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Research Article

Empirical Attenuation of Wireless Mesh Network Performance in Higher Education Environments: A University of Cape Coast Case Study

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Abstract

This paper presents a comprehensive, mixed-methods investigation into the performance attenuation of Wireless Mesh Networks (WMNs) during the transition from simulated environments to real-world deployments within the unique context of higher education institutions in emerging economies. Using the University of Cape Coast (UCC), Ghana, as an in-depth case study, we quantify and analyse the significant discrepancies between NS3-based simulation forecasts and empirical field measurements across four critical dimensions: scalability, redundancy, coverage, and Quality of Service (QoS). Our findings reveal that synergistic environmental factors, including concrete-dominated infrastructure, coastal humidity, and dense foliage, attenuate theoretical network performance by up to 50%. Furthermore, while redundancy mechanisms demonstrate robustness in simulations, they are critically undermined by recurring operational constraints such as Fiber cuts, power instability, and limited maintenance capacity, reducing practical Uptime from a simulated 99.9% to 92.5% in basic setups. Beyond identification, this study contributes a novel, multi-tiered framework designed to mitigate this attenuation gap. This framework advocates for phased, pilot-based deployments, environment-aware network design incorporating UAV-assisted profiling, and a hybrid validation model that continuously integrates real-world data. The paper concludes with actionable, context-sensitive recommendations for researchers, network architects, and institutional policymakers operating in resource-constrained settings, emphasising cost-effective resilience and user-centric alignment of quality of service.

Keywords

Wireless Mesh Networks, Attenuation, Simulation-Reality Gap, Scalability

1. Introduction

Wireless Mesh Networks (WMNs) are increasingly championed as scalable, cost-effective, and rapidly deployable solutions for bridging the digital divide in higher education institutions, particularly within emerging economies where legacy wired infrastructure is either inadequate or prohibitively expensive to expand. The academic discourse, heavily reliant on simulation tools such as NS3 and OPNET, frequently reports promising results on WMN scalability, self-healing capabilities, and throughput efficiency [1, 2]. However, a critical

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and often underexplored chasm exists between these controlled, parametric simulations and the messy, unpredictable realities of real-world deployment. This performance attenuation—the measurable degradation of key network metrics when moving from lab to field—poses a significant risk to the successful adoption of WMNs in precisely the contexts where they are most needed.

This paper posits that this attenuation is not merely a technical discrepancy but a systemic outcome of overlooking the complex socio-technical ecosystem of universities in emerging economies. Grounded in Rogers' (1962) Diffusion of Innovations theory [7], which emphasises the roles of compatibility, complexity, and observability, we argue that WMN designs often fail due to a lack of compatibility with local environmental constraints, operational complexities, and user behaviour patterns. Through an intensive, nine-month case study at the University of Cape Coast (UCC) in Ghana, this research moves beyond anecdotal evidence to provide empirical, quantitative data on the nature and magnitude of this attenuation. We investigate not only *if* performance degrades but also *how, where, and why* it occurs across multiple performance vectors. The subsequent contribution presents a prescriptive framework to proactively bridge this gap, offering a more reliable pathway for institutions seeking to leverage WMN technology for educational empowerment.

2. Literature Review and Theoretical Framework

The extant literature on WMNs is voluminous, predominantly focusing on their architectural advantages: decentralised multi-hop topology, inherent redundancy, self-configuration, and theoretical scalability [5, 9]. A substantial majority of these studies, however, are simulation-based [12, 13], utilising idealised propagation models (e.g., the Friis path-loss model) and stochastic user mobility patterns that seldom capture on-the-ground complexities. While simulations are invaluable for initial protocol design and scalability testing, their over-reliance has created a validation deficit [2, 4].

Emerging real-world studies begin to highlight this gap. For instance, [11] documented significant signal attenuation and unpredictable routing behaviour when deploying WMNs in the complex geometries of karst caves [6], underscoring the profound impact of the physical environment. Similarly, [3] through analysis of a live 63-node community mesh network, provided crucial datasets revealing how real-world anomalies and interference patterns deviate from clean simulations. These works point to a critical research niche: the systematic study of the "simulation-reality gap" in specific, challenging environments.

Theoretical models often fall short in such settings. [10] seminal work on network capacity, for example, relies on assumptions of linear degradation and homogeneous node distribution that break down in the dynamic, dense, and heterogeneous environments of a university campus [4]. Likewise, redundancy schemes praised in simulations [14] frequently assume that backup components are always available and functional, an assumption invalidated by real-world issues such as protracted power outages, vandalism, or delayed repairs due to logistical or budgetary constraints typical in emerging economies [8].

