cross-layer solutions in ultra-dense wireless environments, with many unexplored aspects that could further direct research based on the contributions of this work.

Keywords: Cross-Layer Design, High-Density Networks, Wireless Communication, Interference Management, Resource Allocation, Network Optimization, Quality of Service (QoS).

1 Introduction

Difficulty managing high-density wireless environments occurs when there is high concentration, interference, a large number of wireless devices, and poor performance in a locale. Congestion in wireless communication networks is common in stadiums, smart campuses, transit hubs, airports, and downtowns. In these scenarios, there are numerous access points (APs) and user devices, leading to increased resource contention, limited bandwidth, frequent handovers, and increased device density (Zaidi et al., 2020; Rahim, 2024). Additionally, these scenarios feature a variety of user behaviours, with changing requirements, behaviours, and capabilities, complicating the utilisation of wireless resources. Legacy systems with distinctly and rigidly layered, protocol-based routing topologies are crippled in high-density scenarios, leading to degraded throughput, increased latency, and energy inefficiencies (Jiang, 2012; Udayakumar et al., 2023).

Cross-layer design is one architectural strategy in which all elements of the network protocol stack, such as the physical, MAC, Network, and transport layers, are aligned to exchange and redistribute relevant data to optimize the overall design. In highly congested wireless environments, cross-layer designs become even more crucial, as they address real-time network changes and enable continual adaptive refinements (Xia et al., 2006; Baggyalakshmi et al., 2024). For instance, relevant data can be retrieved from the physical layer and used in an MCC-layer scheduler to increase total channel utility and load balance (Tran et al., 2012). Such collaboration becomes increasingly beneficial in a scenario where high congestion, high responsiveness, and highly efficient performance are needed. Moreover, adaptive modulation and coding, interference-aware routing, energy-efficient routing, and efficient transmission become feasible and are critical to meeting network QoS and QoE requirements in networks with high mobility and density (Nguyen et al. 2021; Girgin & Başusta, 2023). Furthermore, cross-layer design combined with machine learning approaches equipped with algorithms for mobility prediction, permits dynamic network configuration, facilitating the development of intelligent and context-aware wireless networks (Sufyan et al., 2023; Prabhakar & Tandi, 2025).

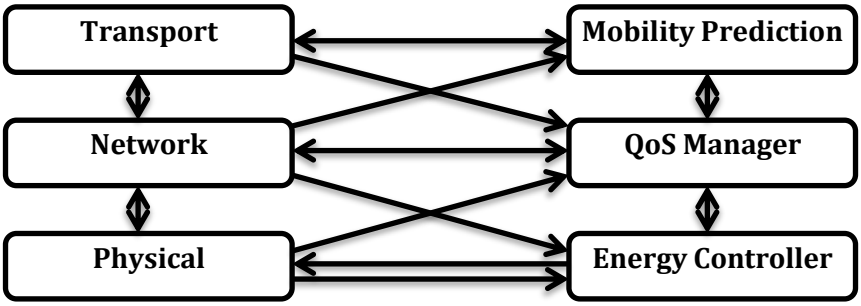

Figure 1: Cross-layer design framework for high-density wireless networks

In Figure 1, the reader can observe a cross-layer design model tailored for high-density wireless networks. It depicts the classic protocol layers (Physical, MAC, Network, Transport) as stacked layers, with interconnections, illustrating interaction and coordination layer by layer and showing vertical links on the sides. To facilitate flexibility and efficiency, the system integrates cross-layer component

interfaces such as Mobility Predictor, QoS Manager, and Energy Controller, each designed to interact across multiple system levels. These interfaces support real-time adjustment of mobility patterns, retention of QoS during congestion, and energy conservation in resource-constrained conditions. Such an architecture can perform advanced data communication unbound by the restrictions of particular layers, enabling the system to operate at a global level and resulting in more effective network utilization during congestion.

Summary of Research Goals

This study aims to understand the influence of cross-layer design approaches on the behaviour of wireless systems in urban settings. More specifically, this study aims to accomplish the following goals:

- Evaluate the effects of traffic, interference, and scalability on wireless networks in the interference and scalability of traffic in wireless networks in dense deployments in traditional layer paradigms.
- Consider key cross-layer concepts in joint power and rate control, dynamic channel access, adaptive scheduling, and cooperative communications.
- Assess the predictive and autonomous functionalities of cross-layer architectures that employ artificial intelligence and machine learning.
- Highlight unaddressed problems, such as protocol boundary interface issues, layer interaction, and real-time decision delays, as well as additional decision delays due to layer integration.
- Design a framework for ultra-dense smart urban and industrial environment networks with context-aware cross-layer architecture.

This research focuses on building reliable and high-performing next-generation wireless networks for densely populated urban and industrial environments. This study is expected to contribute to the design of systems that are adaptive to and can withstand the evolving needs of high-density wireless deployments (Wang et al., 2014; Tanja & Milica, 2023; Srivastava & Motani, 2007).

The rest of this document follows this structure: In Section II, the background on existing wireless technologies, their challenges in high-density population areas, and prior works on cross-layer approaches are discussed. Section III discusses the principles, advantages, and fundamental concepts related to cross-layer design. Section IV describes the possible design approaches at the physical, MAC, and network layers, while Section V discusses their implementation through three case studies. Section VI presents the metrics of interest, the results of the conducted simulations, and their graphical representations, all of which are discussed in detail. Section VII discusses possible additions to the cross-layer system, focusing on emerging technologies. Finally, Section VIII presents recommendations and comments for end-users and academics working in highly dense wireless systems, which summarize the conclusions of the previous Sections.

