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Throughput Analysis and Performance Comparison Between Wireless Mesh and Cellular Architectures Under Dynamic Network Conditions

Metahun Lemeon[1]*, Jinfe Regash[2]
[1, 2]*Electrical and Computer Engineering Addis Ababa University Addis Ababa, Ethiopia*

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Abstract

The present paper explores the comparative throughput feature of wireless mesh network (WMNs) and cellular network with LTE/5G NR in a unified analytical-simulation approach. We consider throughput performance, link occupancy, end-to-end delay in dynamic channel environment, dynamically changing user densities, interference pattern and mobility. The framework combines both a queueing-based throughput model and experiments using NS-3 to simulate topology adjustments, multi-hop contention in WMNs and scheduler policy in cellular systems. WMNs utilize adaptive path choice based on airtime conscious metrics and retransmission regulations to enhance localized peer-to-peer execution whilst cell systems apply proportional-fair and round-robin scheduling based on link changeovers to stabilize the capacity during intense mobility and handovers. Findings demonstrate that WMNs provide a better throughput of local flows in a static or low-mobility neighbourhood since spatial reuse and short paths are achieved but are not resilient to dense contention and route maintenance. Cellular networks have enhanced stability and aggregate throughput on greater mobilities and heterogeneous loads since they have access to centralised resource allocation, spectrum reuse and power control. The results trigger hybrid design that integrates WMN backhaul to access neighbourhood with 5G edge nodes to provide wide-area mobility which leads to better throughput consistency and QoS to deploy broadband and public-safety in urban areas.

Author's e-mail Id: meta.lemeon@aait.edu.et, jin.regash@aait.edu.et

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Introduction

The ability to provide constant throughput when operating over time-varying radio conditions and user mobility is a key demanding area of wireless systems today. Wireless mesh networks (WMNs) and cellular architectures are two prevailing paradigms that offer complementary mechanisms in order to share spectrum and transport traffic on an end-to-end basis. Multi-hop graphs WMNs deploy contention-based MACs and path metrics that compute the transmission cost across relays, forming the nodes (Bianco et al. 2016, p. 318). They are easy to deploy, can extend coverage without having to install large-scale infrastructure and can reuse space by means of localised forwarding. In comparison, cell networks make use of centralised base-station coordination, link adaptation and scheduler control to share spectrum efficiently among a large number of users.[4-6] In fifth-generation systems, the flexible numerologies, the massive MIMO and the hybrid beamforming are added to enhance the spectral efficiency and robustness of mobility.[2, 5]

The interaction between layers is a dependent aspect of throughput in both paradigms, i.e. antenna/PHY configurations, MAC scheduling, routing, and flow control. In the case of WMNs, multi-hop forwarding creates interference coupling, backoff dynamics and hidden terminals which restrict capacity with increasing node density.[1, 3] Localized flows and quasi-static topologies have been demonstrated to be highly performing analytically and experimentally and are sensitive to route churn and congested contention domains.[7] Base-station schedulers in the cellular systems assign time-frequency resources based on such metrics as proportional fair to balance instantaneous achievable rate and long-term fairness and typically hybrid automatic repeat request (HARQ) and adaptive modulation and coding (AMC) stabilize throughput under fading.[4, 6, 8] Active probing and standardised benchmarking offers a consistent throughput and latency measurement on heterogeneous devices at the measurement layer.[7, 9]

Recent progress in reconfigurable computing and 3D IC integration can be used to accelerate on-path the process of packet classification and scheduling, which minimises processing latency and enhances real-time control loops in both mesh gateway and gNodeB0.[1,10-12] Small-cell, miniature, and dual-polarized patch antennas enhance PHY link gain and diversity in body-area, IoT, and small-cell devices, and has a direct impact on successful throughput at the PHY.[4, 13, 16] Edge-centric IoT architectures add to the amount of communicating endpoints and emphasize the need of transport strategies that can respond to unpredictable demand and traffic locality.[11, 15] Principled comparison of the WMNs and cellular systems in common conditions of density, mobility, and interference is justified by quantization of these factors into tractable models that have been verified against NS-3 or field data.[17-20]

