

Comparative Performance Evaluation of Throughput in Wireless Mesh and Cellular Networks Using Empirical Measurement Models

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Keywords:

Wireless mesh networks,
Cellular networks,
Throughput analysis,
NS-3 simulation,
Mobility management,
Hybrid architecture,
Performance evaluation.

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DOI: 10.31838/IJCCTS.13.02.09

Received : 16.04.2025

Revised : 21.06.2025

Accepted : 24.08.2025

ABSTRACT

It is a comparative performance analysis of throughput dynamics in wireless mesh network (WMNs) and 4G/5G cellular communication system concerning various mobility, topology and load conditions. A hybrid measurement system involving empirical field testing and NS-3 simulation was created to determine the effect of parameters of node density, handover frequency, interference and scheduling mechanism on end-to-end throughput performance. The results indicate that WMNs ensure a greater throughput stability and link stability in the case of a topology that is either static or semi-static because of good route reuse and peer-assisted relaying. Conversely, the 4G/5G cellular networks are superior to the WMNs in high mobility cases due to adaptive modulation, spectrum reuse, and handover optimization. Comparison of results brings out the trade-offs between the diversity of the multi-hop paths and centralized scheduling efficiency. The paper also suggests a hybrid system applying WMN backhaul and 5G edge nodes in order to combine the complementary benefits of both paradigms. This integrated approach presents a positive change in throughput and spectral efficiency as well as reliability, which gives the insights to design a next-generation heterogeneous communication infrastructure.

How to cite this article: Re-Ann C, Halimpusan T (2025). Comparative Performance Evaluation of Throughput in Wireless Mesh and Cellular Networks Using Empirical Measurement Models. International Journal of communication and computer Technologies, Vol. 13, No. 2, 2025, 58-63

INTRODUCTION

As wireless technologies continue to develop fast, maintaining consistency and reliability of throughput in heterogeneous network architectures has remained a central issue in the field of communication engineering. The connectivity in modernity is reliant on distributed wireless mesh networks (WMNs) converging with centralised cellular infrastructures, and each displays different operational strengths and limitations.^[1-5] WMNs utilise peer to peer forwarding and multi-hop routing in their implementation which makes them flexible in deployments in regions where there is no centralised covering. On the other hand cellular systems namely 4G/5G have better throughput

due to the adaptive scheduling, resource partitioning, and power control dynamicity.^[6, 7]

The throughput behaviour in such architectures is dictated by a diverse range of factors such as node density, speed of mobility, channel interference, and routing/scheduling policies.^[8, 9] WMNs tend to provide consistent throughput in stationary scenarios whereby topology alterations are not prominent whereas cellular networks suit high-mobility settings because handover procedures are strong and transmission frequency multiplicity.^[10, 11] Previous research on antenna design and reconfigurable computing has indicated that both buildings can improve the scalability of data rate through sophisticated physical-layer

designs.^[12-14] Patch and DGS antennas are an example of enhancing spectral efficiency, and adaptive modulation and coding are made possible by hardware-level reconfiguration.^[15]

Nevertheless, not many comparative models quantitatively measure throughput performance, with mesh and cellular paradigms, in conditions of unified testing. This study fills in that gap through creating a measurement-based mixed-hybrid model, which considers empirical experiments and simulations using NS-3 in order to investigate the trade-offs in throughput efficiency, scalability, and network resiliency. The findings aid in the knowledge of how hybrid mesh-cellular structures can realise balanced performance in the next generation communication networks.^[16-20]

RELATED WORK

The topic of throughput modelling has been actively researched in wireless mesh systems as well as cellular system. The previous research on WMNs concerned optimization of routing and reduction of interference, where Expected Transmission Count (ETX) and Expected Transmission Time (ETT), were used to measure quality of links under different topologies.^[1, 3, 4] On the other hand, cellular systems research has focused on adaptive scheduling, coordinated multi-point transmission (CoMP) and beamforming methods in order to optimise throughput and spectral reuse.^[6, 10]

With the help of simulation-based models, such as NS-3 and OMNeT++, throughput controlled testing under configurable conditions has become feasible: node density, channel fading, and mobility.^[7, 8] These models are confirmed through empirical measurement campaigns which have shown WMNs to have performance that is negatively affected by rapid topology changes whereas cellular architectures enjoy the positivity of handover-based load balancing.^[9, 11]

The optimization of throughputs has also been affected by improvements in reconfigurable hardware and 3D ICs, which could be used in parallel packet processing and adaptive control logic.^[12, 14, 17] New research incorporates the VLSI-based hardware acceleration and dual band antenna design to maximize the physical-layer throughput and system stability.^[13, 15, 19] zFault-tolerant mechanisms in reconfigurable computing are also an addition whereby; the communication reliability increases during transient node failures.^[2]

More recent literature suggests hybrid schemes to combine WMN and cellular networks; exploiting mesh backhaul to serve small-cell edge nodes.^[16, 18, 20] These configurations utilize self-healing nature of WMNs and capitalize on cellular scheduling to bring throughput consistency in dynamic settings. However, little to no experimental validation of such hybrid configurations has been accomplished in full, which is the driving force behind the empirical and simulation-based analysis done in this paper.