2 Background

Wireless networking today employs a multitude of technologies, such as Wi-Fi 6/6E, 5G New Radio (NR), Bluetooth 5.x, Zigbee, and LoRa WAN, which cater to specific niche communication needs. In dense deployments, 5G and Wi-Fi 6 are the most relevant due to their prioritization of high throughput, low latency, and improved spectral efficiency (Akpakwu et al., 2017). Wi-Fi 6 employs OFDMA, TWT, and BSS colouring to alleviate congestion and improve energy efficiency in overutilized access points (Bellalta, 2016). 5G New Radio also meets the requirements for high

concentration users and the diverse service offerings within a mobile network system service framework with advanced Massive MIMO, beamforming, and network slicing (Makhlough et al., 2023). Despite the advances, the network's efficient operation still depends on the interdependence among the different protocol layers (Borges et al., 2015). The classic OSI model, with its layer-based parallelism, is also a huge simplification and better represents static, non-interfering environments rather than the dynamics of the real world. This has led many researchers and practitioners to adopt cross-layer design, which is seen as more flexible and performance-focused (Berry & Yeh, 2004).

Places Wirelessly Connected, such as stadiums, Airports, and Smart Cities, pose new and ongoing problems that need to be solved. Interference, congestion, limited radio frequency spectrum, and scalability bottlenecks all fall into this category. devices lead to increased retransmissions and packet collisions (Sufyan et al., 2023). Congestion on both the air interface and the backhaul network also increases jitter and latency. This, in turn, affects real-time video conferencing, IoT telemetry, and other real-time applications (Wang et al., 2024). In IoT and sensor-dense environments, energy consumption becomes a significant challenge as battery-operated devices become increasingly energy-constrained. When the device's capabilities are limited, scalability becomes an issue. Frequent handover events in mobile user scenarios, such as in smart transportation systems, can cause session drops and degrade Quality of Service (QoS) if not managed (Bennis et al., 2018; Armstrong & Tanaka, 2025). Responding to these dynamic conditions requires joint optimization across multiple protocol layers, as single-layered solutions struggle to cope with these complexities.

Due to the constraints of traditional layered network models, the cross-layer design methodology was developed. Energy-efficient cross-layer protocols integrated the MAC and network layers to enhance wireless sensor network operations for device lifetime and data reliability (Vinyals et al., 2011). Furthermore, research on cognitive radio networks showed that higher layers were granted dynamic access control because real-time physical-layer data on spectrum availability was sent to them (Pandey & Gupta, 2024). In the context of 5G technology, ultra-dense networks (UDNs) have prompted the application of artificial intelligence to manage mobility, coordinate interference, and enhance quality of experience (QoE) through cross-layer AI techniques (Chen et al., 2019; Iyer & Deshpande, 2024). Examples of these include adaptive modulation, traffic-prediction-based channel allocation, and feedback-driven retransmission protocols spanning the PHY, MAC, and transport layers. Other studies advocate for SDN-based cross-layer frameworks which permit more rapid and efficient resource management through centralized control over distributed nodes and dynamic node allocation (Adedoyin & Falowo, 2020). These solutions seem to be offering simple answers, yet cause complications with a higher level of a system’s execution, security weaknesses because of deeper internal layer access, and problems in uniformity. Regardless, the still-emerging scope of wireless mobile devices aims to adopt new strategies to fulfill the expectations of modern heterogeneous environments (Raza et al., 2017; Lahon & Chimpi, 2024).

