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Optimal routing metrics for scalable and energy-efficient distributed wireless networks

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Abstract : Distributed wireless networks provide scalable and decentralized connectivity for applications ranging from IoT and vehicular communication to emergency response. However, unlocking their full potential requires overcoming persistent challenges, including inefficient routing strategies, energy limitations, and interference management. Traditional routing metrics—primarily based on hop count or heuristic combinations—fail to optimize throughput, energy efficiency, and reliability, particularly as network size increases. To address these limitations, we systematically analyze the multi-layer networking problem and derive optimized routing metrics that simultaneously maximize total network throughput, minimize energy consumption, enhance path reliability, and enable effective load balancing. Our proposed metrics—centered on link length square, inverse channel gain, and link utilization—are rigorously evaluated through extensive simulations. Results demonstrate substantial performance gains over traditional hop-count-based approaches, with improvements of several-fold in end-to-end throughput and up to 20 dB in power efficiency. These metrics consistently deliver high capacity, low latency, and robust operation in realistic large-scale urban scenarios—historically a major obstacle for ad hoc networks. These findings pave the way for practical, sustainable deployment of large-scale distributed wireless networks.

Keywords : Wireless ad hoc networks; routing metric; multi-layer optimization; energy efficiency; wireless distributed networks

1 Introduction

Distributed wireless networks rely on multi-hop communication, in which devices cooperatively relay data across multiple wireless links without centralized infrastructure. This paradigm enables long-range point-to-point (P2P) connectivity and has long been viewed as a promising foundation for large-scale, infrastructure-free communication. Such networks could support the growing demand for *ultra-dense and ubiquitous connectivity* over large geographic areas [5]. Modern digital ecosystems increasingly involve massive numbers of heterogeneous agents—including humans, vehicles, sensors, and autonomous systems—whose interactions drive smart-city infrastructures and large-scale Internet-of-Things (IoT) deployments [4, 6, 8]. Providing this level of dense, resilient connectivity using centralized cellular architectures alone is becoming increasingly challenging in terms of scalability and cost. At the same time, the global digital ecosystem is shifting toward *fully distributed systems*. Paradigms such as edge computing, blockchain, and Web3 promote decentralization of computation, trust, and ownership [15]. While computation, security, and control are increasingly decentralized, connectivity remains predominantly centralized. Distributed wireless networking thus emerges as a key enabler of truly end-to-end decentralized communication. Moreover, recent technological advances have strengthened the feasibility of large-scale distributed wireless networks. Progress in wireless transmission (e.g., massive MIMO, beamforming, and millimeter-wave communications), distributed intelligence via machine learning, and increasingly capable user devices enables unprecedented spatial reuse, adaptability, and cooperation. Together, these trends point toward a *unified*, large-scale, infrastructure-free network based on *fully multi-hop communication*, capable of supporting both human-centric and machine-driven interactions [13]. However, existing distributed wireless systems typically exhibit limited multi-hop capability, short communication ranges, or application-specific designs (e.g., Wi-Fi, MANETs, VANETs, and mesh networks). A truly scalable, metropolitan-scale, infrastructure-free network supporting millions of users has therefore remained elusive [11]. Recent work has challenged this pessimistic view. By analyzing real-world interaction patterns and asymptotic P2P capacity bounds, [13] demonstrated the theoretical feasibility of nearly scale-free distributed wireless networks.

Nevertheless, significant *practical challenges* remain—most notably the absence of routing metrics for massive multi-hop networks that can simultaneously preserve spatial reuse, network capacity, and energy efficiency as the network scales [11]. In distributed wireless networks, routing metrics play a fundamentally more critical role than in wired systems, as routing decisions directly affect not only rate allocation but also the availability of transmission resources due to the shared wireless medium. Historically, minimizing physical distance or hop count has been the predominant metric due to its simplicity and use in evaluating asymptotic capacity in large-scale networks [2, 12, 22]. However, this simplicity sacrifices performance optimization, often selecting longer, unreliable, and more energy-consuming links, thus significantly reducing overall throughput, particularly as the network scales [1]. Motivated by these limitations, numerous routing metrics that incorporate channel quality and network traffic have been proposed [7, 9, 14, 20, 21]. However, no single metric consistently outperforms others across diverse network scenarios [1]. This inconsistency largely arises from heuristic designs rather than systematic, optimization-driven formulations. Even recent approaches often rely on weighted combinations of traditional metrics [17], without explicitly addressing the full set of ad hoc network constraints, including reliability, throughput, energy efficiency, and load balancing. Moreover, any practical routing metric must remain comparable to hop count in terms of implementation simplicity, overhead, and operational practicality.