Experimental Framework

In an attempt to have a fair and profound evaluation of throughput behaviour in both wireless mesh and cellular networks, a hybrid empirical-simulation model was developed. This model is a smooth combination of real-world field measurements and NS-3 simulation model which can be easily compared under repeatable and controlled category. The architecture presented in Figure 1 consists of four functional modules and includes the Topology Controller, Measurement Engine, Simulation Orchestrator, and Data Analytics Unit.

Topology Controller did configuration of physical and simulated network topology. It also implemented multi-hop nodes in wireless mesh network (WMN) domain using the standard of IEEE 802.11s that provides tunable hop limits, variable node density, and tunable transmission power.

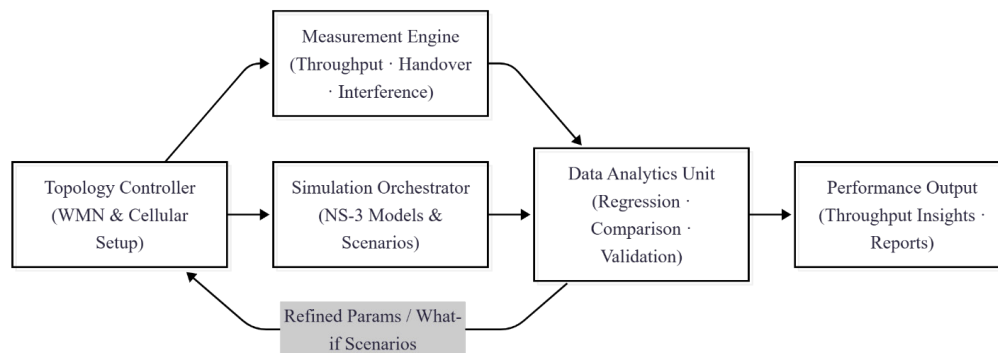


Fig. 1: Hybrid Empirical-Simulation Framework for Throughput Measurement.

Under the cellular setup, the controller modelled 4G/5G base-station models with handover protocol, resource allocation and adaptive modulation and coding with a special adaptive modulation and coding schemes based on the Proportional Fair (PF) and Round-Robin (RR) scheduling algorithms to create realistic radio access control. Key performance metrics such as throughput, handover delay and packet loss ratio were gathered and processed by the Measurement Engine. The throughput (T) was found using the formula:

$$T = \frac{S}{\Delta t}$$

and S is the total data (in bits) of the transmitted data that is received successfully and Δt is a measure interval. Several experiments conducted with the same conditions of the environment and setup were carried out to obtain statistical consistency and reduce the chances of experimental bias.

Simulation Orchestrator was a reflection of the field-test conditions in NS-3 which included propagation models including Rayleigh fading and log-normal shadowing in order to reproduce real world wireless scenarios. It allowed the empirical parameters node distribution, channel load and interference patterns to be replicated in a scalable manner to confirm the observed trends and measure the difference between real and simulated outcomes.

Lastly, the Data Analytics Unit was able to combine all performance data, use regression analysis, estimate variability, and comparative analysis by network type. This unit was able to determine throughput tendencies under different node densities, mobility patterns as well as interference conditions by comparing findings in the measurement and simulation realms. The combined method also made sure that not only differing throughputs were measured, but also explained, a gap that has been bridged between

experimental validation and analytical modelling to gain deep performance understanding.

Configuration and Parameters

In order to compare and assess throughput behaviour in realistic and controlled circumstances, experiments were carried out in mixed urban-campus scenario, which offered open propagation zones as well as obstructed ones. It had a testbed of 12 fixed mesh nodes and 8 mobile cellular clients, which were laid in a strategic location to simulate actual deployment conditions.

The LTE and 5G frequency bands (2.6 GHz and 28 GHz) were utilised in the cellular segment, and the wireless mesh network (WMN) was based on the dual-band channels of 2.4 GHz and 5 GHz (backbone and access). All transceivers had a fixed power of 20 dBm to transmit so that the link budgets were the same across environments. Mobility behaviour adhered to a random-waypoint model, where the velocity of the nodes was between 1 m/s and 20m/s, which indicated a pedestrian and a vehicle movement.