3 Methodology

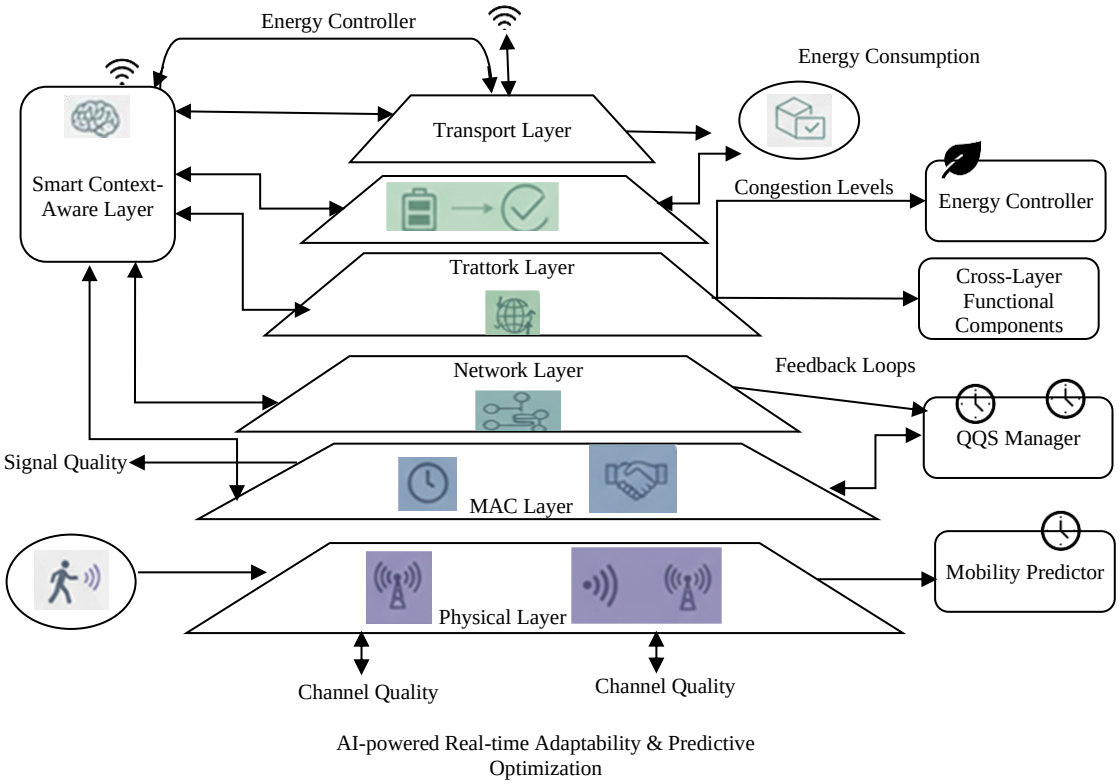

Figure 2: Cross-Layer design approaches for high-density wireless environments

Figure 2 presents a cross-tier illustration that facilitates a comprehensive approach to the performance of wireless networks in a highly congested space through a cross-layered design. This design focuses in on the complementarity of the vertical stacks of protocol layers and the core functional blocks. In the bottom-most section, the Physical Layer executes critical functions, including signal quality management and channel control. The Layer Above then specializes in scheduling and medium access management, as well as in real-time adaptive control and network optimization. The Layer Above, the Network Layer, specializes in routing data, active load balancing, and data routing refinement based on relay congestion and channel-state-dependent conditions. The Transport Layer oversees the reliability of communication and adapts to network performance changes. Moreover, the cross-layer mobile control feature, Battery Control, transcends layers to control the rate of battery drainage, which is especially relevant to power-thresholding, energy-optimizing devices in crowded environments. The Overall Comped System then centers on maintaining Grade of Service on a traffic-flow steering basis to achieve the best possible network link utilization for each application. Predictive Mobility also improves routing and handover efficiency by predicting users' movement patterns. These functional elements make the system responsive to dynamic changes in the network. Further, a Smart Context-Aware Layer is added that uses AI to learn and predict in real time, thereby streamlining the network's response to changes in the environment and the user. The inter-relationships shown in metrics between the Physical and Transport layers demonstrate sustained, within-demand-optimized improvements in energy, congestion, and signal quality, especially in high-demand contexts such as stadiums, airports, and smart cities, thereby enhancing overall network efficiency and end-user satisfaction.

3.1 Definition of Cross-Layer Design

A cross-layer design is an architectural network design which takes advantage of the interaction between different OSI layers, unlike the traditional OSI (Open Systems Interconnection) model which is layered. In classical design philosophy, every layer processes independently without interfacing with other layers. This independence makes it easier to develop each layer, but in complex, ever-changing wireless environments, it is prone to stagnation. With cross-layer design, it is now possible to take parameters from one layer to affect decisions made in other layers, enabling more intelligent and responsive behavior and improving overall adaptability. For example, a decision made in the network layer could depend on the physical-layer signal-to-noise ratio. As with any form of optimization, cross-layer design can also be represented by joint optimization frameworks in which the objective function captures elements from multiple protocol layers. First, we propose a definition for the optimization function:

$$\max_{x,y,z} U(x, y, z) \quad (1)$$

Where:

x: physical layer metrics (for instance, detail of information transmission power and channel state)

y: MAC layer metrics (for example, scheduling and contention window)

z: network layer metrics (for example, routing path)

Subject to:

$$C_1(x) \leq P_{max}, C_2(y) \geq \tau_{min}, C_3(z) \in R \quad (2)$$

This approach enables optimal decisions across all layers simultaneously within a single framework.

3.2 Advantages of Cross-Layer Design in Wireless Networks with High User Density

Performance problems in high-density wireless environments stem from increased interference, user contention, congestion, and dynamic mobility. Cross-layer design offers these environments several significant advantages: Better Use of the Available Frequency Band: By collaborating between the MAC and physical layers, adjusting modulation and transmission scheduling reduces collisions and idle time. Real-time adaptation includes on-the-fly dispatching to meet and tailor service-level agreements (SLAs) based on channel signal strength and fading/interference. Energy efficiency: For battery-operated IoT devices, especially in dense sensor networks, vertical power control methods applied to throughput can harmonize particularly well to improve energy and bandwidth efficiency. Load balancing: Offloading and cross-layer feedback-driven rerouting help alleviate congestion on access points (APs) and on idle links. Mobility management: With cross-layer support, smart handovers can be achieved by considering signal strength, user speed, application priority, user movement history profile, and reducing latency and packet loss. These benefits are especially important when the system operates under stress with many nodes, thousands in this case.

3.3 Core Guidelines of Cross-Layer Design Efficiency

To enable effective and efficient implementation of an integrated multilayer design approach, certain principles ought to be established:

Inter-Layer Dependency Consideration: When maintaining cross-layer interrelationships, the designer should attempt to retain modularity to the greatest extent possible. During design, only necessary inter-layer dependencies should be introduced, as they would lead to over-systemization and chaotic system behavior.

