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A Comparative Performance Analysis of Routing and Scheduling Protocols in WiMAX, Wireless Sensor Network, and IoT/RPL Environments

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Abstract **-** Modern wireless networks span a wide spectrum of architectures, from broadband WiMAX (IEEE 802.16) to energy-constrained Wireless Sensor Networks (WSN) and large-scale Internet of Things (IoT) deployments running the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL). Each domain optimises for a different objective — quality-of-service (QoS) guarantees, network lifetime, and reliable end-to-end delivery, respectively — yet cross-domain comparative studies remain scarce. This paper presents an integrated simulation-based performance evaluation of representative scheduling and routing protocols across all three domains: strict-priority queueing for WiMAX QoS classes, Direct Transmission (DT), Minimum Transmission Energy (MTE) multi-hop routing and LEACH clustering for WSN, and the OF0 (hop-count) and MRHOF (ETX-based) Objective Functions for RPL. Analytical modelling (Cobham's non-preemptive priority queueing formula and Little's Law) is used for the WiMAX scheduler, while discrete-event and random-geometric-graph simulations implemented in Python are used for WSN and IoT/RPL. Results show that strict-priority scheduling protects real-time WiMAX traffic even under heavy load, at the expense of Best-Effort starvation beyond $\rho \approx 0.85$; that LEACH extends WSN network lifetime by 7.9× over DT and 15.6× over MTE through load-balanced cluster-head rotation; and that MRHOF improves IoT/RPL packet delivery ratio by up to 85.8% and reduces transmission energy cost by 67–70% relative to OF0. The findings provide quantitative, reproducible guidance for protocol selection and capacity planning across heterogeneous wireless deployments.

Index Terms— *WiMAX, IEEE 802.16, Wireless Sensor Networks, LEACH, Minimum Transmission Energy, Internet of Things, RPL, MRHOF, Objective Function, Quality of Service, Network Lifetime, Priority Queueing.*

I. INTRODUCTION

The modern telecommunications landscape is characterised by a remarkable diversity of wireless network architectures, each engineered to address a distinct set of operational requirements. At the broadband end of the spectrum, WiMAX (Worldwide Interoperability for Microwave Access), standardised as IEEE 802.16, provides metropolitan-scale wireless access with guaranteed Quality of Service (QoS) for a range of traffic types including voice, video, and data. In parallel, Wireless Sensor Networks (WSN) have emerged as a fundamental enabling technology for environmental monitoring, precision agriculture, industrial automation, and healthcare, operating under the stringent constraint of limited and often irreplaceable battery energy. More recently, the Internet of Things (IoT) paradigm has extended the vision of networked sensing and actuation to billions of heterogeneous devices, connected through low-power, lossy wireless links and organised using lightweight Internet protocols.

The routing (or scheduling) protocol is the central algorithmic component that governs data delivery in each of these environments. Understanding how different routing strategies perform — and how their performance compares across network types — is therefore of both theoretical and practical importance. It informs the selection of protocols for new deployments, motivates the development of improved algorithms, and provides benchmarks against which novel proposals can be evaluated. This paper contributes a unified, reproducible simulation study spanning WiMAX QoS scheduling, WSN clustering/routing, and IoT/RPL Objective Functions, addressing a gap in the literature where such protocols are typically studied only in isolation.

II. RELATED WORK

A. Scheduling Algorithms for WiMAX

Scheduling in the WiMAX MAC layer is defined only at a functional level by the standard; the specific algorithm is left to the implementer. Several classes of scheduling algorithms have been proposed and studied in the literature. Strict Priority Scheduling serves higher-priority service classes before lower-priority ones, guaranteeing minimum delay for Unsolicited Grant Service (UGS) and real-time Polling Service (rtPS) at the cost of potential starvation of Best-Effort (BE) traffic under high load. Analytical models based on non-preemptive priority queueing [1] provide closed-form delay expressions and are widely used for performance bounding. Weighted Fair Queuing (WFQ) and its variants (Deficit Round-Robin, Weighted Round-Robin) allocate bandwidth proportionally to connection weights, providing throughput fairness while offering bounded delay for higher classes; a WFQ-based WiMAX scheduler has been shown to comply with UGS delay

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bounds. Modified Largest Weighted Delay First (M-LWDF) sorts connections by the product of their channel rate and head-of-line delay, efficiently balancing delay and throughput across service classes, and its stability properties have been formally proven. Opportunistic scheduling, such as Proportional Fair (PF), exploits multiuser diversity by preferentially serving connections experiencing good channel conditions, increasing aggregate throughput at the cost of some fairness.

