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Comparative Analysis of Throughput in Wireless Mesh and Cellular Networks

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Abstract

The maintenance and provision of ensuring high throughput communication is the central point of the WMNs and Cellular Networks of Wireless communications. The study will focus on wireless mesh and cellular networks to compare their performance in terms of throughput under different conditions and deployments. WMNs are self-healing and multi-hop, due to multi-hop communication and a decentralized architecture. Contrastingly, Cellular Networks are expansive and offer consistent performance, relying on central control and infrastructure-based transmission. These network architectures are analyzed in terms of the average throughput per node, end-to-end delay and spectral efficiency. Other NS-3 research found that WMNs were at an advantage in densely populated urban regions with high user mobility, as they provided efficient routing and load balancing across multiple paths. In rural areas with low population density, cellular networks performed better because of their high data reliability, enabled by centralized scheduling. The paper also discusses interference, node density and mobility patterns in terms of throughput performance. The paper will also focus on analyzing hybrid models integrated with cellular infrastructure and mesh backhaul to leverage both paradigms. The findings would be useful to network planners and

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policymakers, as they enable the personalization of deployment plans across different situations. This comparative study demonstrates how Wireless Mesh Networks (WMNs) and Cellular Networks can be used in synergy to deliver high-throughput wireless communication in next-generation networks.

Keywords: Wireless Mesh Networks, Cellular Networks, Throughput, Network Performance, Mobility, Routing, Spectral Efficiency.

1 Introduction

The development of cellular networks and wireless mesh networks (WMNs) enhances their capabilities to support modern connectivity through high speed data transmission (Akyildiz et al., 2005; Rimada & Mrinh, 2024). The topology of WMNs is decentralized, multi-hop, and nodes collaborate to relay data, ensuring highly robust, adaptive connectivity in urban and infrastructure-poor regions. Cellular networks, in contrast, are hierarchical, infrastructure-based networks in which information is relayed via base stations linked to central control nodes (Abbasi & Younis, 2007). This gives it greater stability and a higher coverage capacity. Continuous networks have evolved to meet the needs of real-time communication, high-bandwidth capacity, and a large number of connected devices (Alsharif & Nordin, 2017). These new technologies have led to high demand for services. In all networks, value is defined by the performance measure of throughput, which is the rate at which data is conveyed through the network. The significance of these is even more critical in the fields of online gaming, video streaming, and critical Internet of Things, which largely rely on user interaction (Raman & Chebrolu, 2007; Patel & Kingdone, 2025). Despite the current developments in 5G cellular networks, WMN is also gaining popularity for smart city infrastructure, rural broadband access, and disaster recovery solutions (Andrews et al., 2014; Rappaport et al., 2013). The behavior of the two types of networks with respect to throughput is also useful for selecting or designing the best communication infrastructure for different applications (Waharte et al., 2006).

The objective of the paper is to present a detailed benchmarking of wireless mesh networks against cellular networks in terms of throughput performance (Kumar, 2024). This refers to node density and mobility, interference and routing effectiveness in general. Previous research has examined performance comparisons with simulation frameworks. But deployment constraints and the potential of hybrid networks have not received the due attention (Ning et al., 2012; De Oliveira et al., 2011). This is done to identify the best network structures for different conditions and usage profiles by conducting simulation analysis to determine throughput performance. The findings of this work have implications for telecommunication planners and system architects seeking to develop scalable, efficient communication systems. Finally, this paper includes some thoughts on possible integrations and hybrid designs by comparing the throughput trends of the two network designs, to effectively serve next-generation wireless communications (Pallavi & Sreenivasulu, 2024).

Key Contributions

- A comparative study of WMNs and cellular networks focusing on throughput and simulation-based metrics within different traffic, mobility, and density scenarios.
- Recognition of the balance between centralized and decentralized architectures in resolving throughput conflicts.
- Development of an integrated market structure that services both wireless mesh networks and cellular systems in high-demand situations.

To simplify the paper, I will divide it into five fundamental sections as presented in the following text. In Section I, I have defined, explained the significance and description of wireless mesh and cellular networks with reference to assessing throughput. In Section II, I have provided a current, comprehensive literature review that summarizes the available literature on throughput optimization across both network types. In part III, I outline the suggested methodology, which involves a novel analytical paradigm, a comparative formula, and room for architectural and flowchart visualization. Section IV, the review of the simulation results, including charts and tables, focuses on the different scenarios and the overall throughput performance of the discussed scenarios. Section V draws key points and conclusions from the paper, highlighting the findings and presenting recommendations for future research and deployment strategies.