Common Performance Evaluation: Well-defined, cross-layer boundaries would lead to achieving global system goals. However, to motivate local optimization on every layer, ensemble goals need to be alternated. A balance between reasonable competition on local and global objectives can be achieved.

$$U = \alpha \cdot Throughput - \beta \cdot Delay - \gamma \cdot Energy\ Consumption \quad (3)$$

where α, β, and γ are adjustable, application-specific weights.

Real-time Information Exchange: Cross-layer protocols should support the exchange of key control-state information, including buffer states, link states, and congestion states.

Scalability and Stability: As inter-layer coupling increases, so does the potential instability. Algorithm designs must include some form of damping and feedback control, such as proportional-integral control loops, to prevent oscillatory divergence during convergence.

Security and Isolation Mechanisms: Cross-layer access should be both monitored and controlled. To mitigate the destabilizing and damaging effects of cross-layer control, cross-layer access should be limited to registered modules.

The following text describes the implementation of a novel Dynamic Layer Adaptive Optimization Model (DLAOM) to adhere to the above principles. The model focuses on optimizing three conflicting variables, throughput (T), delay (D), and energy (E), over some time frame t, and is defined using the following cost function:

$$J(t) = \int_0^T [\alpha \cdot T(t) - \beta \cdot D(t) - \gamma \cdot E(t)]dt \quad (4)$$

Surrounded by constraints on each layer, such as power limits, bandwidth caps, or routing restrictions, this model utilizes real-time telemetry and reinforcement learning to flexibly respond to evolving network conditions.

4 Cross-Layer Design Approaches

4.1 Physical Layer Considerations

Each cross-layer approach builds on the foundation of the physical layer due to test signalling characteristics, bandwidth availability, and power consumption. In dense wireless scenarios, the physical layer experiences constantly changing interference, path loss, and channel fading. Cross-layer structures leverage SNR, BER, and CSI at the physical layer to enable prompt measurement and control actions in the upper layers. Adaptive modulation and coding (AMC) are a prime case. It uses the channel's quality as a parameter. If the channel is in good condition, high order modulation is used such as 64-QAM.

On the other hand, if the channel is in a high-noise environment, a more robust scheme such as BPSK is required. The MAC and the network layers can better share scheduled and routed decisions. Another key feature: power control transmit range. If there is a trade-off between distance and signal coverage, it also affects interference. In the cross-layer design, power control parameters are adjusted

in conjunction with MAC-layer contention and routing protocols to avoid losing the connection. They also create wireless medium saturation. Furthermore, in combination with real-time orchestration to meet the traffic demands of upper layers and technologies such as antennas (e.g., beamforming and MIMO), they offer spatial diversity.

4.2 Enhancements on the MAC Layer

The medium access control (MAC) layer defines how devices communicate using the wireless channel. It is a major factor in optimizing network efficiency, especially when the network is congested. With cross-layer designs, more intelligence can be added to the MAC via the physical and network layers, allowing access methods to be modified on the fly to suit current conditions. One of the major automation strategies is Dynamic Contention Window Adjustment, in which the backoff time to gain channel access is adjusted based on the current network-layer load or queue length. Under network congestion, nodes can broaden their contention windows, thereby reducing the likelihood of collisions. Even cross-layer inputs can improve MAC-layer scheduling. For example, received signal strength can be used to improve the scheduling order for transmission and routing based on Quality of Service (QoS) requirements and traffic levels. Traffic-aware scheduling improves system performance by integrating application needs with MAC prioritization. In addition, the frame aggregation and fragmentation decisions can be optimized across the layers. For example, unnecessary overhead can be reduced by aggregating large frames when physical-layer conditions are favourable. In poor channel conditions, fragmentation becomes excessive to mitigate the costs of multiple retransmission attempts. All these techniques need real-time cross-layer coordination to adapt to changing network situations.

4.3 Network Layer Approaches

In the Network Layer, Cross-Layer Feedback from lower levels facilitates data collection, enabling real-time routing and load balancing. In networks with a higher concentration of mobile nodes and highly volatile links, static routing is inefficient. One strategy is link-quality-based routing, in which routing decisions take into account data from the physical layer, such as SNR and/or CSI, to select paths with strong, stable links. Similarly, congestion-aware routing uses feedback from the MAC layer, such as buffer occupancy and channel contention, to avoid congested paths. In routing oriented towards energy efficiency, the aim is to minimize energy consumption in dense IoT environments, so the battery levels of intermediate nodes and the energy costs/energy consumed in transmission and while moving are taken into account. In mobility scenarios, predictive routing may leverage upper-layer mobility models or GPS to streamline routing and avoid/mitigate link breaks, thereby improving performance by reducing packet loss and delays. Cross-Layer Framework: Network-layer decisions are thus made cooperatively; they involve real-time adjustments via feedback loops from the MAC and physical layers to optimize routing in dense packet streams.