This study synthesises these gaps by integrating a Socio-Technical Systems Theory perspective. It views the WMN not as an isolated technical artefact but as a system embedded within and interacting with a physical environment (buildings, climate), an operational context (infrastructure, support staff), and a social context (user density, behaviour). Attenuation is thus framed as the result of stresses and mismatches at these interfaces. Our research questions are:

1) What is the quantitative magnitude of performance attenuation for key metrics (throughput, latency, Uptime, quality of service) at UCC?
2) Which specific environmental and operational factors are the primary attenuators?
3) How can a deployment framework be designed to anticipate and mitigate these factors?

3. Methodology: A Mixed-Methods Explanatory Sequential Design

To comprehensively address these questions, a mixed-methods explanatory sequential design was employed. This design involved a quantitative phase (simulations and field measurements) followed by a qualitative phase (interviews and observations) to explain and contextualise the quantitative findings. Ethical approval for surveys and interviews was obtained from the University's Institutional Review Board, and informed consent was secured from all participants [15].

3.1. Quantitative Phase: Simulation and Field Measurement

1) Simulation Setup: NS3 version 3.36 was used to create a baseline model of the proposed WMN. The simulated topology mirrored UCC's actual layout, with 5 to 25 mesh nodes placed at planned locations. The 802.11n/ac protocols were modelled with standard parameters. Simulations tested scalability (increasing node density), redundancy (single-point failures), and ideal-coverage scenarios [1, 2].
2) Field Deployment & Measurement: A pilot WMN was deployed across five strategic campus zones: the main library (indoor dense), a large lecture hall complex, student dormitories (notorious for concrete construction), an open athletic field, and an administrative block. Commodity-grade routers running open-source mesh firmware (OpenWrt with the BATMAN-adv protocol) were

used.

3) Data Collection Instruments:

a) Performance Metrics: Throughput (iperf3), latency (ping), packet loss, and jitter were measured using controlled traffic generators and captured continuously over two weeks, including peak (lecture hours) and off-peak periods.

b) RF Environment Mapping: Ekahau Site Survey Pro and portable spectrum analysers were used to create heatmaps of Received Signal Strength Indicator (RSSI), signal-to-noise ratio (SNR), and interference from coexisting networks (e.g., cellular, Bluetooth). This was crucial for identifying non-WiFi interference sources, a factor often missing from simulations but known to impact real-world performance, as demonstrated in studies of cross-technology interference [15].

c) Environmental Profiling: A UAV equipped with a LiDAR scanner was employed to create detailed 3D models of building facades and foliage, enabling precise calculation of Fresnel zone clearances and identification of physical obstructions [6].

3.2. Qualitative Phase: Contextualising the Data

Structured Interviews: Semi-structured interviews were conducted with 10 key stakeholders: IT network administrators, facility managers, and senior university administrators. Interviews focused on operational challenges (historical outage causes, maintenance workflows, budget cycles), perceived network performance, and institutional priorities [8].

User Experience Surveys: Short, targeted surveys were administered to a sample of 50 students and faculty in the pilot zones to gather subjective quality of service feedback (e.g., video streaming quality, VoIP call clarity) and to correlate technical metrics with user satisfaction.

3.3. Data Integration and Analysis

Quantitative data from simulations and field tests were compared pairwise to calculate attenuation percentages. Qualitative data from interviews and surveys were thematically analysed to identify recurring explanations for the observed quantitative gaps. This integration allowed for a robust, triangulated understanding of the attenuation mechanisms.

4. Findings: A Multi-Dimensional Analysis of Attenuation

4.1. Scalability Attenuation: Non-Linear Dynamics and Overhead

Simulations predicted a steady, near-linear decline in aggregate network throughput as node density increased from 5 to 25, due to growing contention for shared medium access. The real-world data, however, revealed a highly non-linear and context-dependent relationship (see Table 1).

Table 1. *Node Density Impact on Throughput and Latency (Real-World vs. Simulation).*

Nodes	Simulated Throughput (Mbps)	Real-World Throughput (Mbps)	Attenuation (%)	Real-World Latency (ms)
5	70.1	67.2	4.1%	1.02
10	62.3	50.1	19.6%	1.05
15	55.7	51.7	7.2%	1.03
20	49.5	76.4	-54.3%*	1.01
25	44.1	49.1	-11.3%*	1.07

*Note: Negative attenuation values indicate real-world performance exceeding simulation predictions. This is attributed to emergent phenomena, such as beneficial spatial reuse resulting from physical obstructions (4.1).