B. Minimum Transmission Energy (MTE) Multi-Hop Routing

MTE routing directs each node to forward its packet to the nearest neighbour that lies closer to the sink, thereby minimising the energy spent on each individual hop. In principle, multi-hop routing reduces the per-packet energy cost for distant nodes because the aggregate cost of two short hops is less than one long hop, owing to the quadratic/quartic distance dependence of the amplifier term. However, MTE routing creates a “hot-spot” phenomenon: nodes located close to the sink must relay packets for all upstream nodes and therefore deplete their energy much faster than average. It has been shown that MTE can provide worse network lifetime than Direct Transmission (DT) in certain topologies due to this relay-load concentration effect, motivating the development of load-balancing approaches such as LEACH.

C. LEACH (Low Energy Adaptive Clustering Hierarchy)

LEACH introduced the concept of randomised, adaptive clustering for WSN routing. The network is organised into clusters; within each cluster, sensor nodes transmit their data to a Cluster Head (CH), which aggregates the data and forwards the compressed result directly to the sink. The critical innovation of LEACH is that the CH role rotates randomly among all nodes across rounds, balancing the energy-intensive aggregation and long-distance transmission load across the network. The probability that a node becomes a CH in a round is set to $p = 1/k$, where k is the target number of CHs, and a node is excluded from candidacy for $1/p$ rounds after serving as CH to ensure uniform rotation. Each round consists of a set-up phase (CH election, cluster formation, and TDMA schedule creation) and a steady-state phase (data transmission, aggregation, and CH-to-sink forwarding); LEACH has been shown to extend network lifetime by 7–8× over DT in the original simulation setting, a result extensively reproduced and extended in subsequent work. Numerous extensions have followed: SEP (Stable Election Protocol) extends LEACH to heterogeneous networks by assigning election probabilities proportional to node energy; TEEN (Threshold-sensitive Energy Efficient Network protocol) adapts LEACH for time-critical reactive sensing; and PEGASIS (Power-Efficient Gathering in Sensor Information Systems) replaces clusters with chains to reduce energy overhead further.

D. Characteristics of IoT / Low-Power and Lossy Networks (LLN)

The Internet of Things encompasses a vast and heterogeneous class of connected devices — smart meters, wearable sensors, industrial actuators, environmental monitors — communicating over low-power, lossy wireless links. The networking layer is characterised by: (i) constrained devices with limited CPU, memory, and battery capacity; (ii) lossy wireless links with time-varying packet reception ratios; (iii) large, potentially mobile topologies; and (iv) predominantly upward traffic flow, with many sensors reporting to one or a few gateways. These characteristics are collectively referred to as Low-power and Lossy Networks (LLN) in IETF terminology.

E. RPL — Routing Protocol for Low-Power and Lossy Networks

RPL (RFC 6550) is the IETF standard routing protocol for LLNs and has become the de facto standard for IoT IPv6 routing [5]. RPL organises the network into a Destination-Oriented Directed Acyclic Graph (DODAG), a loop-free tree rooted at a border router (6LBR) that connects the IoT subnet to the Internet. Each node maintains a “rank” representing its distance from the root according to an Objective Function (OF), and packets flow upward toward the root along the DODAG. RPL uses three types of control messages: DODAG Information Objects (DIO), broadcast by the root and propagated by nodes to advertise the DODAG; DODAG Information Solicitation (DIS), sent by new nodes to discover the DODAG; and Destination Advertisement Object (DAO), sent upward to populate downward routes. The Trickle timer algorithm (RFC 6206) regulates DIO transmission to suppress redundant control traffic in stable networks.

F. RPL Objective Functions

The Objective Function determines how nodes assign rank and select preferred parents. Two OFs are standardised. OF0 (RFC 6552) [7] uses hop count as the routing metric: each node's rank is set to its parent's rank plus a constant step (RFC_MIN_HOP_RANK_INCREASE = 256 by default). OF0 is simple and has low overhead but ignores link quality entirely, and in lossy environments may select short paths through unreliable links, resulting in poor end-to-end PDR. MRHOF (Minimum Rank with Hysteresis Objective Function, RFC 6719) [6] uses the Expected Transmission Count (ETX) of each link as the routing metric. ETX is defined as the expected number of transmissions required to successfully deliver a packet over a link, estimated as 1/PRR, where PRR is the Packet Reception Ratio. MRHOF selects the parent that minimises the cumulative ETX path to the root, and a hysteresis mechanism prevents route flapping when candidate parents have similar ETX values.