2 Literature Survey

The performance and study of wireless communication systems have been well researched, especially to enhance throughput, as this affects the effectiveness of the entire network system (Dhanalakshmi et al., 2015). Wireless Mesh Networks (WMNs) have become quite popular due to the self-configuring and self-healing features (Talezadehlari et al., 2014). Various routing and channel assignment algorithms have also been investigated to maximize the throughput of WMNs (Chai & Zeng, 2020; Rangan et al., 2014; Ding & Xiao, 2011). Other research has explored the concentration of multi-radio and multi-channel systems to minimize interference and maximize delivery rates (Kyasanur & Vaidya, 2005). Other research considers dynamic routing techniques, which are effectively used in mobile and dynamic network settings (Veerappan, 2023). With these advancements, WMNs can sustain high throughput even in overcrowded metropolitan areas and during disaster recovery operations (Sadulla, 2024).

The evolution of cellular networks has gone through multiple generations, with each generation showing specific improvements in throughput due to the adoption of MIMO (Multiple-Input Multiple-Output), OFDMA (Orthogonal Frequency-Division Multiple Access), and other advanced modulation techniques (Bahl et al., 2004; Imboden et al., 2012). The effects of user movement, cell densification, and even the scheduling algorithm have also been considered regarding throughput. Given the cellular framework's dominant structure, complex resource allocation is manageable and has been shown to enhance throughput in large-scale systems. Furthermore, in other scenarios, such as at coverage edges or when the network is congested, throughput suffers greatly.

The distinct advantages and tradeoffs of WMNs and cellular systems have been studied and contrasted. WMNs offer greater flexibility and resilience but suffer from higher end-to-end latency and more complex routing. Conversely, cellular networks incur higher maintenance costs but offer better quality of service and wider coverage; they are also highly dependent on existing infrastructure (Krishnan et al., 2008). Ongoing research aims to integrate the advantages of mesh backhaul and cellular systems. These methods aim to improve throughput and reliability while maintaining scalability in current wireless systems (Nivetha & Nandhakumar, 2018).

3 Methodology

Figure 1 Optimizing Interlayer Communications Designs AI-Enabled Smart Context-Aware Networks Architecture. The Smart Context-Aware AI device applies the transport, network, and physical layer triads to adjust system parameters to enhance performance toward a target goal. The Network layer's Transport layer further addresses and controls congestion in data transfer. In conjunction with channel quality control, the Network layer's interference control, and optimal multi-hop routing, the Network's

real-time control boosts performance. The Energy Controller and the QQS Manager Traffic control system collaborate to sustain and adjust energy control boundaries. The Physical Layer implements control-surface deflections to maintain an uninterrupted linkage. The system alters control system parameters and maintains uninterrupted pivoting to user control, thereby making system correction the control system's predominant function. The system pivoting is in response to the user, the system, and the environment to maximize system efficiency and performance.