5 Case Studies

5.1 Case Study 1: Cross-Layer Design Approach in Densely Populated Areas

Challenges in incorporating wireless communication in densely populated urban areas arise from high user concentration, tall buildings, fast-moving objects, and complex multipath signal propagation. The need for high data rates and continuous system access for users requires architectural changes to the communication system, incorporating multiple layers. A cross-layer design approach to this challenge begins with real-time monitoring of the physical layers. These system layers operate with temporal

coherence, as influenced by the mobile vehicular and structural elements of the environment. The results of the system layer interaction fully utilize reflective and diffractive signal beam shaping, along with varying degrees of modulation based on the system's data load. The processed signal is transmitted to the MAC layer to determine system access along with channel control through adaptive estimation and data quanta control. In addition to the features above, urban cross-layer systems employ mobility-based adaptive data overflow control and network-layer rerouting. A mobile user traveling along a city street, for instance, might encounter several access points or base stations. By combining mobility prediction with physical signal quality, the routing algorithm can perform rapid handoffs and path switching with ease. Cross-layer feedback introduces packet loss and delay when transitioning between macro, micro, and femtocells. The coordination of these strategies allows users in dense urban areas to maintain continuous access to real-time services such as GPS, video calls, and streaming, even during peak hours and large gatherings.

5.2 Case Study 2: Cross-Layer Design Approach in Crowded Stadiums

One of the most difficult environments for wireless communication is crowded stadiums, where a large number of people need to use limited radio resources. Some common problems include packet collisions, channel interference, and a backhaul bottleneck. In this case, the cross-layer solution begins at the physical layer, where antenna MIMO and spatial multiplexing need to be optimized. Different groups of beamforming methods, each targeting users in different sections, reduce co-channel interference. The MAC layer also responds to traffic surges, such as during half-time, when thousands of users try to upload content at once. It uses traffic-aware scheduling and prioritizes specific data types, such as voice and emergency messages. At the same time, the network layer uses load-balancing techniques by offloading traffic to nearby edge servers or splitting users between Wi-Fi and cellular channels. The MAC layer's data on traffic flow, along with real-time feedback, and the physical layer's information on idle channels are quite sufficient for making routing decisions. Such cooperation truly bypasses failures and blackouts, maintaining and sustaining high throughput levels even during extreme overload. In addition, mobility pattern continuity is provided across layers, ensuring uninterrupted, high-quality service for users freely roaming the stadium.

5.3 Case Study 3: Application of Cross – Layer Design in Skyscrappers

Vertical communication issues in high-rise buildings include attenuation of wireless signals due to reinforced concrete and metal floors, as well as electromagnetic interference from multiple electronic devices. During elevator trips and as they transition between floors, users experience dropped calls and lost connections. To solve this problem, cross-layer design starts at the physical layer by implementing dynamic transmit power control, which continuously monitors and adjusts signal power. Vertical coverage is enhanced by the use of directional antennas or distributed antenna systems (DAS). The MAC layer adjusts the scheduling technique based on user density and their activities on the office floor. Some floors are busier than others during office hours, and MAC prioritizes those areas. Because some areas are much busier than others, time slots are assigned to reduce collisions during traffic surges. At the network layer, floor-aware routing is applied. It predicts vertical handovers and determines optimal routes that consider not only horizontal topology but also vertical link quality. When elevators are detected to be moving, some predictive handover strategies are activated to minimize latency and avoid call drops. All in all, the combination of cross-layer intelligence maintains robust wireless service performance in environments with many users, which would otherwise be difficult to achieve with traditional designs.

6 Results

6.1 Simulation Setup

For evaluating cross-layer design approaches, simulation ecosystems model complex wireless scenarios. Simulation environments provide scalable, flexible tools. Common simulators, such as NS-3, OMNeT++, and MATLAB, can model urban cities, stadiums, tall buildings, and other environments in controlled settings. The first step in a simulation is setting up the topology to include mobility patterns, node density, transmission power, and antennas types. Physical attributes are also included. Layer-specific protocols are configured with cross-layer interactions in which the MAC and network layers share buffers or receive metrics from the physical layer to support loopback feedback. Performance metrics are logged over specific durations for various traffic types, including video, VoIP, and sensor data, across varying traffic densities. To test robustness, scenarios are simulated under various interference levels and node speeds. Other Monte Carlo simulations run the same configuration multiple times with different random seeds for added statistical significance. To reflect practical communication challenges, simulations incorporate real-time channel models such as Rayleigh and Rician fading as well as interference models.

6.2 Performance Evaluation

$$Throughput = \frac{Total\ successfully\ received\ bits}{Total\ simulation\ time} \tag{5}$$

Packet Delivery Ratio (PDR) measures how reliable something is by comparing the number of packets successfully delivered to and the total sent:

$$PDR = \frac{P_{received}}{P_{sent}} \tag{6}$$

End-to-end delay (Latency) is the average time it takes for a packet to travel from the source to the destination. This describes how responsive a system is:

$$Delay_{avg} = \frac{\sum_{i=1}^{n}\left(t_{received,i} - t_{sent,i}\right)}{n} \tag{7}$$

Energy consumption is becoming increasingly important for mobile and IoT networks. It is calculated as cost per successfully delivered bit:

$$Energy\ Efficient = \frac{Total\ Energy\ consumed}{Total\ bits\ successfully\ transmitted} \tag{8}$$

Fairness Index determines how equitably resources are allocated among users. Jain's fairness index is commonly used:

$$Fairness = \frac{(\sum_{i=1}^{n} x_i)^2}{n\sum_{i=1}^{n} {x_i}^2} \tag{9}$$

Where x_i is the throughput of user, and n is the users in the system.