To address these limitations, we systematically consider network performance as inherently multi-layered, influenced by route selection, Medium Access Control (MAC) resource allocation, and physical-layer power management. Rather than optimizing individual traffic demands, our goal is to maximize the total network performance, a critical factor in wireless ad hoc networks. We demonstrate that maximizing total P2P capacity is ideally achieved when the power allocation problem results in evenly distributed active link capacities for any P2P stream. In such a configuration, incorporating natural network coverage constraints, we propose minimizing the area occupied by all hops of each P2P connection as an optimum method to maximize total P2P capacity. We show in practice that this space minimization can be approximated by a more practically measurable metric, namely the inverse of channel gain. This approach coincides with minimizing total energy consumption and, equivalently, minimizing outage probabilities [1]. Specifically, this paper contributes:

- We show that maximizing aggregate P2P network throughput in large-scale distributed wireless networks requires routing paths that minimize the sum of squared link lengths. In practice, link lengths can be accurately approximated by inverse channel gains, yielding a routing metric that is both more informative and more robust under realistic wireless conditions; simulation results confirm the equivalence of these two formulations. Moreover, under fixed P2P rate constraints, the same metric emerges from minimizing transmit power, and is consistent with reliability-oriented routing based on inverse SNR. Together, these results demonstrate that a single low-complexity routing structure is aligned with throughput scalability, energy efficiency, and path reliability.
- Our simulations reveal substantial improvements over the hop-count metric in network throughput and transmission power efficiency, while maintaining or improving performance at scale. By incorporating link utilization into the routing metric, the proposed approach achieves effective load balancing under high traffic conditions with thousands of nodes, preventing buffer overflow. Simulation results confirm that the inverse channel-gain exploits channel diversity to reduce energy consumption, achieving energy-efficiency gains of up to 20 dB, thereby enabling more sustainable networking. Finally, by introducing a threshold within the routing metric, hop counts and network load are controlled, and end-to-end delay is reduced.

The remainder of the paper is organized as follows: Section 2 provides a review of key existing literature. Section 3 presents optimal routing metrics. Section 4 presents the simulation results and their analysis. Finally, Section 5 outlines future research directions and concludes the paper.

2 Background

Wireless ad hoc networking has long been studied at moderate scales, particularly in the context of mobile ad hoc networks (MANETs). However, as networks grow to millions of nodes, the dominant limitation is no longer protocol design for limited-hop distributed networking, but whether end-to-end communication can remain feasible at all. Unlike wired networks, connectivity in wireless ad hoc systems is inherently multi-layered. As a result, routing decisions—dictated by routing metrics—implicitly shape physical-layer interference, spatial reuse, energy consumption, and ultimately network capacity. Despite this coupling, many routing protocols still rely on simple link costs such as hop count, which optimize path length without regard to scalability or efficient resource reuse. To visualize the impact of poorly designed routing metrics, such as hop count, on large-scale networks, it is necessary to examine the fundamental connectivity constraints that govern resource reuse and total network performance. Under uniform random node placement, ensuring that *all* nodes remain connected requires the maximum transmission range to scale with the network size n. Specifically, classical results show that the minimum transmission range required to guarantee connectivity with high probability scales as $r(n) = \Theta\left(\sqrt{\ln n}\right)$ [12]. This scaling is dictated by the most isolated nodes in the network. While such a transmission range is necessary to ensure global connectivity, applying it uniformly across all links is highly inefficient and becomes increasingly detrimental as the network grows. For a two-dimensional distributed wireless network operating under spatial reuse constraints, the achievable P2P capacity, C_{P2P}, governed by the fundamental trade-off between spatial reuse and multi-hop routing, satisfies the following scaling law [13]:

$$C_{P2P} \propto \frac{1}{r(n)}. \tag{1}$$

Thus, *minimizing the effective transmission range of active links is essential for maintaining network throughput.*