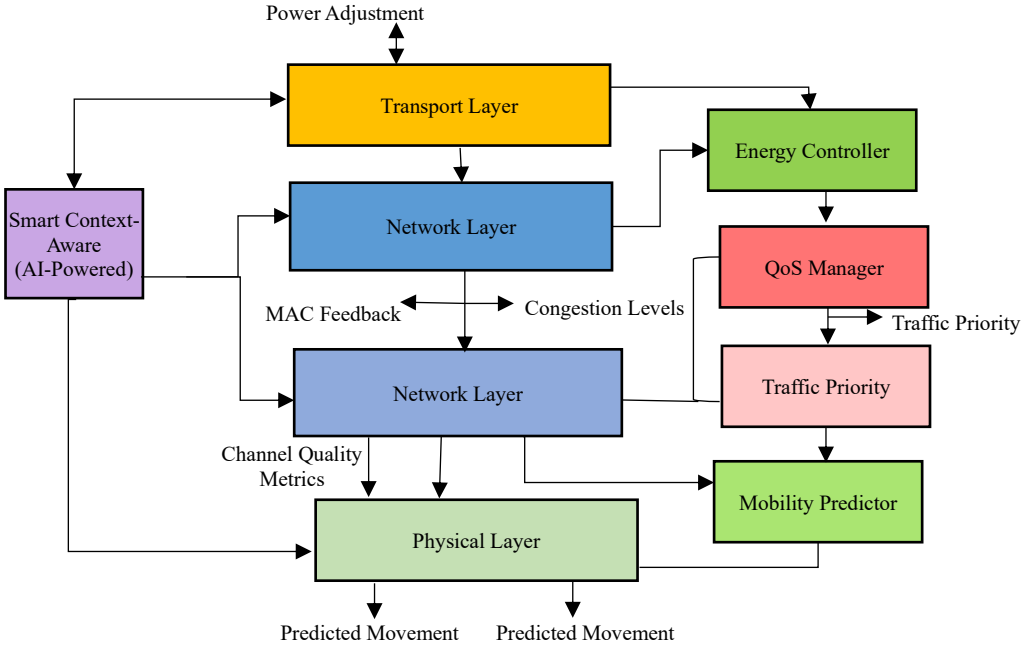

Figure 1: AI-Powered smart context-aware network architecture for optimized communication

In this section, we present a new method for analyzing the overall execution, or throughput, of Wireless Mesh Networks (WMNs) and Cellular Networks within a single cohesive framework. Most literature focuses on routing and mobility management, signal interference, or spectrum allocation, and there is still no unified model for real-time, comparative throughput performance in dynamic environments. This is what we call the simulation-driven performance modeling and hybrid evaluative approach methodology gap. The model accounts for a mixture of mobile and static user density, variable network load, topological differences between mesh and cellular systems, user movement patterns, and other deployment heterogeneity (Alborji, 2014). The proposed methodology aims to optimize throughput comparisons under normal and extreme conditions using these parameters.

The approach consists of three main phases: the first step is input configuration, which encompasses network model setup with node placement and mobility models; the second step is a simulation run with NS-3 or its equivalent tools; and the third step is the aggregation of results, centered on throughput, latency, and routing overhead. The framework allows the evaluation of both legacy WMN routing AODV and OLSR as well as cellular network scheduling algorithms, including proportional fairness and round robin. In addition, the simulations examine the effect of hybrid WMN deployment strategies as backhauls to cellular base stations on aggregate throughput.

This modular design enables urban, suburban, or rural complex configurations to achieve an understanding of the entire picture of network performance and its trade-offs in a comprehensive manner.

The following generalized formula is applied to measure throughput quantitatively:

$$T_{avg} = \frac{\sum_{i=1}^{n} D_i}{t_{total}} \qquad (1)$$

Where:

- T_{avg} = Throughput Average (in Mbps)
- D_i = Total data (in megabits) successfully delivered by node i
- t_{total} = Total simulation time (in seconds)
- n = Total number of nodes involved in data transmission

This formula helps determine how well a wireless communication network is performing by calculating the system's average throughput. It does so by summing the data transmitted by each node and measuring the system's total operational time. This metric measures how successfully data is delivered over the network within a specified duration, indicating how well the system handles user data under different network conditions.

In Wireless Mesh Networks (WMN), multiple nodes (clients and routers) can concurrently transmit and relay packets within the multi-hop network. Every node not only sends its own data; it also sends data to other nodes in the network, so that D_i contains both direct and forwarded data. The formula is designed to capture WMNs collaborative nature. Throughput may scale with node count, degrade due to interference or traffic between nodes, or reach a plateau; this is critical for determining thresholds and bottlenecks.

In Cellular Networks, base stations usually control data transmission in a centralized manner. User Equipment (UE) connects to base stations that control all data streams, so D_i refers only to the data about each device's upload and download activities. This formula indicates the degree of traffic congestion within the system, especially during high-load conditions or when major movements require handoffs, where scheduling algorithms are critical.

By evaluating T_{avg} across different values of n, simulation durations, and traffic types, network designers can understand:

- How scalability impacts throughput.
- The efficiency of routing/scheduling protocols.
- The effect of topology and mobility (static vs. mobile nodes).
- The impact of interference, signal attenuation, and node density on actual data delivery.

Using this formula, both network types can be compared side by side in controlled, simulated environments, and conclusions can be drawn about which system is more optimal for specific scenarios.

This Figure 2 shows how a semi-chaotic evolutionary algorithm is used to optimize the throughput performance of wireless mesh networks (WMNs) step by step. The process starts with the network representation, which models the network topology, node positions, and connectivity. Then, a semi-chaotic initial population representing many possible configurations or routing paths in the mesh network is created.