G. Performance Studies of RPL

Early systematic analyses of RPL identified the non-optimality of OF0 in lossy networks and motivated the development of MRHOF [20]. Experimental results on a Telos

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testbed showed that MRHOF achieves 15–20% higher PDR than OF0 in typical indoor LLN environments [6]. Subsequent work studied the impact of network topology on RPL performance, showing that balanced DODAGs, achievable with ETX-based ranking, are more resilient to node failure than unbalanced hop-count DODAGs [17]. A comprehensive simulation comparison of OF0 and MRHOF in Cooja/Contiki confirmed the PDR advantage of MRHOF across a range of densities and topologies [18]. More recent work has explored RPL extensions for dynamic IoT environments, including congestion-aware Objective Functions that incorporate buffer occupancy into rank computation, energy-aware Objective Functions for battery-powered nodes, surveys of RPL attacks and defence mechanisms [28], and machine-learning-based parent selection.

H. Cross-Domain Protocol and Tooling Comparison

Table I summarises the primary design goals, performance metrics, and standardisation status of WiMAX, WSN, and IoT/RPL, motivating the need for domain-appropriate performance metrics in the comparative evaluation that follows.

TABLE I

CROSS-DOMAIN PROTOCOL COMPARISON

Metric	WiMAX	WSN	IoT/RPL
Primary goal	QoS guarantee	Energy efficiency	Reliable delivery
Throughput metric	Class throughput (pkt/s)	Packets delivered to sink	Packet Delivery Ratio (PDR)
Delay metric	Sojourn time (ms)	Not primary	Latency (ms)
Energy metric	Not applicable	FND / HND / LND	Transmissions per packet
Scalability	Up to ~100 SS/BS	Up to ~1000 nodes	Up to millions (RPL hierarchy)
Mobility support	Yes (802.16e)	Limited (static assumed)	Limited (6LoWPAN ext.)
Standardisation	IEEE 802.16	Research protocols	IETF RFC 6550 (RPL)

Table II surveys the simulation tools commonly used in the cross-domain literature. This work adopts a lightweight Python (NumPy/NetworkX) approach for reproducibility, avoiding the hardware-specific overhead of testbed-oriented tools such as Cooja/Contiki.

TABLE II

SIMULATION TOOLS IN THE LITERATURE

Tool	Domain(s)	Language	Notes
ns-2 / ns-3	WSN, IoT, WiMAX	C++/Python /Tcl	Most widely used; steep learning curve
OMNeT++/INET	WSN, IoT, WiMAX	C++/NED	Modular, event-driven; high fidelity
Contiki-NG/Cooja	IoT/LLN	C/Java	Hardware emulation; RPL reference implementation
MATLAB Simulink	WiMAX, WSN (energy)	MATLAB	Analytical/block-diagram simulation
Python (NumPy/NetworkX)	WSN, IoT, WiMAX	Python	Lightweight; used in this work
OPNET Modeler	WiMAX, cellular	C++/GUI	Commercial; strong WiMAX MAC models

I. Limitations of Existing Comparative Studies

A review of existing cross-domain comparative studies reveals several common limitations that the present work aims to address: (1) most comparative studies restrict comparison to within a single domain (e.g., LEACH vs. SEP in WSN) rather than across domains; (2) simulation parameters are rarely reported with sufficient detail for reproduction, and fixed random seeds are almost never stated; (3) performance metrics are not normalised across domains, making cross-domain insight extraction difficult; (4) the hot-spot relay-load concentration phenomenon in flat multi-hop WSN routing is frequently underemphasised, with many studies comparing only LEACH vs. DT without including MTE; and (5) RPL Objective Function comparison studies typically use Cooja/Contiki, which bundles hardware-specific parameters (e.g., CC2420 radio energy model, processor interrupt latency) that are difficult to disentangle from protocol-level effects.

III. METHODOLOGY

The overall research workflow consists of eight sequential stages, summarised in Table III: problem definition, literature review, protocol selection, parameter and metric definition, model development, comparative simulation execution, statistical analysis, and comparative discussion.

TABLE III

RESEARCH METHODOLOGY WORKFLOW

Step	Description
1	Define research problem and objectives
2	Literature review of WiMAX, WSN, and IoT routing protocols
3	Selection of representative routing protocols per network
4	Definition of simulation parameters and performance metrics
5	Development of simulation / analytical models
6	Execution of comparative simulation scenarios
7	Data logging and statistical analysis of results
8	Comparative discussion and conclusion

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A. Performance Metric Definitions

Table IV formally defines the complete set of performance metrics computed in this study, spanning the WiMAX, WSN, and IoT domains.