However, routing strategies based on hop count or similar metrics tend to select the longest feasible links, pushing $r(n)$ toward its connectivity bound $\Theta(\sqrt{\ln n})$. This causes the P2P capacity to decay as $\Theta(1/\sqrt{\ln n})$. Importantly, this degradation is not merely a performance issue—it is a fundamental scalability failure. Moreover, by prioritizing path length alone, such metrics not only accelerate the collapse of total throughput and P2P capacity as the network scales, but also degrade link reliability and energy efficiency [1]. In particular, long single-hop transmissions consume disproportionately more energy than multiple shorter hops, leading to rapid battery depletion and rendering large-scale deployments operationally impractical.

For moderate-size multi-hop ad hoc networks and MANETs, a broad class of routing metrics has been proposed to address the limitations of hop-count routing. Reliability-aware metrics such as Expected Transmission Count (ETX) [7] and its extensions, including ETT and WCETT, improve packet delivery probability and channel utilization, but do not explicitly control transmission range growth or energy expenditure. Energy-centric approaches, such as Minimum Total Power Routing (MTPR) [20] and battery-aware variants including MBCR and MMBCR [21], extend network lifetime but may overload critical nodes and do not address spatial reuse at scale. Load-aware metrics [14] attempt to balance traffic, but typically incur increased measurement, coordination, and control overhead.

As ad hoc networks scale, flat routing architectures become infeasible and are often replaced by hierarchical routing schemes. In this case, many previously proposed metrics do not scale due to routing-table size, state dissemination overhead, or computational complexity. As a result, hop count regains popularity—not because of efficiency, but because of its simplicity and scalability. An alternative approach is geographic routing [18, 19] offer local decision-making and low overhead, but remain sensitive to topology irregularities, obstacles, and localization errors. More fundamentally, because such methods lack network-state awareness, their primary objective is reachability over large geographic areas rather than throughput or energy efficiency. While the aforementioned approaches are effective in moderate-sized networks for specific objectives, they invariably sacrifice other critical dimensions. In massive-scale multi-hop networks, none of these methods alone is sufficient. Practical deployment requires the *simultaneous* achievement of high aggregate network throughput, energy efficiency, spatial reuse efficiency, and low operational complexity, while maintaining performance as the network size grows. Addressing these requirements extends beyond routing metrics alone and must be approached structurally. Focusing specifically on routing metrics, only a limited number of works derive routing metrics from explicit optimization principles. Such approaches often consider single-flow optimization [1] or rely on greedy local decisions [18, 19], which are insufficient for maximizing network-wide throughput in dense, interference-limited environments. Many recent routing cost approaches [10, 17] combine existing metrics heuristically, without fundamentally resolving the multi-layer coupling between routing decisions, interference, spatial reuse, and aggregate throughput—the dominant constraint in massive-scale multi-hop communication. Furthermore, numerous schemes significantly increase routing overhead and computational complexity [17] without delivering proportional performance gains.

To the best of our knowledge, no existing routing metric has been explicitly designed to maximize total network throughput while remaining scalable with network size. To address these limitations, we model routing in distributed wireless networks as a multi-layer optimization problem with scalability as the primary design objective. Rather than optimizing individual flows, our formulation emphasizes maximizing aggregate P2P throughput, which is the key enabler of large-scale ad hoc connectivity. Within this framework, we derive routing metrics that account for energy efficiency, reliability, load balancing, and—critically—bounded transmission range.

3 Optimal routing metrics

We consider a large-scale distributed wireless network in which each node generates P2P traffic. The objective is to maximize the aggregate network throughput, defined as the expected sum of end-to-end rates over all simultaneously active P2P connections. This maximization is subject to fundamental constraints imposed by transmission ranges, flow service rates, node transmit power limits, and fixed network coverage. The resulting problem is a network-wide stochastic optimization over routing, power control, and spatial reuse, from which we derive a routing policy that is necessary for maximizing aggregate throughput in Theorem 1. A key implication of Theorem 1 is that fixed transmit powers are generally suboptimal; instead, optimal operation requires power adaptation so that all links along a P2P route operate at an equalized rate.