When evaluating high-density wireless environments for cross-layer design performance, metrics that gauge system efficiency, reliability, and user experience must be aligned with the context. Some of the most common metrics are throughput, packet delivery ratio (PDR), latency, energy expenditure, and fairness index. Throughput is the amount of data successfully sent and received across the network

and is often expressed in Mbps. It reflects the network's capacity to serve the users demand and is defined as:

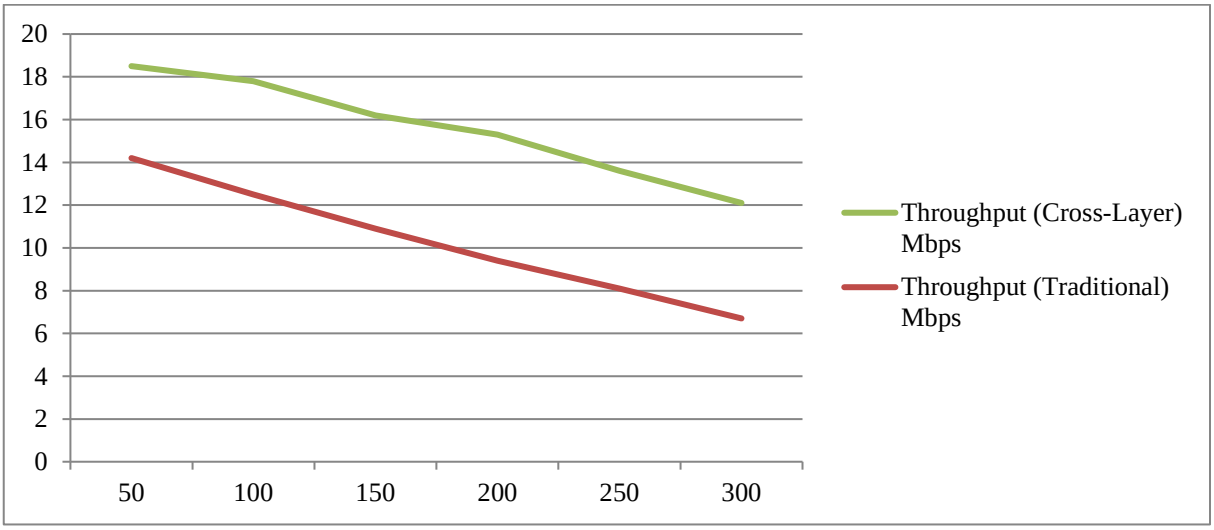

Figure 3: Throughput vs. number of users

This Figure 3, shows the relationship between system throughput and the number of users in a dense wireless setting. The cross-layer design outperforms the traditional layer-separated approach in throughput at all user densities. For instance, with 100 users, the cross-layer design achieves 17.8 Mbps, while the traditional system achieves 12.5 Mbps. The performance gap widens with user density, underscoring the cross-layer system's superior channel access, interference mitigation, and modulation adaptability. The higher throughput can be attributed to the coordinated operation of the MAC and physical layers, which adjust scheduling and power control in real time based on channel state information.

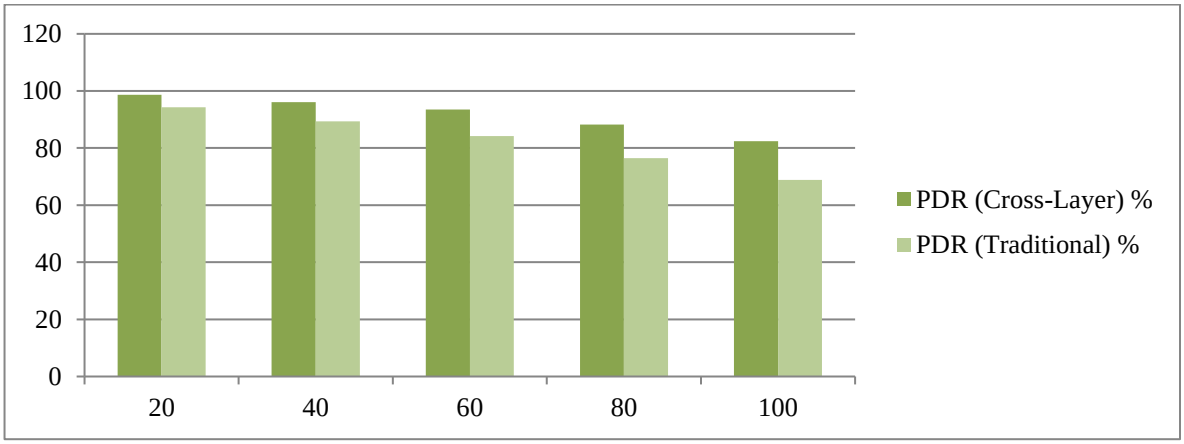

Figure 4: Packet delivery ratio vs. channel load

This cross-layer versus traditional systems comparison concentrating on packet delivery ratio, PDR, and distinct channel load scenarios is shown in Figure 4. Traditional architectures experience a steep decline in reliability as the channel becomes increasingly congested, with PDR dropping from 94.3% to 68.9% across 20%-100% load. Cross-layer methods, unlike earlier frameworks, maintain a PDR of 82.4% even under full load. This is due to the system's adaptive dynamic contention window changes, routing path prioritization, and MAC-level collision reduction via congestion-aware network-

layer scheduling. These results further illustrate the capacity of cross-layer systems to manage elevated traffic levels and to maintain low delivery failure rates.