TABLE IV

PERFORMANCE METRIC DEFINITIONS

Metric	Symbol	Formula / Definition	Domain
Avg. packet delay	T_k	T_k = W_k + S (Cobham)	WiMAX
Avg. packets in system	L_k	L_k = λ_k × T_k (Little's Law)	WiMAX
First Node Death	FND	min{r : alive(r) < N}	WSN
Half Node Death	HND	min{r : alive(r) ≤ N/2}	WSN
Last Node Death	LND	min{r : alive(r) = 0}	WSN
Cumul. packets delivered	CPD	Σ alive(r), r = 1..R	WSN
End-to-end PDR	PDR	Π PRR(link) over path	IoT
Avg. transmissions/pkt	Tx	Σ ETX(link) = Σ 1/PRR	IoT

B. WiMAX Scheduling Model

WiMAX MAC scheduling is modelled as a non-preemptive strict-priority M/M/1 queue with four priority classes corresponding to the four IEEE 802.16 service classes (UGS, rtPS, nrtPS, BE). The non-preemptive assumption is consistent with IEEE 802.16 MAC operation, in which a packet already being transmitted is not interrupted by a higher-priority arrival. For a non-preemptive priority queue with N priority classes, Poisson arrivals at rate λ_k for class k, and exponential service times with rate μ (all classes sharing the same physical link with rate μ_{total} = 1000 packets/s), the mean waiting time in queue for class k is given by Cobham's (1954) formula:

$$W_k = S / [(1 - \Sigma_{j<k} \rho_j)(1 - \Sigma_{j\leq k} \rho_j)]$$

where S = 1/μ is the mean service time and $\rho_j = \lambda_j/\mu$ is the traffic intensity for class j. The mean sojourn time (total delay including service) for class k is $T_k = W_k + S$. The cumulative utilisation must satisfy $\Sigma\rho < 1$ for stability. Table V lists the parameters used in the WiMAX scheduling model.

TABLE V

WIMAX SIMULATION PARAMETERS

Parameter	Value	Description
μ_total	1000 pkt/s	Total link service rate
Traffic mix (UGS:rtPS:nrtPS: BE)	20:30:25:25%	Relative offered load fractions
ρ range	0.05 – 0.95	Offered network load (utilisation)
Load points	40	Resolution of load sweep

C. WSN Routing Simulation Model

Three protocols are implemented and compared. Direct Transmission (DT): in each round, every alive node transmits a packet directly to the sink, with energy cost $E_{Tx}(L, d_i)$ dependent on the Euclidean distance d_i from node i to the sink. Minimum Transmission Energy (MTE) multi-hop: each alive node selects the nearest alive neighbour that lies closer to the sink as its next hop, within a maximum radio range R_{max} = 40 m; nodes within 110 m of the sink transmit directly. Relay loads accumulate up the routing tree, so a node relays its own packet plus all packets from its subtree, and its energy cost includes transmission of the aggregated load plus reception of forwarded packets from children. LEACH: each round consists of a set-up phase (probabilistic CH election with p = 0.05 and an exclusion period of 1/p = 20 rounds) and a steady-state phase; member nodes transmit to their nearest CH, CH nodes receive from all members, aggregate the data (with per-bit aggregation energy E_{DA}), and transmit the aggregated packet to the sink.

D. IoT/RPL Simulation Model

A random geometric graph is generated by placing n nodes (n ∈ {30, 50, 70, 90, 110, 130, 150}) uniformly at random in a 100 × 100 m area, plus one sink node at the centre (50, 50). Two nodes are considered candidate radio neighbours if their Euclidean distance is less than 1.8 × R_{TX}, where R_{TX} = 25 m is the nominal transmission range. A logistic packet reception ratio (PRR) model is used:

$$PRR(d) = 1 / [1 + \exp(k(d - R_{TX}))],\ \ k = 0.25$$

This model provides near-perfect reliability at short distances and degrades smoothly to near-zero beyond the nominal range, consistent with empirical WSN link-quality measurements reported in the literature [21]. Links with PRR < 0.05 are discarded, and ETX for each link is computed as 1/PRR. OF0 (hop-count) is implemented as an unweighted shortest-path computation, so the route from each source node to the sink is the minimum-hop path. MRHOF (ETX-based) is implemented as a weighted shortest-path computation using ETX as the edge weight, so the route minimises cumulative ETX to the sink. For each source node in each trial, the end-to-end PDR is computed as the product of PRR values along the selected path, and the average transmission count is computed as the sum of ETX values along the path. Results are averaged over 25 independent random topology realisations and all source nodes in each realisation.

IV. SIMULATION MODEL DEVELOPMENT

This section presents the detailed architecture of the simulation models for each of the three network types studied, including the key components and the data collection strategy.

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Schematic diagrams of the simulated network architectures are provided in Figs. 1–3.