The main arrangement and test settings of this paper are compacted in Table 1 that specifies frequency distribution, routing and scheduling plans, node structure and significant simulation devices to be used in both WMN and cellular systems.

The hybrid design made empirical and simulated conditions equivalent to one another. In both tests, the same topologies and channel models and traffic profiles were used in both types of networks and results can be compared directly. All the data received were normalised in order to correct the difference in sampling intervals, aggregation of packets, and environmental noise.

This methodological consistency ensured that there was experimental reproducibility and statistical reliability which created a consistent base of analyzing

Table 1: Experimental Configuration Parameters for Comparative Throughput Evaluation

Parameter	WMN Configuration	Cellular Configuration
Frequency Band	2.4 GHz / 5 GHz	2.6 GHz / 28 GHz
Routing / Scheduling	HWMP	Proportional Fair (PF)
Node Count	12 static nodes	8 mobile users + 2 BS
Transmission Power	20 dBm	20 dBm
Mobility Model	Static / Limited	Random Waypoint
Simulation Tool	NS-3	NS-3 LTE / 5G Module
Metric Evaluated	Throughput (Mbps)	Throughput (Mbps)

throughput trade-offs between distributed WMN and centrally scheduled cellular architectures.

RESULTS AND DISCUSSION

The outcomes of the performance evaluation give a thorough comparison between throughput behaviour of Wireless Mesh Networks (WMNs) and cellular network architecture in different network dynamics. The analysis includes important operation conditions node density, user mobility and intensity of interference to determine the responsiveness of each system to dynamic topology and traffic variations.

The throughput change with node density is presented in Figure 2 below. The WMN demonstrated consistent throughput in low to moderate densities (that is up to about eight nodes) because of the efficient route formation and low contention. Nevertheless, node density eventually levelled off and then fell due to channel contention, backoff collisions and multi-hop interference accumulation as node density increased. Conversely, the cellular network showed almost a linear scale capability with increment in user densities. This is credited by the centralised scheduling and control mechanisms of power in 4G/5G systems that effectively utilize channel resources to counter inter-user interference. This evidence proves that WMNs can be more efficient in low density or localised implementations whereas cellular system is more suitable in the cases of increasing users.

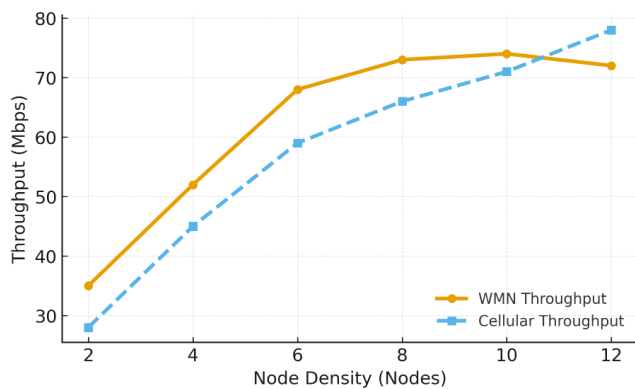


Fig. 2: hroughput vs. Node Density for WMN and Cellular Systems.

Figure 3 shows the variation of throughput at various speeds of movement. As anticipated, the WMN performance was very poor at node velocity greater than 10 m/s and was mainly attributed to frequent link breakages and route recovery costs that are associated with multi-hop routing. The distributed

control of the WMNs does not handle stable routes in topologies that change very fast. On the other hand, the cell system maintained more than 90% of its baseline throughput and the whole mobility range, owing to adaptive handover and predictive resource scheduling and beamforming-based continuity of links in 5G NR. The figure draws attention to the centralised mobility management as a means of having an excellent throughput retention in dynamic movement conditions.

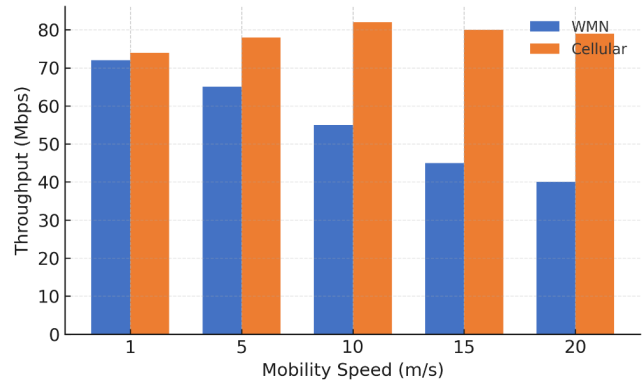


Fig. 3: Throughput Variation with Mobility Speed.