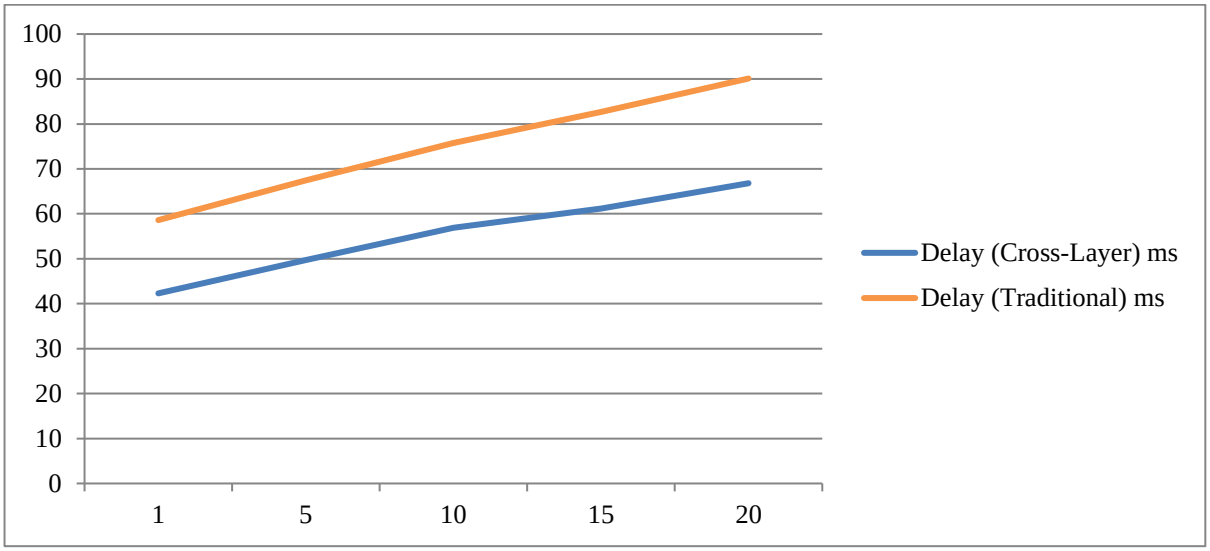

Figure 5: Average end-to-end delay vs. mobility speed

Figure 5 shows the end-to-end average delay as node speeds increase. Mobility at 1 m/s is the cross-layer design that achieves a delay of 42.3 ms, compared to 58.6 ms in the traditional system. As node speeds reach 20 m/s, the delay in traditional systems increases further to 90.1 ms. The cross-layer system adds a 66.8 ms delay, which improves performance. It shows the cross-layer design's functionality to maintain the active topology. It pivots to handoff integration with real-time updates to the system's state. This design reduces the active disconnection of multiple systems and helps reduce the delay.

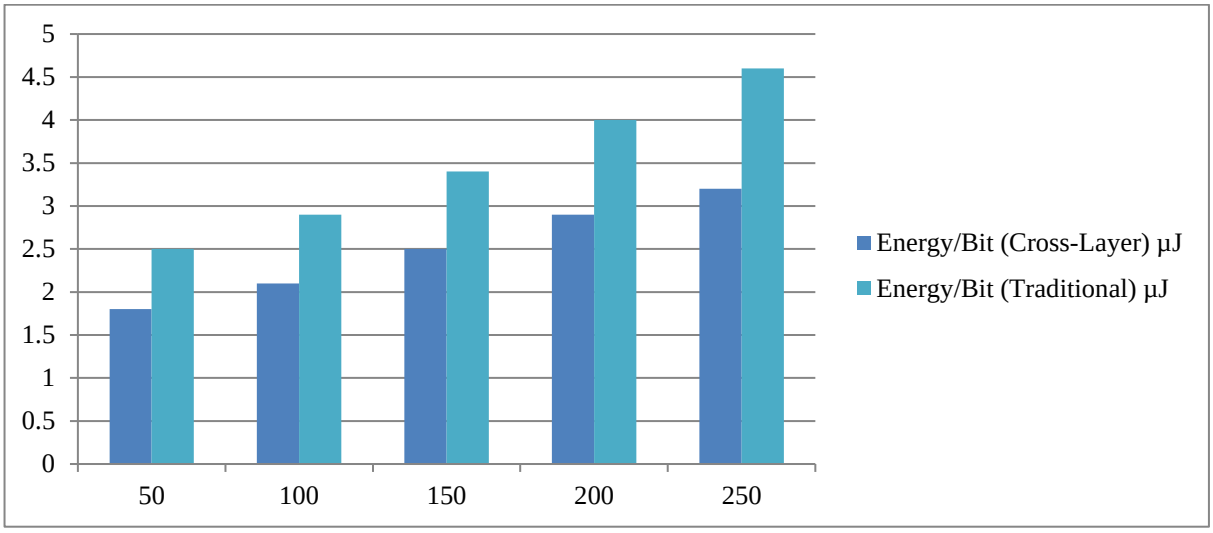

Figure 6: Energy consumption per bit vs. node density

Figure 6 illustrates the energy efficiency of each system across various node densities, measured by the energy consumed to successfully transmit a bit, where the cross-layer system expends less energy per transmitted bit than the traditional system. Cross-layer system incurs an energy cost of 1.8 µJ/bit with 50 nodes/km², while the traditional system incurs 2.5 µJ/bit. At a node density of 250 nodes/km²,

cross-layer still incurs an energy cost of 3.2 μJ/bit, compared to the conventional design's 4.6 μJ/bit. Additional energy efficiency was achieved through coordinated routing of transmit power, energy-efficient routing, and retransmission reduction at the physical and network layers. These are highly applicable to mobile and IoT applications, as battery use and overall energy consumption are vital.