Theorem 1 (Optimal throughput maximization routing policy). Consider a large-scale distributed wireless network with node density ρ, where randomly distributed nodes generate P2P traffic according to a stationary stochastic demand process. Let $\mathcal{F}$ denote the set of simultaneously active P2P connections, and let each connection $i \in \mathcal{F}$ be routed over a multi-hop path composed of j_i links with lengths $\{r_{ik}\}_{k=1}^{j_i}$. Assume a homogeneous physical layer: all transmitters use the same bandwidth and PHY/MAC technology, and links share a common wireless medium with interference-limited spatial reuse. Then, any routing and power allocation policy that maximizes the expected aggregate P2P throughput,

$$\mathbb{E}\left[\sum_{i\in\mathcal{F}} C_i^{P2P}\right],$$

subject to transmit power constraints and total network coverage, must satisfy the following structural condition: each P2P route must minimize the sum of squared link lengths,

$$\sum_{k=1}^{j_i} r_k^2.$$

Proof. Consider a set of m simultaneously active P2P connections. The aggregate network throughput is defined as

$$\sum_{i=1}^{m} C_i^{P2P},$$

where the end-to-end throughput of connection i is limited by its bottleneck hop,

$$C_i^{P2P} = \min_{k=1,\dots,j_i} C_i^k, \tag{2}$$

with C_i^k denoting the achievable rate of the kth hop on the route of flow i. This follows from a store-and-forward model, since any hop with capacity below the end-to-end rate would accumulate backlog and constrain the sustainable flow rate.

If a hop operates with capacity strictly larger than the bottleneck, i.e., $C_i^k > \min_\ell C_i^\ell$, then the excess capacity does not increase C_i^{P2P} and therefore provides no throughput benefit. In a shared wireless environment, link capacities depend monotonically on transmit power through the received SINR. Let $C_i^k(P_i^k)$ denote the capacity of hop k as a function of its transmit power P_i^k, under a fixed interference pattern. If a flow is operated at its bottleneck rate C_i^{P2P}, then for any hop satisfying $C_i^k(P_i^k) > C_i^{P2P}$, the transmit power can be reduced until $C_i^k(P_i^k) = C_i^{P2P}$ without reducing the end-to-end throughput. Such power equalization across hops preserves the achievable rate of the considered flow while reducing unnecessary transmit power and interference.

Thus, each P2P connection i can be characterized as a set of links whose capacities satisfy $C_i^k(P_i^k) = C_i^{P2P}$ and that collectively consume a spatial resource A_i due to interference and spatial reuse constraints. Since the total network coverage for n nodes with node density ρ is fixed to n/ρ, the aggregate spatial resource consumption across all simultaneous P2P connections is subject to the inherent constraint

$$\sum_{i=1}^{m} A_i \le \frac{n}{\rho}.$$

For a multi-hop route composed of j links, the total spatial footprint is

$$A_i = \sum_{k=1}^{j} S_{ik},$$

where S_{ik} represents the interference footprint of the kth link. This additivity holds because each active link requires a dedicated spatial interference region, enforced through spatial separation, scheduling, or orthogonal channel usage.

Under standard interference models, the spatial footprint of a single transmission scales proportionally to the square of its link length, i.e., $S_{ik} \propto r_{ik}^2$. Since all links operate with identical bandwidth and homogeneous PHY/MAC characteristics, each hop contributes equally—up to its link length—to spatial resource consumption. As a result, the total spatial footprint of a j_i-hop P2P connection scales as

$$A_i = \sum_{k=1}^{j_i} S_{ik} \ \propto \ \sum_{k=1}^{j_i} r_{ik}^2.$$

Since the total network coverage is fixed, maximizing the expected aggregate P2P throughput requires maximizing the number of simultaneously active connections m. For any P2P flow i, all hops along its route must sustain the same end-to-end rate C_i^{P2P}. Once a hop k satisfies $C_i^k(P_i^k) \geq C_i^{P2P}$, any additional capacity on that link does not increase throughput. Importantly, increasing the per-connection rate C_i^{P2P} does not maximize aggregate throughput. While total throughput scales linearly with the number of simultaneously active connections m, which is governed by spatial reuse, increasing C_i^{P2P} requires additional spatial reservation and yields at best logarithmic gains. Consequently, maximizing aggregate throughput reduces to minimizing the spatial footprint A_i consumed per connection, thereby maximizing m. This implies that any routing policy maximizing network-wide throughput must minimize $\sum_{k=1}^{j} r_k^2$ for each P2P route. □