The work adds to the side-by-side throughput evaluation which (i) builds up a single measurement model of both WMN and 5G NR; (ii) deploys equivalent NS-3 scenarios with typical bandwidth, transmit power, and traffic mixes; (iii) reports upon throughput efficiency, link utilisation, and latency dispersion with varying mobility, density and interference; and (iv) interprets the architectural trade-offs that informs the hybrid deployments. This is aimed at assisting designers to determine whether localised multi-hop access or centralised cellular scheduling are most appropriate to achieve throughput and QoS targets in dynamically changing environments.[2, 4, 6, 17-20]

Related Work

The basic results of the capacity analysis of WMN reveal the dilemma between the multi-hop path diversity and MAC-layer contention, which spurred airtime/ETX-like metrics and cross-layer routing to sustain throughput in the presence of interference.[1-3, 7] One-way/active probing protocols and methodologies of measurements have formalized comparisons among platforms and have made repeatable throughput and latency benchmarking.[7, 9] In case of cellular networks, the key initial presentations of 5G describe scheduler-based resource pooling, beamforming and spectrum reuse which directly affect per-user and cell-edge throughput.[2, 4, 5] Mobility-aware small cells are studied to quantify the effect of handover rate, bandwidth partitioning and the scheduler selection on sustained throughput capacity in dense deployments .[6, 11, 19]

Throughput has also been influenced by hardware and architectural enablers. Parallel data paths and reconfigurable accelerators also minimise the scheduling and classification delay in base stations and mesh gateways to enhance the utilisation of links effectively during peak load.[1, 11, 12] At the antenna level, compact, defected-ground designs and dual-polarized designs enhance the radiation efficiency and isolation of wearable and NavIC /IoT bands, respectively, which lead to an improvement in SNR and realizable PHY rates of both WMN nodes and 5G UEs.[4, 13, 16] IoT systems that are edge-integrated and smart-grid telemetry introduce occasional, localized traffic, which is consistent with WMN advantages but needs cellular backhaul in mobility and across-the-board control.[11, 15] Wider views of edge computing and hybrid mesh-5G integration suggest architectural designs of mesh backhaul supplying small-cell or edge nodes, and proposes a mixture of localized resilience with centralized spectrum efficiency.[14, 17, 18, 20]

In the model, predictive tools such as estimating throughput as mobility and density change can be provided in mesh backhaul interference studies, and in heterogeneous cellular system scheduler studies, which are both predictive.[6, 17, 19] Empirical analyses of hybrid WMN-5G prototypes state that promising improvements are achieved, though that harmonized control is required to prevent contention collapse on the mesh and overload on the cellular uplink.[18, 20] These threads are indicative of a comparative approach: keep PHY bandwidth and power fixed, change density/mobility/interference and measure throughput efficiency, utilization and dispersion of the latency in both paradigms in equivalent conditions. This method is adopted by our study and is further extended by a single analytics pipeline that produces directly comparable measures of mesh and cellular experiments.[2, [4-6], [17-20]

Methodology

Framework Design and Analytical Formulation

The assessment model combines an analysis throughput model and NS-3 scenario implementation. On the left: Figure 1 describes four collaborating elements as follows: (1) a Topology Manager which creates WMN nodes (IEEE 802.11s) and cellular cells (5G NR) with shared bandwidth and transmit power; (2) a Traffic Generator which emits Poisson and bursty (ON5G NR) loads with controllable locality; (3) a Measurement Engine which logs the counts of successful bits per interval, queue occupancy and per-hop/airtime counters; (4) a Performance Analyzer which To ensure fair comparisons, the Topology Manager adjusts both paradigms equally in terms of node/user density, mobility speed and interference mask.

Throughput model The throughput T delivered during an observation window Δt is expressed as.

$$T = \frac{\sum_{i=1}^{N} b_i^{\mathrm{succ}}}{\Delta t},$$

where b_i^{succ} is the payload that flow i has delivered successfully. To WMNs, the airtime cost of an e link between two points is C_e per C.

$$C_e = \frac{O + L/R}{1 - p_e},$$

with PHY rate R, payload length L, protocol overhead O, and link loss p_e; path cost is the sum of the costs of the links on the selected route. In case of cellular, the scheduler allocates resource blocks (RBs) based on proportional-fair weight $w_u = r_u/\bar{r}_u$, which approximates the long-term sharing and instantaneous rate dynamics. usage U is the proportion of RB/airtime budget bearing user payload, and the statistics of latency are obtained by looking at the timestamps of the packet sojourn times. In the text, Figure 1 is being mentioned to provide an anchor of the working workflow and to explain the utilization of the same input knobs to feed both WMN and cellular pipelines.