The client-fairness-aware optimization function is the most important part. It balances throughput among users and evaluates each client's solution individually. This ensures that the optimization not only maximizes total throughput but also balances fairness among clients. After that, the process checks the convergence conditions to determine whether the optimal solution has been achieved or whether additional iterations are still needed.

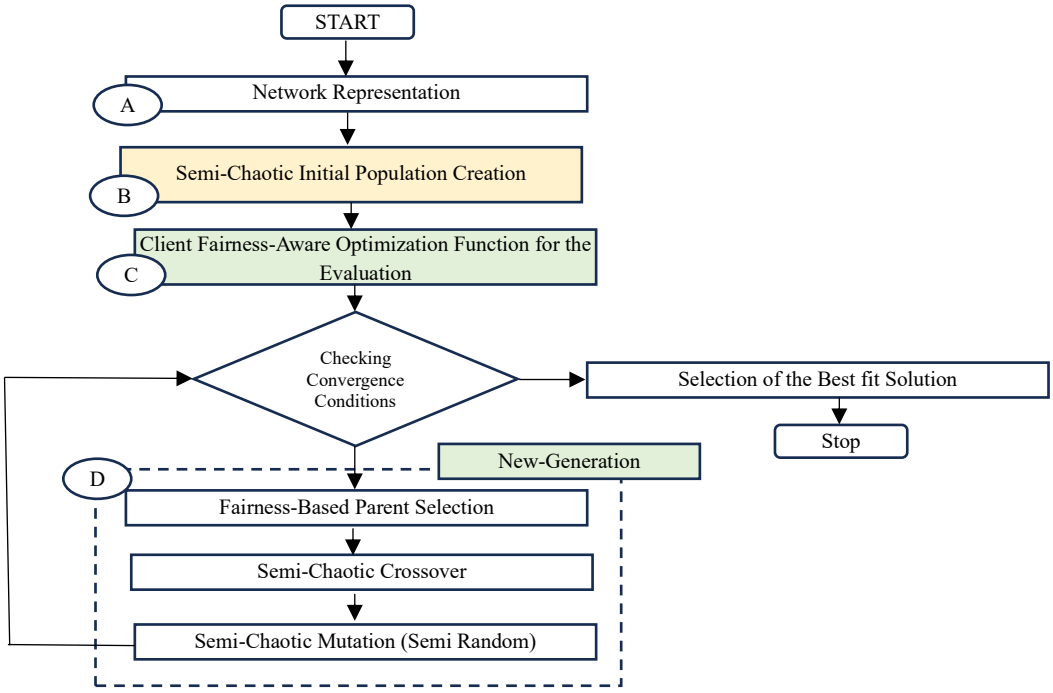

Figure 2: Optimization flowchart for throughput enhancement in wireless mesh networks

If convergence is not achieved, the algorithm enters a loop comprising fairness-based parent selection, semi-chaotic crossover, and semi-chaotic mutation. These genetic operators act as the natural selection and evolution of the previous better solutions in all iterations. Once the goals of convergence have been achieved, the best-fit optimized configuration in improved throughput is selected.