From another viewpoint, the routing structure derived in Theorem 1 can be interpreted through channel-aware metrics. Specifically, the path loss between a transmitter and receiver separated by a distance r_k scales as r_k^{α}, where α is the path loss exponent. Thus, the channel gain satisfies $h_k \propto r_k^{-\alpha}$. As the spatial footprint of a link scales as r_k^2, it follows that

$$r_k^2 \propto \frac{1}{h_k^{2/\alpha}}.$$

Therefore, minimizing $\sum_k r_k^2$ is equivalent to minimizing $\sum_k 1/h_k^{2/\alpha}$. Because $h_k > 0$ and $\alpha > 0$, this metric is monotonic in $1/h_k$, allowing the routing metric to be approximated by $\sum_k 1/h_k$, which is typically easier to measure in practice and better reflects instantaneous channel quality.

Alternatively, if the objective is to minimize total transmit power subject to maintaining a fixed end-to-end rate for each P2P connection, the same routing structure emerges. For a given connection i, assume a constant received power threshold c_i across all intermediate hops. Since the received power satisfies $P_k^r = P_k^t h_k$, the required transmit power on hop k is $P_k^t = c_i/h_k$. The total transmit power along the route is therefore proportional to $\sum_k 1/h_k$. Thus, the routing metric derived from throughput maximization is also consistent with minimizing energy expenditure under fixed-rate constraints. Moreover, as shown in [1], minimizing $\sum_k 1/\mathrm{SNR}_k$ yields the most reliable communication path. Under equal transmit power and uniform noise assumptions, $\mathrm{SNR}_k = P^t h_k/N_0$, and minimizing $\sum_k 1/\mathrm{SNR}_k$ reduces to minimizing $\sum_k 1/h_k$. This demonstrates that the routing structure derived from throughput considerations is aligned with reliability-oriented metrics. These observations highlight that achieving favorable trade-offs between throughput, energy efficiency, and reliability does not require combining multiple heuristic metrics. Instead, the same routing structure emerges independently from different network-wide considerations, reinforcing the fundamental role of spatial reuse and link geometry in large-scale distributed wireless networks.

However, further refinements are possible to improve load balancing and Quality-of-Service (QoS) performance. The routing structure derived above focuses on maximizing aggregate network throughput and does not explicitly account for instantaneous traffic conditions, which may lead to congestion on heavily utilized links. To incorporate traffic awareness, we introduce the link utilization factor u_k, defined as the ratio of the occupied queue capacity of link k to its maximum queue capacity. This yields traffic-aware routing costs such as $r_k^2/(1-u_k)$ or $1/(h_k(1-u_k))$, which penalize highly congested links and encourage traffic redistribution. These modified metrics do not alter the underlying routing structure derived from throughput considerations but improve load balancing under dynamic traffic conditions. In addition, minimizing $\sum_k r_k^2$ alone may favor excessively short hops, leading to unnecessary increases in hop count without proportional throughput gains. To mitigate this effect, we introduce a fixed offset r_0 and consider $(r_k + r_0)^2$, which assigns a non-zero cost to very short links. This prevents overly fragmented routes and promotes a more balanced trade-off between hop count and spatial reuse. An analogous refinement for channel-aware metrics is obtained by replacing $1/h_k$ with $1/\min(h_k, h_0)$, where h_0 acts as a lower bound on the effective channel gain. As a result, the refined routing metrics evaluated in the subsequent section are: (1) $r_k^2/(1-u_k)$, (2) $1/(h_k(1-u_k))$, (3) $(r_k + r_0)^2/(1-u_k)$, and (4) $1/(\min(h_k, h_0)(1-u_k))$. The comparative performance of these variants is examined through simulation in the following section.