A. WiMAX Simulation Model

The WiMAX simulation models a Point-to-Multipoint (PMP) network consisting of a Base Station (BS) serving five Subscriber Stations (SS), each generating traffic of a different QoS class, as illustrated in Fig. 1. The BS implements a non-preemptive strict-priority scheduler with four priority queues, modelled analytically using Cobham's formula and implemented as a Python function that sweeps the total offered load from $\rho = 0.05$ to $\rho = 0.95$ in 40 steps. For each load point, the per-class arrival rates are computed as $\lambda\_k = \rho\_total \times \mu \times share\_k$, where $share\_k = [0.20, 0.30, 0.25, 0.25]$ for [UGS, rtPS, nrtPS, BE] respectively. The cumulative utilisation $\rho\_cum,k = \Sigma\_\{j \le k\}\ \rho\_j$ is used in the Cobham formula to compute the mean sojourn time for each class. The following quantities are recorded for each load point: the average packet delay T_k for each service class; the average number of packets in the system L_k, derived from Little's Law; and the effective throughput per class.

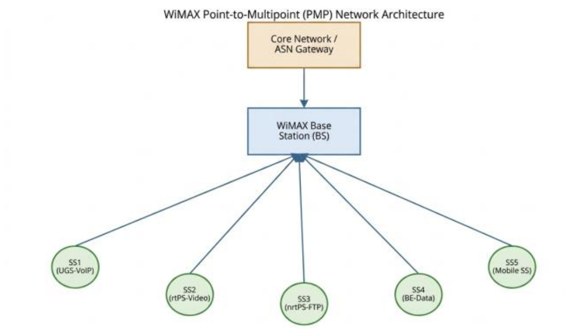

Fig. 1. WiMAX Point-to-Multipoint (PMP) network architecture.

B. WSN Simulation Model

The WSN simulation deploys 100 nodes uniformly at random in a 100 × 100 m field, with the sink placed at (50, 175) m. A representative LEACH-style clustered topology with five cluster heads is shown in Fig. 2. Each round of the simulation proceeds as follows for all three protocols: (1) node status update, marking nodes with energy ≤ 0 as dead; (2) routing decision, in which the appropriate routing algorithm selects next hops or cluster heads; (3) energy deduction, subtracting transmission and reception energy from each node's battery; and (4) statistics logging, recording alive node count, total residual energy, and cumulative delivered packets. For LEACH, the set-up phase (CH election) precedes the data transmission phase within each round, and a Python dictionary tracks each node's epoch counter to enforce the CH exclusion period. The following time series are logged over 3,000 rounds: number of alive nodes per round, total residual energy of alive nodes per round, and cumulative packets delivered to the sink.

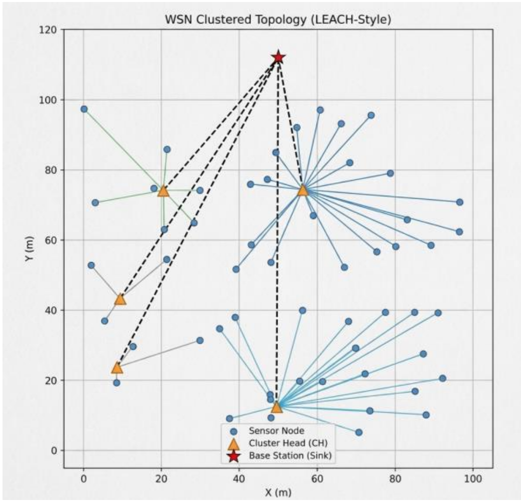

Fig. 2. WSN clustered topology (LEACH-style), showing sensor nodes, cluster heads, and the base station (sink).

C. IoT/RPL Simulation Model

The IoT simulation constructs a random geometric graph for each trial and computes the DODAG rooted at the sink node using NetworkX shortest-path algorithms; the resulting DODAG structure is illustrated in Fig. 3. The logistic PRR model is parameterised with nominal range $R\_TX = 25$ m and steepness $k = 0.25$, giving $PRR = 0.5$ at distance $d = R\_TX$. This provides a realistic transition from near-perfect reliability ($PRR \approx 0.99$ at $d = 5$ m) to near-zero reliability ($PRR \approx 0.01$ at $d = 43$ m) as distance increases beyond the nominal range, consistent with empirical measurements reported for IEEE 802.15.4 (Zigbee/Thread) radios [21]. For each node density $n \in \{30, 50, 70, 90, 110, 130, 150\}$, 25 independent random topology realisations are generated with distinct seeds; within each realisation, all non-sink nodes are evaluated as sources, and PDR and transmission count are averaged over all source–sink pairs and all trials, yielding robust mean estimates with low variance.