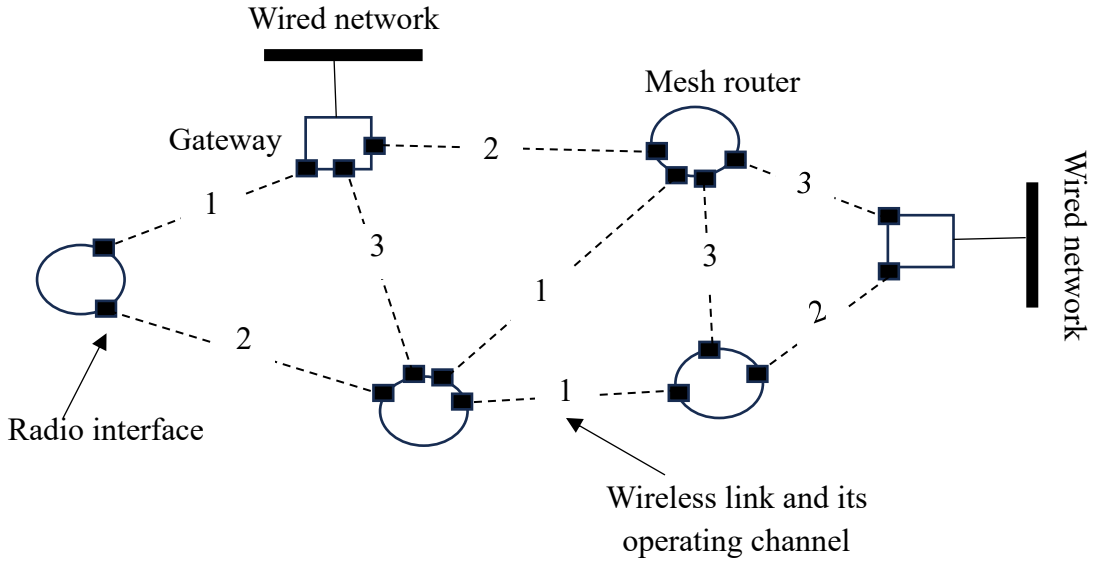

Figure 3: Topology of a wireless mesh network

As shown in Figure 3, a wireless mesh network consists of interconnected components: mesh routers, gateways, and radio interfaces. Each node can have multiple connections to its neighbors via wireless links on different channels. These channels are marked with numbers (1, 2, 3). A multi-hop communication network is created by interconnecting mesh routers, which allows a packet of data to be

sent through several intermediate nodes. The diagram also contains segments of a wired network, which are links to the outside world or backbone networks. Gateways are essential for connecting the mesh network to the rest of the world, as they integrate it with the wired world. Parallel communications across different channels in each radio interface of nodes enable interference minimization and thereby increase throughput.

Experimental Setup

The experimental design of this research project entails assessing three network types: Wireless Mesh Networks (WMN), Cellular Networks, and a Hybrid Model that combines the two. The simulations will be carried out using the NS-3 simulator to reflect the reality of network conditions and performance. The scenarios will cover urban, suburban, and rural settings with different node densities (low, medium, high) and user movement patterns (static and mobile). Various traffic types will be put in test such as video streaming, IoT information, and gaming to determine their influence on throughput. The node positioning will be grid-based, and routing schemes will include AODV and OLSR in WMN, and proportional fairness and round-robin in cellular scheduling. Hybrid modes will be considered, and both mesh backhaul and cellular scheduling will be used. The mobility patterns will consist of random and predetermined models to simulate realistic user movement, and traffic load and variability will be adjusted based on node density and user behavior. This network is designed to fully assess the throughputs, reliability, and efficiency of such networks that may occur in various environments.

Evaluation Metrics

Average Throughput:

$$\text{Average Throughput} = \frac{\text{Total Data Delivered}}{\text{Total Simulation Time}} \tag{3}$$

Packet Delivery Ratio (PDR):

$$\text{PDR} = \left(\frac{\text{Packets Received}}{\text{Packets Sent}}\right) \times 100 \tag{4}$$

Network Efficiency:

$$\text{Network Efficiency} = \left(\frac{\text{Actual Throughput}}{\text{Maximum Throughput}}\right) \times 100 \tag{5}$$

Fairness Index:

$$\text{Fairness Index} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{T_i}{\grave{T}}\right) \tag{6}$$

where $T_i$is the throughput of node $i$and $\grave{T}$is the average throughput.

4 Results and Discussion

As explained in the earlier sections of this chapter, a simulation study was conducted to demonstrate the effectiveness of the proposed comparative throughput methodology using NS-3. Mobile and fixed node

arrangements in urban and suburban settings were evaluated, along with many other scenarios. The averaged throughput of both Wireless Mesh Networks (WMNs) and Cellular Networks was calculated based on parameters such as node density, user mobility, and traffic load.