4 Simulation and analysis

To evaluate the structural properties of the proposed routing metrics, we developed a dedicated Python-based discrete-event simulator. Our goal is a systematic comparison of routing *metrics* under identical physical- and MAC-layer assumptions. Although a large number of routing metrics have been proposed for MANETs and VANETs [17], many of them rely on complex measurements, frequent information exchange, or high computational and memory overhead. Such requirements significantly limit their applicability in networks with thousands to millions of nodes. Thus, we focus on metrics that are viable in massive-scale multi-hop networks. For this reason, we compare the proposed metrics against each other and against the hop-count metric, which serves as a baseline. Hop count is selected not for efficiency, but for practicality and widespread use in large-scale distributed wireless networks [2, 12, 13]. Its simplicity enables efficient cost measurement, low-overhead information dissemination, scalable route computation, and minimal memory usage, making it one of the few routing metrics that can realistically scale to networks with millions of nodes. In contrast to many existing approaches, the proposed routing metrics are explicitly designed to preserve these scalability properties. The r^2 metric relies only on link-length information, which can be obtained from node locations (e.g., via GPS) and broadcast locally. Link utilization is measured locally at each node and exchanged only among neighbors, while channel gain can be estimated through lightweight broadcast reference signals. These operations introduce no additional protocol complexity beyond that required for hop count, resulting in comparable control overhead and memory requirements. Accordingly, we evaluate the following routing metrics:

1. Hop count with utilization: $1/(1-u_k)$,
2. Link-length squared with utilization: $r_k^2/(1-u_k)$,
3. Inverse channel gain with utilization: $1/(h_k(1-u_k))$,
4. Link-length squared with offset and utilization: $(r_k + r_0)^2/(1-u_k)$,
5. Inverse channel gain with threshold and utilization: $1/(\min(h_k, h_0)(1-u_k))$.

All routing metrics are evaluated within the same routing algorithm using *shortest-path* computation. In the current simulator, route computation is performed in a centralized manner, where a single processing entity has access to global network information and computes routes for all nodes. As a result, the simulated network size is limited to a few thousand nodes. In practice, maintaining flat routing tables and performing route computation for networks with millions of nodes is not scalable;

addressing this limitation requires hierarchical routing mechanisms or the use of geographic information. Designing and implementing such approaches in an efficient and scalable manner introduces additional challenges, which are beyond the scope of this work and constitute an important direction for future research. Nevertheless, even at the scale considered here, the simulations are sufficient to reveal the fundamental structural properties of the proposed metrics. These properties—rooted in spatial reuse and energy-efficient routing—are intrinsic to the metric design and are expected to persist, and become more pronounced, as network size increases. As a next step, these routing metrics can be integrated into scalable routing architectures that explicitly address large-scale implementation constraints, consistent with the ultimate objective of supporting massive distributed networks with millions of devices. Moreover, we do not explicitly consider node mobility in this study. In general, mobility does not inherently degrade routing efficiency provided that routing nodes receive timely updates of relevant network information, although this typically incurs additional control overhead and more frequent route recomputation. In our setting, this effect is expected to be limited. Although nodes are assumed static, the routing process is traffic-aware and continuously adapts to changes in link utilization. Consequently, routing decisions respond to dynamic traffic conditions that often evolve on a faster time scale than node mobility, allowing the simulations to capture representative—and in some cases more demanding— network dynamics without additional modeling complexity.

Consequently, the network consists of $N = 2000$ nodes randomly distributed according to a uniform spatial distribution with density $1/30^2$ nodes/m^2, covering approximately 1.8 km^2. P2P communication pairs are generated according to a distance-dependent power-law interaction model with exponent 3.05, consistent with empirical human interaction statistics [3, 13]. Each established P2P connection generates packets according to a Poisson process with rate 50 packets/s and a fixed packet size of 1000 bits. The maximum queue capacity per link is 40 packets. The wireless channel model incorporates large-scale path loss, log-normal shadow fading, and small-scale Rayleigh fading. Path loss is modeled as

$$\mathrm{PL}_{\mathrm{dB}} = \alpha \log(d) + 20 \log\left(\frac{4\pi f}{c}\right) - G_r - G_t + X_\sigma,$$