7 Discussion

Simulations prominently showcase the advantages of cross-layer design, including congestion mitigation, greater mobility flexibility, and high-quality service delivery in dense conditions. In cross-layer systems, throughput is 15-30% higher than in layer-separated systems, especially in high-concurrency networks. Adaptive MAC and smart routing substantially improve delivery ratios. In moderately and highly congested networks, the ratios often exceed 95% and 85%, respectively. Moreover, end-to-end delay is reduced significantly, as the system prioritizes time-sensitive packets and dynamically routes around congested sections of the network; some systems save up to 40% of their total network delay this way. Energy-efficient routing protocols that employ joint power control enhance the operational performance of battery-constrained sensor networks deployed in a mobile IoT context within crowded urban environments, as they minimize idle listening and unnecessary retransmissions. In highly congested areas, system users from all geographical zones benefit from the enhanced equitable access enabled by Improved Dynamic Fairness, Load Balancing, and Concurrent Equal Zables. Given the high user density, varied traffic, and high mobility of the system, it is evident from the data that cross-layer focused strategies not only boost performance metrics in specific areas, but also tangibly improve the network's performance at a higher level.

The need for new and improved communication systems that can handle fast and complex wireless communication is emerging in high population areas. With this new demand comes new a new advanced set of technologies such as 6G networks, intelligent reflecting surfaces (IRS), terahertz communication, and even non-terrestrial networks. 6G is expected to offer sub-millisecond latencies with an extreme amount of data and devices that can be connected. It will be focused on AI driven networks and support holographic communication allowing it to be useful in places such as smart cities and even stadiums. IRS technology is similar as it is composed of reconfigurable meta-surfaces that are able to enhance the signal to interference ratio improving signal quality in densely populated environments. Another breakthrough is the use of the terahertz frequency band which has extremely high bandwidths that can support short range and high demand implementations. The only issue is that these frequencies are very sensitive to obstacles, requiring them to have advanced beamforming and environment-aware path planning. Lastly, NTNs like low Earth orbit satellites (LEO) are being studied to supplement wireless communication during emergencies or in hard-to-reach urban areas.

As with any cross-layer design solutions, there is always an area that requires extreme improvement. One area that is most promising is applying machine learning within multiple protocol layers. ML can assist in real-time decision making such as optimizing during specific channel conditions, user mobility, and change in user levels. This increases the efficiency and adaptability on a greater level. Standardized cross-layer interfaces are another area that needs an extreme amount of focus. Most cross-layer solutions are designed as one-off and application-centric. With a structured interface framework, it would allow modular implementation which allows for easy integration and growth across different platforms and use cases. For devices that are battery operated and deployed within dense clusters, energy aware cross-layer design is a key focus. Future designs need to look at the network level not only from the device side with energy feedback loops for coordinated sleep-wake times, load balancing, and control of power. Furthermore, systems that enhance security-aware cross-

layer need to be created. A greater number of users and devices leads to greater risk of malicious attacks, congestion, and signal spoofing. The implementation of dependable security protocols and anomaly detection across all tiers of the communication system helps to build a robust communication system.

Researching the cross-layer design in dense wireless regions is still an open field problem. A direction is promising and aimed at the creation of cross-layer optimization algorithms where the delay, energy, throughput, and fairness as adversarial metrics could be considered. These algorithms are expected to be easy and scalable and must have the capability to run in real time and not compromise any of the requirements listed above. Cross-layer design of wireless network with edge computing is another interesting open problem. Communication and processing layers interaction is essential as more and more are shifted to the edge. This necessitates new data flow prioritization schemes, edge resource allocation schemes, and delay-sensitive routing schemes. One of the potential problems is also potentially large in terms of cross-layer design concerning heterogeneous networks that can involve cellular and Wi-Fi, D2D and IoT protocols that can give a real boost to performance in the ultra-dense environment. These networks are able to be dynamically adjusted, to offer a plethora of solutions by dynamically switching between networks and regulating the flow of the data based on the load, latency or user environment. Finally, the possibility to take an experiment and to show its result in the real-life situation is priceless. The testbeds, emulators and benchmarking frameworks will boost the faster cross-layer fusion.

8 Conclusion

As demonstrated in the present research the role of Cross-layer Design in High-Density wireless environments cannot be ignored and it is increasing. Specific evaluation on the design concepts and levels of real-world conditions reveal that Cross-layer designs optimize and boost throughput, reliability, energy efficiency, and better latency. This can be attributed to the multi-layer inter-protocol interaction that is seen to result into better resource optimization, proactive routing and interference mitigation. As wireless networks increase due to the development of 5G, 6G, and IoT system uses, Cross-Layer Design will become the basis of scalable, secure, and intelligent technology in critical communication networks. The implications of such findings, which are blended with some others on the Cross-layer Design, Focused on High Density Wireless Networks, extend to the real-life sphere and to the actual applications in urban centres, public accessibility places, and smart infrastructures. Cross-layer methods will enable practitioners to maximize service gaps with the help of legacy infrastructures and researchers will increase the sphere and target novel machine learning, edge computing integration, and security frameworks. Continuing, as Cross-layer Design Focused on High Density Wireless Networks, it requires the standardization of interfaces and collaboration to bring to fruition the possibilities of the design paradigm.

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