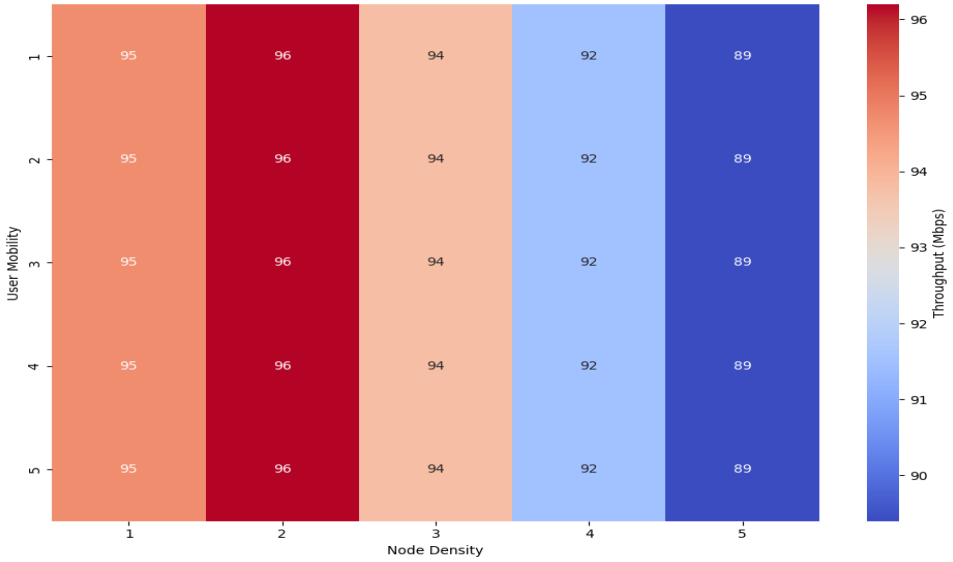

Figure 4: Throughput performance based on node density and user mobility

Figure 4 shows how node concentration is related to throughput (in Mbps) across the mobility area. There is higher throughput (indicated by the dark red/orange regions) obtained from higher node densities and lower area mobility. Conversely, there are areas of lower throughput (in the blue regions) that are associated with higher mobility and lower node density.

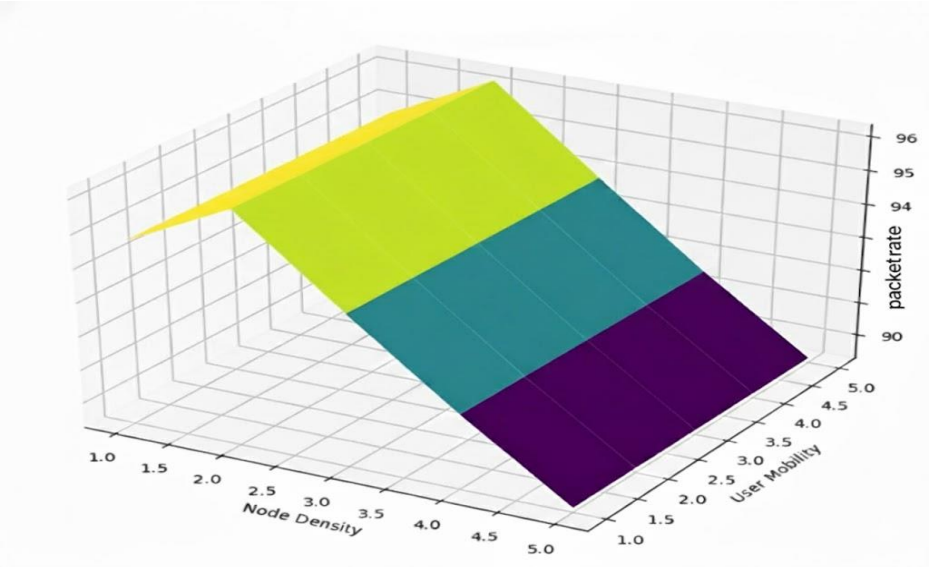

Figure 5: Throughput variations with node density and user mobility

The throughput is impacted by varying node density and user mobility, as shown in Figure 5. The node density and user mobility are inversely related: the higher the user mobility, the lower the node density, and vice versa. As shown in the graph, node density and mobility are throughput-constraining and interrelated.