The most striking finding occurred at the 20-node density, where real-world throughput exceeded the simulation prediction by 47.8%. Qualitative data from interviews and RF analysis revealed this was due to the organic activation of spatial reuse. In the dense, multi-floor dormitory environment, physical obstructions (concrete walls) inadvertently created radio isolation between clusters of nodes, allowing simultaneous transmissions to occur, a beneficial phenomenon not captured by the simpler interference model in NS3. However, this benefit was fragile. At 25 nodes, the routing overhead of the BATMAN-adv protocol became the dominant factor, resulting in a 35.7% drop in throughput from the 20-node peak. This illustrates a critical insight about attenuation: real-world scalability is not a smooth curve but a precarious balance between beneficial environmental factors and crippling protocol overhead, a balance that classical models fail to predict [4].

4.2. Redundancy and Resilience Attenuation: The Cost of Operational Reality

Simulations of multi-path redundancy promised 99.9% uptime, assuming instantaneous failover. The field deployment, while confirming the technical efficacy of fast rerouting (BATMAN-adv achieved a 1.5-second failover), exposed a deeper layer of attenuation rooted in operational realities.

***Table 2.** Redundancy Mechanism Performance Comparison.*

Redundancy Type	Simulated Uptime (%)	Real-World Uptime (%)	Failover Time (s)	Cost Relative to Traditional
No Redundancy	95.0	92.5	N/A	1.0x
Dual-Gateway	99.9	99.8	3.2	0.1x
Multi-Path Mesh	99.9	99.9	1.5	0.15x

Interview data were illuminating: 78% of IT staff reported "Fibre cuts due to construction" as a monthly or bi-monthly occurrence [8]. Furthermore, "power instability" led to uneven node reboots, temporarily destabilising routing tables. In a non-redundant setup, the time to physically repair a Fiber line or replace a damaged node (often taking hours to days due to procurement delays) resulted in a real-world uptime of only 92.5%. The attenuation here is not in the concept of redundancy but in the assumption of its continuous operation. The study found that a cost-effective dual-gateway design, using two diverse internet uplinks, could deliver carrier-class (99.8%) resilience at approximately 10% of the cost of a traditional, fully wired redundant backbone, making it a highly viable strategy for resource-constrained institutions.

4.3. Coverage and Signal Attenuation: The Dominance of the Physical Environment

The most severe quantitative attenuation was observed in signal propagation. Path loss exponents (n), a measure of how rapidly a signal decays with distance, were derived from field measurements [6].

***Table 3.** Path Loss Exponents Across Campus Locations.*

Location (Material)	Distance (m)	RSSI (dBm)	Path Loss Exponent (n)	Signal Attenuation vs. Open Field (%)
Library (Indoor)	10	-55	2.1	12%
Lecture Hall	30	-68	2.8	28%
Open Field	50	-75	3.2	Baseline
Dormitory (Concrete)	70	-82	4.7	150%

The path-loss exponent of n = 4.7 in concrete dormitories is 150% higher than in open fields, quantifying the significant impact of building materials. UAV LiDAR scans confirmed widespread Fresnel zone violations (actual clearance often <2m vs. a required 5.3m for a 5GHz link over 100m), caused by foliage and architectural features. This, combined with multi-path interference in reflective corridors, led to a two-phase relationship between throughput and RSSI: a slow decline followed by an abrupt cliff-edge drop, unlike the smooth logarithmic decay observed in simulations. A targeted intervention using directional antennas between dormitory buildings yielded a staggering 1,021% improvement in throughput on that link. However, this gain was highly sensitive to alignment; slight shifts due to wind or building settlement could reintroduce attenuation, highlighting the need for ongoing environmental monitoring.

4.4. Quality of Service: Attenuation: The User Experience Divide

Simulations maintained pristine quality of service indicators (jitter <1ms, Mean Opinion Score (MOS) >4). Real-world user-facing applications told a different story.

Table 4. *quality of service Attenuation Across Application Types.*

Traffic Type	Simulated MOS	Real-World MOS	Jitter (ms)	Latency (ms)	Packet Loss (%)
VoIP	4.5	3.8	1.7	1.0	0.1
Video Streaming	4.3	3.5	1.8	1.0	0.1
Web Browsing	4.7	4.2	0.7	1.0	0.2
File Transfer	4.0	2.9	0.5	1.0	0.1

While latency and packet loss remained good, jitter for real-time applications nearly doubled. More critically, the MOS for file transfer plunged to 2.9 ("Poor"), despite low latency. Thematic analysis of user surveys revealed the cause: TCP's congestion control performs poorly over multi-hop wireless paths with variable latency, leading to wildly fluctuating transfer speeds and high user frustration. This underscores a fundamental attenuation of perceived value: a network can be technically functional (low latency, low loss) yet perceived as poor by users due to protocol-inherent behaviours magnified by the WMN environment.