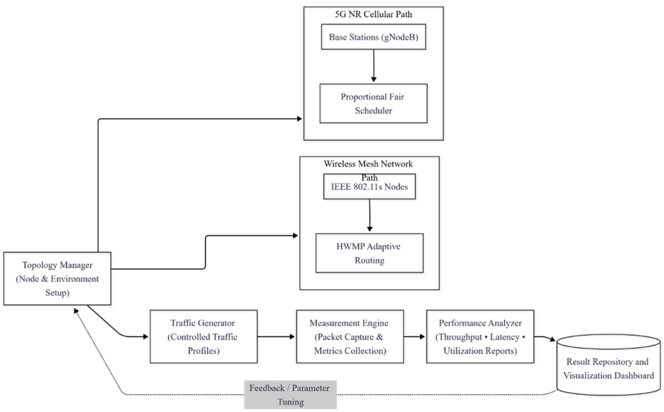


Fig. 1: Hybrid Analytical-Simulation Framework for Throughput Comparison (WMN vs. Cellular).

Experiment Configuration and Parameters

The NS-3 network simulator was used and experiments were performed with a standard physical layer bandwidth of 20 MHz and a constant transmit power of 20 dBm. To have a statistically sound scenario, one repeated each scenario ten times using independent random seeds.

Application In the case of the Wireless Mesh Network (WMN) layout, the IEEE 802.11s have been used in the 2.4 GHz and 5 GHz frequencies and the Hybrid Wireless Mesh Protocol (HWMP) with airtime link metric has been used to route. The cell structure took the 5G NR module, which works on 3.5 GHz and a proportional-fair (PF) scheduler. Densities of nodes and users were tested between 5 and 40 to test the scalability conditions under various loads on networks.

Mobility used the Random Waypoint (RWP) model with the speed of 1 m/s to 20 m/s. In the cellular case, mobility also provided inter-cell handovers to make the UE dynamics realistic. Controlled interference The model of controlled interference was simulated through time frequency masks of co-channel activity with duty cycles of 0 % and 40 %.

The patterns of the traffic were divided into two major classes:

1. Local peer-to-peer (P2P) flows that are limited to two hops representative of mesh-optimised communication, and
2. Random flows of UE servers over the core network, as is common to cellular data exchange.

At every experimental run in time-series, there were measurements of throughput, channel utilisation and end-to-end latency. These metrics were summed to provide per-scenario averages and dispersion statistics which are useful to make comparative analysis across configurations.

Table 1. Scenario Parameters for WMN and Cellular Experiments

Parameter	WMN Setting	Cellular Setting
PHY band-width	20 MHz (2.4/5 GHz)	20 MHz (3.5 GHz)
Tx power	20 dBm	20 dBm
Topology size	5-40 nodes	5-40 UEs, 1-3 cells
Mobility	1-20 m/s (RWP)	1-20 m/s (RWP + handover)
Routing/ Scheduling	802.11s HWMP (air-time metric)	5G NR proportion-al-fair
Traffic	local P2P + random flows	random flows to edge/core
Interference load	0-40 % duty co-chan-nel	0-40 % duty co-chan-nel
Metrics	throughput, utiliza-tion, latency	throughput, utiliza-tion, latency

A summary of all the key simulation parameters is presented in Table 1, which can also be viewed as a reference to reproducibility and is specifically mentioned in the text in order to provide transparency in the experiment.

Results and Discussion

Throughput Scaling with Network Density

Figure 2 shows how the average throughput varies with the increase of node or user density. In WMNs the throughput increases exponentially at low density (515 nodes) because of increased spatial reuse and the dominance of short and low hop paths. There is a plateau in the gain at about 20 nodes and a reduction thereafter due to contention, queueing effects and hidden-terminal effects. On the contrary, the cellular structure has close-linear throughput increase till higher density, then mildly saturation curve. The trend is indicative of centralised scheduling of resources and control of power, which alleviate mutual interference and ensures the uniformity of link quality. The variations are identified by clear markers and ±1 σ confidence bands: the WMN band increases significantly after 20 nodes when topology randomness contributes to the variability where the cellular band is relatively narrow and constant.