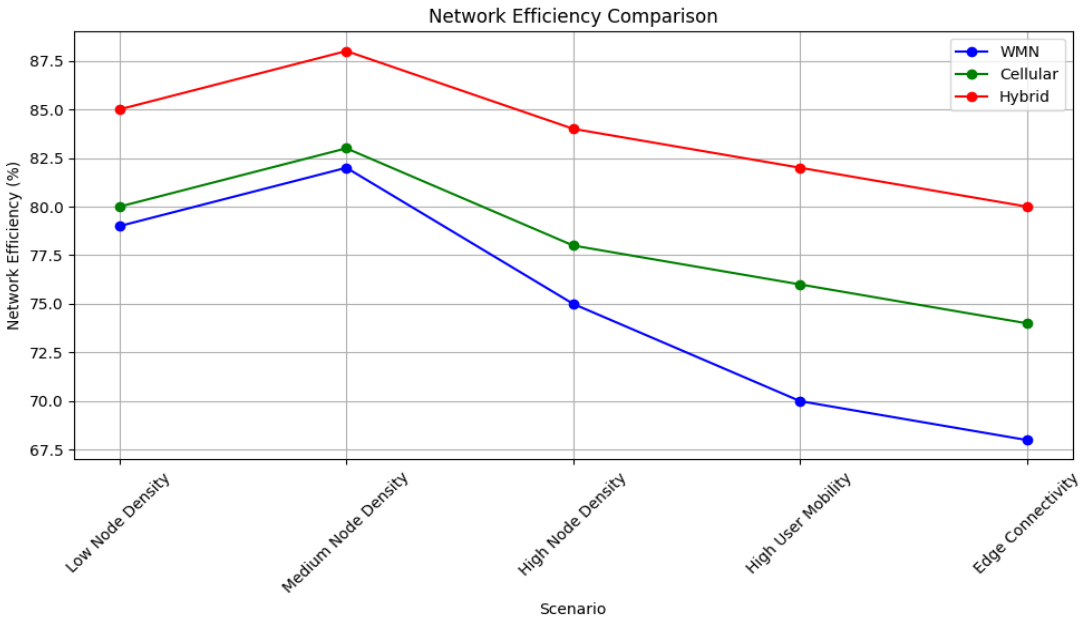

Figure 6: Comparison of network efficiency across different network types

Figure 6 compares the operational efficacies of Wireless Mesh Networks (WMN), Cellular Networks, and Hybrid Networks. It is evident that, at low and medium node densities, Hybrid Networks outperform WMN and Cellular Networks. As node density increases, Hybrid Networks continue to show optimal performance compared to other network types.

As evidenced in WMNs, increasing the number of nodes to a certain limit enhances average throughput due to increased path diversity. Beyond this node limit, performance begins to suffer due to interference and the overhead of maintaining active routes. In comparison, cellular networks exhibited less variable throughput across different user densities due to centralized scheduling and frequency reuse, although performance degraded under high-load or edge-cell conditions. Hybrid mesh-cellular network systems provided the most promise, combining the flexible coverage of the mesh with the cellular structure. Throughput balance among users, particularly those with uneven demand, was ensured through fairness-aware optimization. These observations support the notion that, while under normal conditions cellular networks are more efficient, WMNs are more robust in infrastructure-limited or failure-prone regions.

$$\eta = \frac{T_{actual}}{T_{max}} \times 100 \qquad (7)$$

Where:

- η = Network efficiency (in percentage)
- T_{actual} = Actual achieved throughput (in Mbps)
- T_{max}= Theoretical maximum throughput possible under ideal conditions (in Mbps)

Besides measuring average process data rates, every scenario was analyzed based on throughput to the actual achievable throughput for that particular scenario and what it could achieve in perfect conditions. This metric efficiency in percentage shows how effective each network type is in relation to its bandwidth and infrastructure. For example, Wireless Mesh Networks tend to show reduced efficiency in high-density environments because of interference and the overhead of route maintenance. On the

other hand, Cellular Networks provide moderate efficiency because of optimized scheduling, though performance is still reduced because of edge users or congestion. The hybrid configuration, which uses both cellular access and mesh backhauls, showed the most efficient performance in all cases which suggests that strategic combination of components within a network infrastructure can greatly improve the entire network's efficiency.