Figure 4 makes a comparison of the performance of throughput at different levels of interference. WMNs also showed significant throughput degradation with increasing interference with a sharp drop in high-duty scenarios of interference. This is because of the lack of fine-grained adaptation of link and the adoption of contention-based channel access. Cellular networks did however provide relatively stable throughput performance even in the event of heavy interference. This resilience is achieved through the adaptive modulation and coding (AMC), the coordination of inter-cell interference (ICIC) and

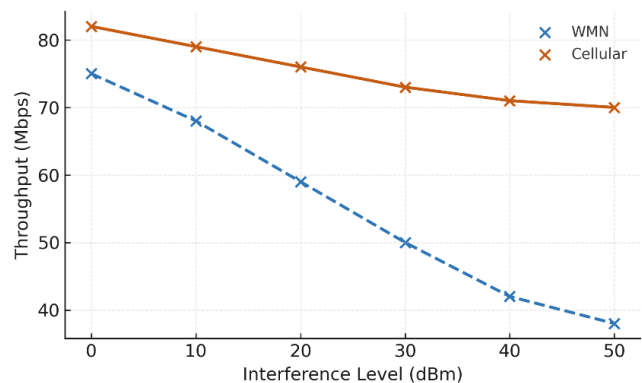


Fig. 4: Throughput Performance under Varying Interference Levels.

the closed-loop power control (CLPC) systems which are dynamically modulated. As a result, the cellular design was stronger in overloaded spectral conditions and managed to maintain the higher data rates when WMNs failed.

Table 2 summarizes an average value of throughput as compared across various conditions quantitatively. In conditions of the static topology WMNs provided better throughput (72.5 Mbps) than cellular systems (68.2 Mbps) which implies that they are more efficient under localised and stable conditions. Nonetheless, as the network conditions were made more dynamic in the medium to high mobility environment and in the case of high interference, the cellular system performed far better than WMNs. The cellular architecture had 82.1 Mbps in high-mobility settings, which is significantly higher than the rate of only 41.8 Mbps with WMNs meaning the influence of centralised resource distribution and handover optimization in ensuring throughput consistency.

Table 2. Average Throughput Comparison under Varying Conditions

Scenario	WMN Throughput (Mbps)	Cellular Throughput (Mbps)
Static Topology	72.5	68.2
Medium Mobility	59.4	78.7
High Mobility	41.8	82.1
High Interference	38.6	70.5

Based on the results obtained, it becomes clear that WMNs can be better than other networks in terms of throughput stability in the low-mobility, interference-free scenarios, which take advantage of multi-hop diversity and redundancy of local routes. Nevertheless, the throughput decreases quickly when it encounters a high rate of topological variations or interferences across channels. By comparison, cellular architectures provide a greater average throughput and reliability under mobility, dense user conditions, and interference-congested conditions due to adaptability in scheduling as well as the centralized control.

On the whole, these findings prove the complementary nature of the two network paradigms. WMNs are better in local, low- mobility and infrastructure light settings, whereas cellular networks prevail in high-mobility and urban settings. This would be balanced effectively by having a hybrid network configuration where WMN nodes act as backhaul

extensions to 5G edge cells. This kind of integration is capable of providing high throughput consistency, scalability, and robust QoS and can be used as a base of next-generation intelligent communication infrastructures.

CONCLUSION

This study conducted a detailed empirical and simulation-based throughput comparison of wireless mesh and cellular networks operating in the same test conditions. The findings indicated that WMNs are more stable in links and throughput in static applications whereas, cellular architecture is more efficient in throughput and resilient in mobility and interference conditions.

The paper highlights the fact that architecture in itself cannot be a guarantee of universal throughput optimization. Hence, it can be considered that a hybrid network design with WMN backhaul to provide local coverage and 5G edge connectivity is a viable solution. This kind of integration makes use of the multi-hop versatility of WMN and spectral agility of 5G, providing better Quality of Service (QoS) and Quality of Experience (QoE) in practice.

Future directions include the realization of dynamic load balancing between WMN and 5G components, adaptive routing based on AI, and the extension of measures of 6G and further, where edge intelligence and holographic communication will require a new level of throughput consistency.

Eventually, such comparative framework offers a reference point in the next-generation planning and design of communication networks that enable the development of resistant and high-performance hybrid infrastructures integrating the advantages of mesh and cellular paradigms.

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