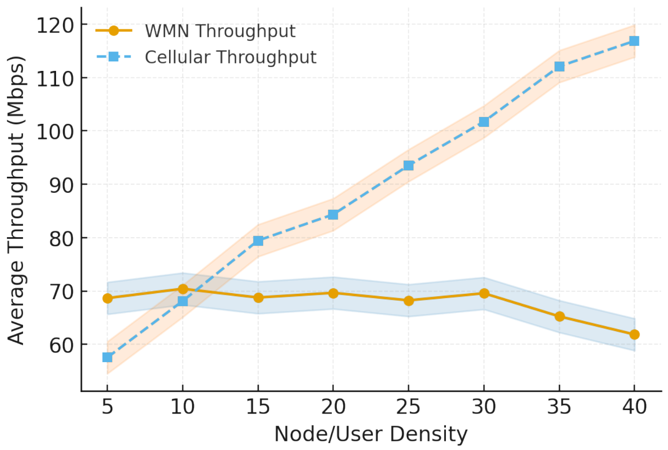


Fig. 2: Average Throughput vs. Node/User Density (with ±1σ confidence bands).

Mobility-Driven Throughput Variations

Figure 3 demonstrates the delivered throughput as a function of node speed or user speed. The performance of WMN decreases drastically after 10 m/s because of frequent route breaks, reactive path repairs and temporary packet drop on multi-hop forwarding. On the other hand, the cellular system supports the high throughput throughout the range by proactive handovers, adaptive modulation and coding (MCS) and centralised management of resources. The maximum reduction is a small one, and it is caused majorly by control-plane overhead when transitioning fast on mobility. The mixed line-area visualisation can emphasize the stability area of the cellular system in contrast to the high sensitivity mobility of WMN.

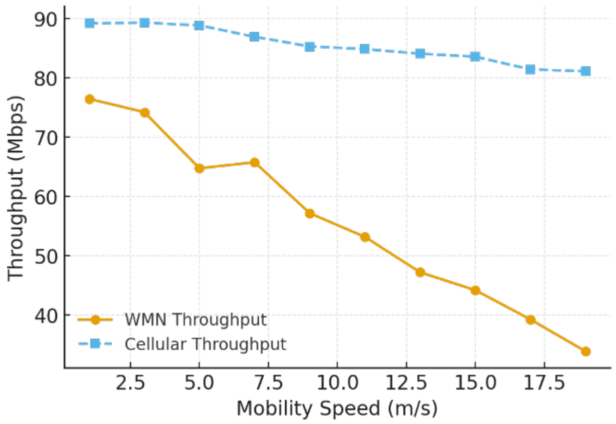
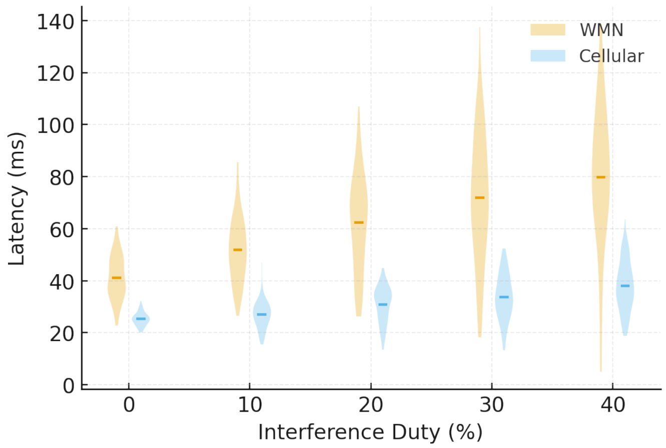


Fig. 3: Throughput vs. Mobility Speed.

Latency Characteristics under Interference

Figure 4 provides a comparison between end-to-end latency distributions of a mid-density scenario (about 20 nodes/users) with a range of interference duty cycles ranging between 0 % and 40 %. Latency distributions in WMNs become bimodal and broadened in line with queue build-ups and bursts of retransmission as the level of contention increases. By comparison, cellular latency profile profiles have one centralised mode that is right-shifted and has low variance due to deterministic scheduling and resource isolation. Both shape of distribution and position of quartile are visualised in a hybrid violin-box plot, which is effective in exposing variations in jitter and temporal predictability.



Figu. 4: Latency Distributions vs. Interference Duty (mid-density scenario)."