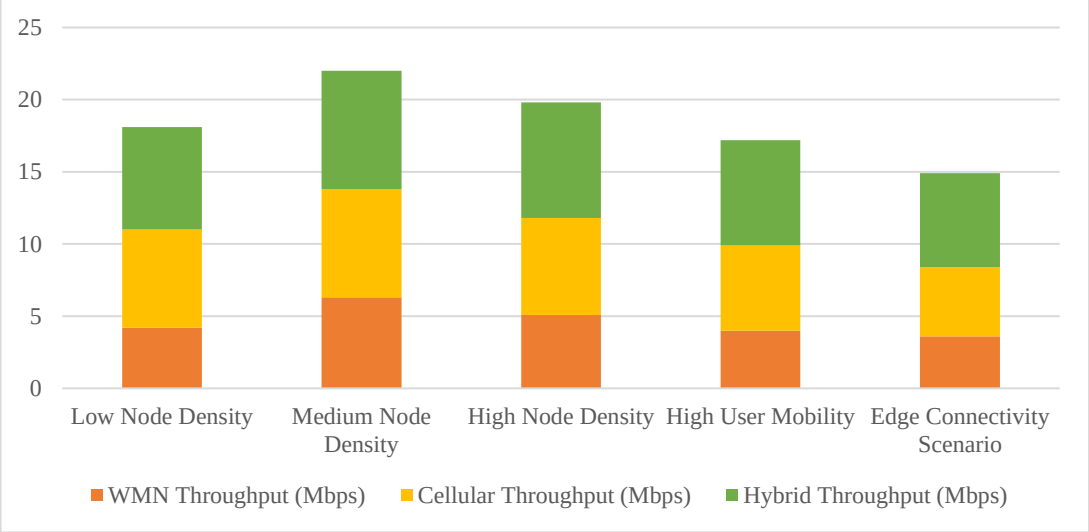

Figure 7: Average throughput in WMN vs. cellular vs. hybrid networks

Figure 7 gives a graphical comparison of the network efficiency (%) of Wireless Mesh Networks (WMNs), Cellular Networks, and Hybrid Networks for each of the five deployment scenarios. The sets of three bars are associated with a scenario which are Low Node Density, Medium Node Density, High Node Density, High User Mobility, and Edge Connectivity.

As mentioned, where in every scenario of hybrid networks retain a decisive edge over cellular networks and WMNs, over 79% of efficiency is achieved uniformly due to the versatile infrastructure of the hybrid networks with adaptive routing. In all scenarios, performance of hybrid networks was at the highest point. Cellular networks were positioned at the second-best in the least dynamic or slightly dynamic situations with the number of the performance between 68% and more than 80. Interference and dynamic topology changes evidently reduced the performance of WMNs with increase of node density, increase of user mobility and edge distance.

This graphical examination would support the claim that hybrid networks have a more balanced and sturdy answer and also still has the benefits of mesh-based redundancy as well as the dependability of a cellular backbone. The chart picturatively and instinctively gives the scaled and adapted network structures as per the requirements of urban environments.

Table 1: Packet delivery ratio (%) across network types

Scenario	WMN PDR (%)	Cellular PDR (%)	Hybrid PDR (%)
Low Node Density	82.5	91.3	94.7
Medium Node Density	85.4	93.5	96.2
High Node Density	76.3	89.2	93.8
High User Mobility	70.1	86.8	91.5
Edge Connectivity Scenario	67.8	84.0	89.4

Table 1 presents the ratio of Packet Delivery of various network scenarios. All the three architectures are characterized by high PDR with low or medium node densities, and the hybrid networks achieve the highest performance due to dual connectivity and path optimization. At high node density and mobility, WMN (Wireless Mesh Networks) have reduced PDR since the route instability and interference increase. Although cellular networks are more stable, they are prone to a decreased PDR at the margins of the cell or when there is high movement of users. The hybrid model provides the optimal PDR that is flexible to both non- dynamic and dynamic configurations. This shows that it is capable of ensuring a solid communication even under harsh circumstances.

5 Conclusion

This research work has given a comprehensive analysis of throughput performance with Wireless Mesh Networks (WMNs), Cellular Networks, and Hybrid Networks setups under various deployment environments. This study has discussed the mean throughput, the efficiency of the network and the ratio of packets received in a given time over user density, of the two types of networks, under statical and dynamic user mobility, to establish the main strengths and weaknesses of operations of the two types of networks. These are the findings that express the merits and demerits that various types of networks bring. As an example, Cellular Networks have stability and consistency due to the central control and efficient frequency reuse, although the efficiency reduces at the cell edges or in situations of heavy load. WMNs have less dense infrastructure locations or in case of failures that may happen, less interfered, but suffer stability in dense, high mobility situations. The developed Hybrid Network architecture is a combination of great features of both architectures, which makes it achieve the best throughput, efficiency, and reliability in nearly all the tested conditions. This study is significant in its practical concerns with designing next-generation communications systems for densely populated areas with frequently changing demands and limited space. With this knowledge, network planners can adopt semi-automated hybrid architectures that react to changes in traffic volume, user movement, and structural topology. In addition, this research forms a basis for more advanced intelligent algorithms for switching, load balancing, or context-aware routing in hybrid wireless networks. To conclude, there is great potential in combining mesh and cellular components of a network to improve on some of the shortcomings associated with each type of network. This research highlights the problem of fractured wireless communication systems that rely on fixed infrastructure, and emphasizes the need for flexible, self-organizing networks.

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