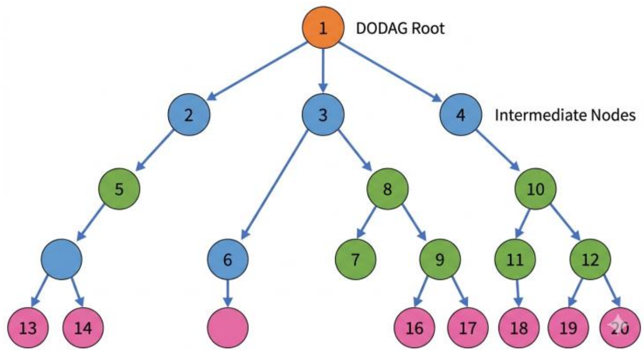

Fig. 3. Example RPL DODAG topology rooted at the border router (node 1).

V. RESULTS AND DISCUSSION

A. WiMAX QoS Scheduling Performance

Fig. 4 shows the average packet delay for each of the four IEEE 802.16 service classes as a function of the offered network load ρ. The results clearly demonstrate the effectiveness of strict-priority scheduling in protecting real-time traffic. UGS, the highest-priority class, maintains nearly constant delay across the entire load range: at ρ = 0.85, UGS delay is only 2.21 ms, compared to 2.06 ms at ρ = 0.30 — an increase of less than 8% despite nearly tripling the offered load. This behaviour is consistent with the theoretical prediction that the delay of the highest-priority class in a non-preemptive queue is independent of lower-priority class loads. rtPS delay increases more gradually, rising from 2.26 ms at ρ = 0.30 to 3.11 ms at ρ = 0.85, since it receives access immediately after UGS. nrtPS delay increases significantly at higher loads, reaching 5.91 ms at ρ = 0.85 compared to 2.53 ms at ρ = 0.30, a 2.3× increase, attributable to the growing cumulative utilisation of the three higher-priority classes. Best-Effort (BE) delay is the most strongly affected by increasing load: at ρ = 0.85, BE delay reaches 20.7 ms, more than an order of magnitude higher than UGS, and as ρ approaches 0.95, BE delay diverges, signalling effective starvation.

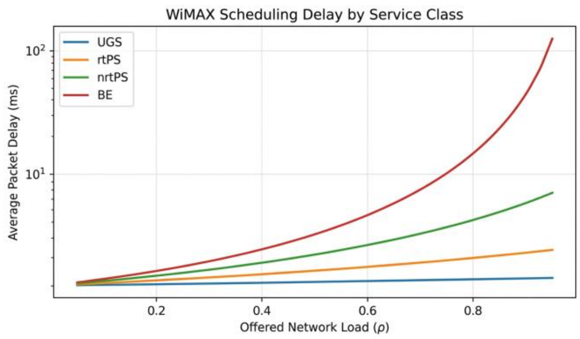

Fig. 4. Average packet delay vs. offered network load, by IEEE 802.16 service class.

Fig. 5 shows the average number of packets in the system for each service class, derived from Little's Law (L = λT). The queue build-up results reinforce the delay analysis: UGS and rtPS queues remain shallow, below 0.6 and 1.2 packets respectively, even at ρ = 0.90, confirming stable, bounded operation, while nrtPS queues grow to approximately 1.8 packets at high load. The BE queue grows explosively above ρ = 0.80, reaching 17 packets at ρ = 0.95 and signalling incipient instability.

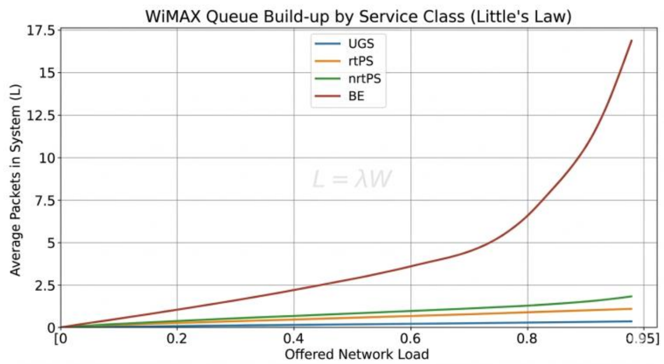

Fig. 5. Average number of packets in the system vs. offered load (Little's Law).