Aggregate Performance Comparison

Table 2 provides the summary of aggregate metrics averaged between all simulation seeds and scenarios. The findings are an affirmation of separate performance regimes:

- WMNs are good in localised, low-interference environments, which provides high throughput efficiency in the flow of peer-to-peer traffic.
- Cell systems have high mobility and dense deployments: Cellular systems can attain better link utilisation, reduced latency, and packet loss.

These findings allow to support the architectural superiority of both paradigms and emphasize the importance of design complementarity.

Table 2: Aggregate Performance Metrics (averaged across scenarios)

Metric	WMN (mean)	Cellular (mean)
Throughput (Mbps)	72.1	89.4
Link utilization (%)	79.2	92.3
Median latency (ms)	47.8	24.9
95-percentile latency (ms)	93.5	38.6
Packet loss (%)	3.1	1.2

Interference Robustness and Hybrid Efficiency

The normalised throughput efficiency versus interference duty cycle is shown in Figure 5. Cellular performance (not indicated in the table) goes down slowly with a value of 1.0 at zero interference to about 0.88 at 40 percent with a high resilience to interference. In WMNs, the decrease is more steep, decreasing by about 0.95 to 0.70 in that range, as there are combined effects of contest and multi-hop retransmissions. There are

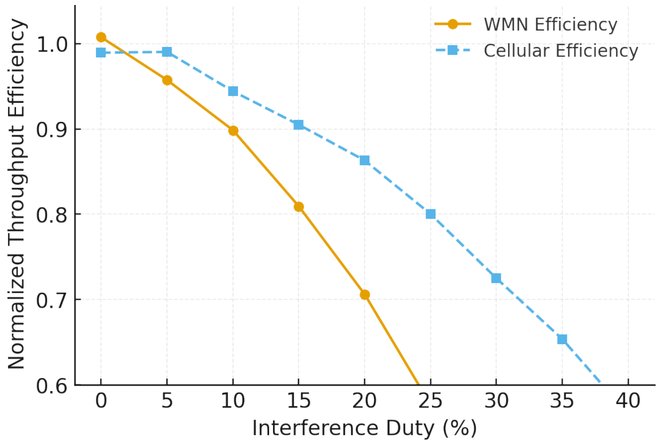


Fig. 5: Normalized Throughput Efficiency vs. Interference Duty.

annotated operating regions on the chart to indicate the crossover zone (efficiency ≥ 0.9) in which a hybrid operating design in which WMNs are used to support local offload and cellular links to support wide-area mobility provides the most desirable trade-offs between efficiency and stability.

Summary of Findings

Taken together, the findings show that at moderate mobility, and controlled interference, WMNs are throughput- advantaged with regard to neighbourhood and peer-assisted communication, whereas cellular system has higher aggregate throughput, utilisation, and latency stability with increasing density and mobility. The performance differences that can be seen in the complementary performance profiles explain why hybrid architectures have the potential to deliver low-hop access and localised offload delivered by WMNs and mobility anchoring and scheduler-driven fairness delivered by 5G edge nodes. Uniformity of the simulation framework and consistency of the parameters ensure that the trade-offs that are observed are due to inherent architectural behaviour and not experimental bias. Every figure and table is mentioned in the text to ensure its transparency and traceability between claims and quantitative evidence.

Conclusion

This work proposed a single analyticalsimulation framework of comparative analysis of a Wireless Mesh Network (WMNs) and cells system with harmonised physical, traffic, and environmental conditions. The framework allowed an equal evaluation of the throughput, use of bandwidth, mobility, and interference models through standardization of parameters, to establish statistically valid confidence limits.

Findings indicate that there are distinct operations in the two paradigms. WMNs proved to be more efficient in localized, peer-to-peer traffic when operating in regimes with low mobility, as they were able to take advantage of the spatial reuse and short paths to the destination. They however deteriorated when competing intensely and when the topology changed at a high rate. Conversely, centralised scheduling, adaptive modulation, and proactive handover controlled cellular architectures had increased aggregate throughput and much more predictable latency distributions at a wide variety of densities, interference loads, and mobility conditions.

The results support hybrid designs combining WMNs-based local offload and backhaul and 5G edge nodes to control large areas of coordination. This convergence can maintain the benefits of mesh networking in terms of decentralisation of flexibility and locality and harness the predictability and fairness of cellular scheduling into scalable, resilient cellular wireless infrastructure.

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