where the carrier frequency is $f = 2.4$ GHz, the path-loss exponent is $\alpha = 3.7$, the shadow fading standard deviation is $\sigma = 8$ dB, and omnidirectional antennas are assumed. The channel gain is given by $h = 10^{-\mathrm{PL}/10} Y$, where Y denotes Rayleigh fading with unit variance. The noise power spectral density is -173.8 dBm/Hz, and the maximum transmission range is set to $30(\sqrt{\log N} + 2)$ meters. Interference management is captured using a protocol-based interference model with reservation parameter $\Delta = 1.2$. The total bandwidth of 40 MHz is divided into 200 subchannels to enable spatial reuse under interference constraints. Links with non-empty queues contend for subchannels, and scheduling is performed in a distributed manner by prioritizing links with larger queue backlogs, based on locally available queue utilization information exchanged among neighboring nodes. The transmit power on each subchannel is selected to satisfy a target SNR of 20 dB when feasible, subject to a maximum power constraint of 50 mW. All simulations are conducted over 5000 time slots, each of duration 0.1 ms. The routing metric offset is set to $r_0 = 15$ m, and the channel-gain threshold h_0 corresponds to the deterministic channel gain at $r_0 = 20$ m.

As a primary indicator of the proposed routing metrics' performance, we examined the total network transmission rate, defined as the sum of all active link capacities per time slot across all routing metrics, depicted in Fig. 1. This summation of link capacities, more than anything else, indicates the potential of *spatial resource reuse* that every routing metric provides. As shown in Fig. 1, each of the four proposed metrics significantly outperforms the minimum hop count metric—by a considerable margin—highlighting the effectiveness of the proposed methods in avoiding the greedy selection of the longest possible hops, which tend to reduce resource reuse. This distinction is also observable, though to a lesser extent, for the link length square with offset and the channel gain with minimum threshold metrics, which help prevent the selection of extremely short links that can also limit resource reuse. The results in Fig. 1 demonstrate that the choice of routing metric, though fundamentally a network layer parameter, has a substantial impact on optimizing throughput at the MAC layer. In other words, activating sets of links—particularly shorter links with favorable channel gain, which are also more reliable—maximizes resource reuse by utilizing subchannels multiple times within each slot.

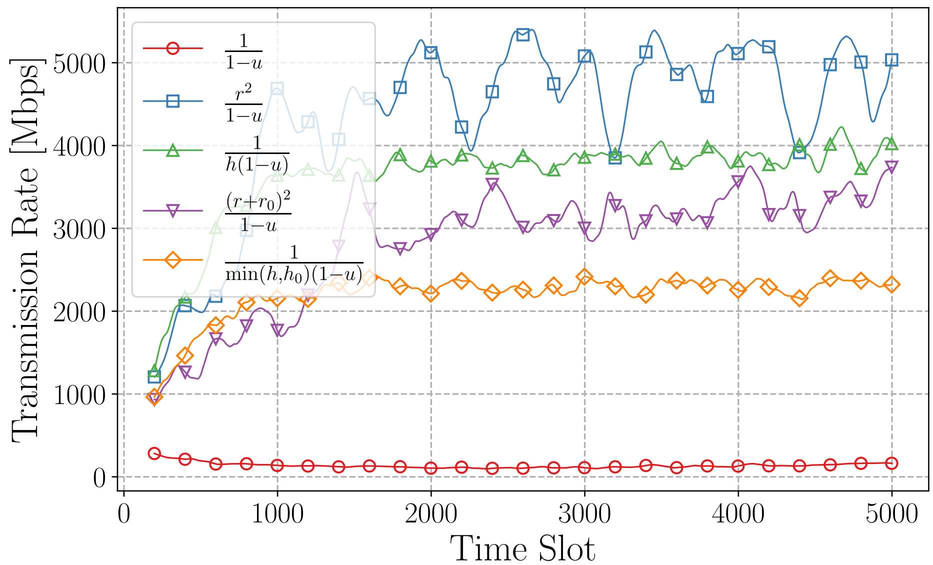

Figure 1: Total network transmission rate, calculated as the sum of all active link capacities in each time slot.