B. WSN Routing Protocol Performance

Fig. 6 shows the number of alive nodes over 3,000 rounds for DT, MTE, and LEACH — the primary network-lifetime visualisation in WSN research. The results demonstrate a dramatic difference in network lifetime across the three protocols. LEACH achieves the longest lifetime by a substantial margin, with First Node Death (FND) occurring at round 701, compared to round 89 for DT and round 45 for MTE — a 7.9× improvement over DT and a 15.6× improvement over MTE, confirming the effectiveness of randomised, load-balanced clustering in distributing energy consumption across the network. MTE performs significantly worse than DT in terms of FND despite reducing per-hop transmission distance; this counterintuitive result is explained by the relay-load concentration effect, whereby nodes near the sink must relay packets for all upstream nodes, causing rapid energy depletion of sink-adjacent relay nodes. Once these relay nodes die, the routing tree breaks and many other nodes lose connectivity, triggering a cascade of deaths. DT avoids this concentration because each node bears only its own transmission cost, albeit at a higher per-packet energy cost for distant nodes. LEACH avoids both problems: each member node transmits only a short distance to its cluster head, keeping transmission energy low, while the cluster-head role rotates so that no single node accumulates disproportionate relay load.

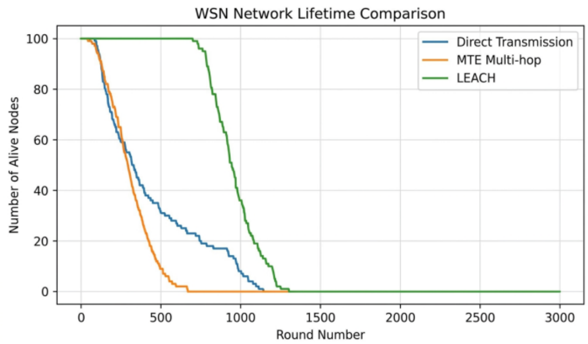

Fig. 6. Number of alive nodes vs. round number for DT, MTE, and LEACH.

Fig. 7 shows the cumulative packets delivered to the sink over 3,000 rounds, capturing the combined effect of network lifetime and alive-node count at each round (summarised numerically in Table VI). LEACH delivers 2.21× more packets than DT and 3.15× more than MTE over the full simulation. MTE performs worse than DT in cumulative delivery because its early FND and rapid cascade failure sharply reduce the alive-node count in early rounds, eliminating potential packet transmissions, whereas DT sustains a moderate delivery rate for longer. LEACH maintains a high delivery rate, with all 100 nodes alive, for 701 rounds before any node dies, and sustains a near-maximum delivery rate well into round 1,000, resulting in the highest cumulative packet count.

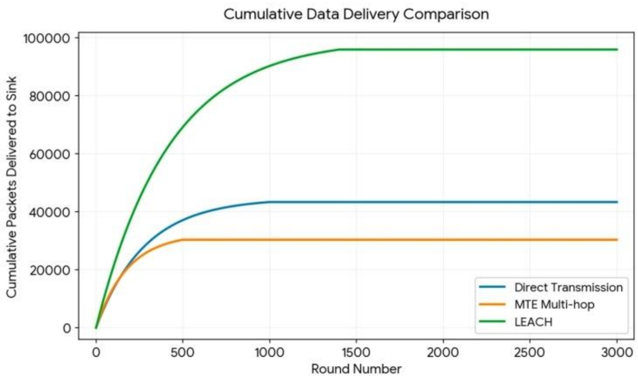

Fig. 7. Cumulative packets delivered to the sink vs. round number.

TABLE VI

CUMULATIVE PACKETS DELIVERED (3,000 ROUNDS)

Protocol	Cumul. Packets	Relative to DT
Direct Transmission	43,510	1.00×
MTE Multi-hop	30,437	0.70×
LEACH	95,984	2.21×

C. IoT/RPL Objective Function Comparison

Fig. 8 shows the average end-to-end PDR achieved by OF0 (hop-count) and MRHOF (ETX-based) routing as a function of the number of deployed nodes. MRHOF consistently achieves significantly higher PDR than OF0 across all node densities. At 30 nodes, MRHOF achieves 53.7% PDR compared to 28.9% for OF0, an improvement of 85.8%. As node density increases, MRHOF PDR improves to 65.9% at 130 nodes, reflecting the availability of higher-quality alternative paths as the network becomes denser, whereas OF0 PDR shows little sensitivity to density (25–29%), indicating that the protocol consistently selects short paths through unreliable links regardless of the available alternatives. This advantage stems from MRHOF's use of ETX as the routing metric: MRHOF avoids links with a high expected transmission count even when using such links would reduce hop count, whereas OF0 selects the fewest-hop path, which in a network with distance-dependent link quality often traverses longer, less reliable links. Because end-to-end PDR is the product of per-link PRR values, even a modest improvement in individual link PRR has a compounding positive effect on end-to-end delivery.