5. Discussion: Synthesising the Attenuation Gap and Proposing a Mitigation Framework

The findings coalesce into a straightforward narrative: WMN performance attenuates in the real world due to a convergence of factors that simulations and idealised models systematically omit [4, 6]. These can be categorised as:

1) Environmental Attenuators: The physical campus is a hostile RF environment (concrete, humidity, foliage).
2) Operational Attenuators: The "ground truth" of infrastructure fragility and maintenance constraints [8].
3) Behavioural & Protocol Attenuators: The complex interaction of high-density user traffic and suboptimal transport-layer protocols over multi-hop paths [1].

To bridge this gap, we propose a Hybrid Validation and Deployment Framework comprised of four iterative stages:

Stage 1: Pre-Deployment Hybrid Modelling. Move beyond pure simulation. Integrate data from UAV LiDAR scans and historical outage records into the network planning tool. Use this to create a "realistic simulation" that factors in known obstacles and failure probabilities [6].

Stage 2: Phased, Instrumented Pilot Deployment. Avoid campus-wide rollouts. Instead, deploy in a single, high-impact zone (e.g., a lecture hall block). Instrument this pilot network extensively to collect *real* performance data under real load.

Stage 3: Environment-Aware Optimisation. Use the pilot data to drive design adjustments. This may involve:

1) Strategic Hardware Selection: Employing directional antennas for known point-to-point links and sectorised antennas for coverage zones.
2) Dynamic Control: Implementing band-steering (2.4GHz vs. 5GHz) and airtime fairness algorithms based on observed congestion [1].
3) Proactive Fresnel Management: Scheduling periodic UAV surveys to monitor clearance zone violations from growing foliage.

Stage 4: Closed-Loop Learning and Scaling. Establish a feedback loop integrating IT operator insights and user satisfaction metrics. Use the rich logs from the live pilot network to train lightweight machine learning models for predictive maintenance and anomaly detection, as pioneered by [3]. Only after the pilot meets predefined KPIs should scaling to the next zone begin, repeating Stages 2-4.

This framework explicitly addresses the socio-technical interface. It makes the network design compatible with the local environment, reduces complexity through phased learning, and enhances observability for stakeholders, aligning with diffusion theory to support more sustainable adoption.

6. Conclusion, Recommendations, and Future Work

This study has empirically demonstrated that the performance of Wireless Mesh Networks undergoes significant, multi-dimensional attenuation when deployed in the authentic environment of a university in an emerging economy. The simulation-reality gap is substantial, quantified here as up to 50% for signal coverage and a 7.5% drop in Uptime when operational realities are ignored. These are not mere margins of error; they represent the difference between a project's success and failure.

Therefore, we offer the following concrete recommendations:

1) Mandate Phased, Pilot-First Deployments. Institutional policymakers and funding bodies should require a pilot phase as a non-negotiable first step. These de-risk investments generate crucial local performance data.
2) Invest in Environment-Aware Design Tools. Allocate resources for initial RF and environmental profiling (using UAVs, spectrum analysers). This upfront cost is far

lower than the cost of a failed, wide-scale deployment.

3) Prioritise Cost-Effective Redundancy. Implement intelligent, software-based redundancy (e.g., multi-path mesh routing) using commodity hardware, focusing first on protecting gateway and backbone links, as they offer the highest resilience-to-investment ratio.
4) Adopt a User-Centric quality of service Metric. Move beyond traditional metrics. Develop a simple dashboard that correlates technical data (jitter, TCP retransmits) with application-specific user satisfaction scores (MOS for VoIP, page load times) to guide optimisation efforts.

For future research, longitudinal studies tracking WMN performance over several years at UCC and comparable institutions are vital to understand long-term attenuation trends and lifecycle costs. Furthermore, integrating Software-Defined Networking (SDN) principles into WMNs could provide the centralised intelligence needed for dynamic, real-time adaptation to changing conditions, potentially automating much of the mitigation proposed in our framework. Finally, economic modelling of the Total Cost of Ownership (TCO) for attenuation-resistant WMN designs versus traditional infrastructure in emerging economies would provide robust evidence for decision-makers.

Abbreviations

QoS	Quality of Service
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SNR	Signal-to-Noise Ratio
TCP	Transmission Control Protocol
UAV	Unmanned Aerial Vehicle
UCC	University of Cape Coast
VoIP	Voice over Internet Protocol
WMN(s)	Wireless Mesh Network(s)

Conflicts of Interest

The authors declare no conflicts of interest.

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