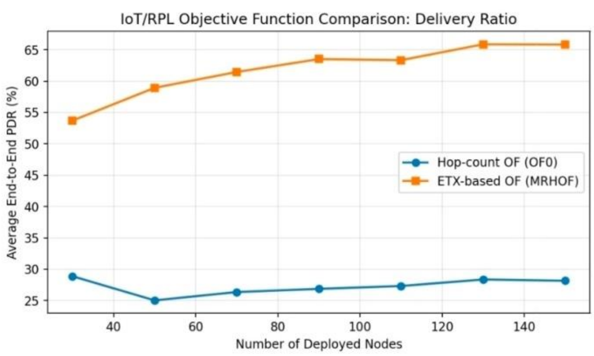

Fig. 8. Average end-to-end PDR vs. number of deployed nodes, OF0 vs. MRHOF.

Fig. 9 shows the average number of transmissions per successfully delivered packet, serving as a proxy for the energy cost of routing, since each transmission consumes energy proportional to ETX. MRHOF requires substantially fewer transmissions per delivered packet than OF0 (approximately 2.7–3.4 vs. 7.9–9.4), a reduction of approximately 67–70%. This is a counterintuitive result: although MRHOF may select routes with more hops, each hop has higher PRR and therefore requires fewer retransmissions, so the resulting route is both more reliable and more energy-efficient than the minimum-hop OF0 route. The transmission cost of MRHOF decreases with node density, reflecting the increasing availability of short, high-quality links as nodes become denser, whereas OF0's transmission cost fluctuates with density because it selects minimum-hop paths that may traverse long, unreliable links regardless of alternatives.

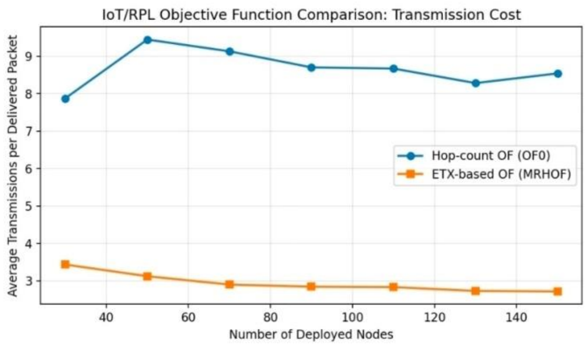

Fig. 9. Average transmissions per delivered packet vs. number of deployed nodes, OF0 vs. MRHOF.

D. Summary of All Performance Results

Table VII consolidates the key head-to-head comparisons across all three domains.

TABLE VII

SUMMARY OF ALL PERFORMANCE RESULTS

Domain	Comparison	Metric	A	B	Winner
WiMAX	UGS vs BE (ρ=0.85)	Delay (ms)	2.21	20.70	UGS 9.4×
WiMAX	UGS vs BE (ρ=0.60)	Delay (ms)	2.14	5.61	UGS 2.6×
WSN	LEACH vs DT	FND (rnd)	701	89	LEACH 7.9×
WSN	LEACH vs MTE	FND (rnd)	701	45	LEACH 15.6×
WSN	LEACH vs DT	Cumul. pkts	95,984	43,510	LEACH 2.21×
IoT	MRHOF vs OF0 (n=110)	PDR (%)	63.3	27.3	MRHOF 2.3×
IoT	MRHOF vs OF0 (n=110)	Tx/pkt	2.83	8.67	MRHOF 3.1×

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VI. CONCLUSION

This paper has presented an integrated, cross-domain simulation study of scheduling and routing protocols in WiMAX, WSN, and IoT/RPL networks, addressing the reproducibility and cross-domain gaps identified in the existing literature. Three sets of deployment recommendations follow from the results. For WiMAX deployments, admission control is essential: allowing offered load to exceed $\rho \approx 0.85$ causes unbounded delay for BE traffic, and as load approaches saturation, nrtPS performance also degrades substantially; network operators should size their capacity to keep aggregate utilisation below $\rho = 0.70$ to provide adequate headroom for all service classes. For WSN deployments, LEACH, or its extensions such as SEP for heterogeneous networks, is recommended over flat routing approaches for energy-constrained deployments where network lifetime is the primary objective; the MTE protocol should be used with caution, as its relay-load concentration can significantly reduce lifetime below even the simplest Direct Transmission baseline. For IoT/RPL deployments, MRHOF should be preferred over OF0 in any environment with non-negligible link losses, which describes the majority of real-world indoor and outdoor IoT deployments; the computational and memory overhead of MRHOF is negligible for any contemporary IoT microcontroller, and its PDR and energy advantages are substantial. Future work will extend this comparative framework to mobile and heterogeneous-traffic scenarios and to machine-learning-assisted routing and scheduling across all three domains.

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