In Fig. 2, we present the distribution of link length squares selected by different routing metrics, which implies the *space occupied by each active link*. The results indicate that our proposed metrics tend to avoid selecting longer links whenever possible. In contrast, under the hop count metric, the distribution naturally extends toward the maximum transmission range, as expected. This distinction is not only evident in the variation of transmission ranges for a given network size but is also significant because the expected transmission range for all our metrics *does not scale* with the maximum transmission range or network size—the frequency of longer links rapidly decreases as their length increases. This demonstrates that, with appropriately designed routing metrics, the inherent randomness of node positions and their impact on network capacity can be effectively managed. As a result, even though the maximum transmission range scales as $\Theta(\sqrt{\ln n})$, see Section 2, the overall transmission range $r(n)$ can remain bounded. Furthermore, while the routing metric based on channel gain generally aligns with the link length square metric at a large scale, its distribution differs slightly due to the independent effects of shadow fading and Rayleigh fading in link selection by the inverse channel gain metrics.

As the *primary throughput indicator*, in Fig. 3, we present the ratio of P2P data successfully delivered to destination nodes to the total data injected by all source nodes, with an average P2P rate of 100 Mbps. The results show that while the minimum hop count algorithm delivers only a fraction of the injected data—with the remainder accumulating in network queues—all four proposed metrics can deliver data at rates multiple times higher than the minimum hop count method. Interestingly, the link length square with offset and the channel gain with threshold metrics, despite having a lower total transmission range, see Fig. 1, outperform the other methods in terms of the end-to-end delivery ratio. This can be attributed to two factors. First, the offset-length metric reduces the number of hops required, thereby decreasing retransmission times and circulating packets within the network. Second, it provides improved load distribution. Unlike metrics without an offset, which may repeatedly select the same set of links and thereby create power and traffic bottlenecks, the offset-based approach promotes more balanced route selection. This helps distribute traffic more evenly across the network, avoids persistent congestion along specific paths, and enables more widespread spatial resource reuse pattern. As a result, data spends less time in network queues and is delivered more quickly, leading to reduced latency and a higher delivery ratio, as illustrated by the results in Fig. 4. Furthermore,

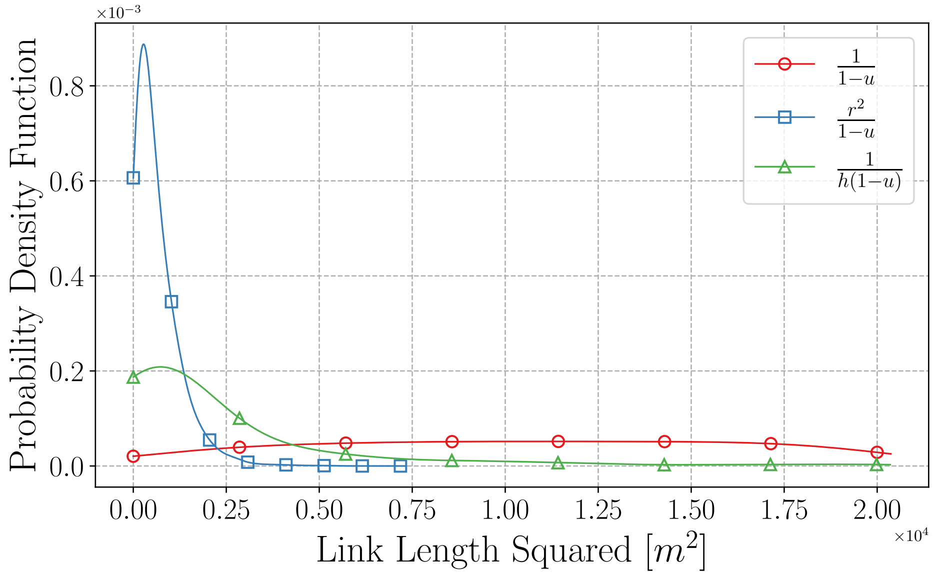

Figure 2: Distribution of squared link lengths for all active links, smoothed using Gaussian kernel density estimation.

as mentioned in Theorem 1, maximizing P2P delivered traffic requires maintaining nearly equal link capacities. If only one link has a lower capacity, it becomes a bottleneck for the entire flow. Since the link length square metric does not account for small-scale path loss due to fading, it may occasionally select short links that nonetheless experience significant fading-induced attenuation. Maintaining a fixed SNR on such links can result in excessive cross-interference with other active links and lead to uneven link capacities, ultimately wasting the excess capacity of high-quality links in P2P data delivery.

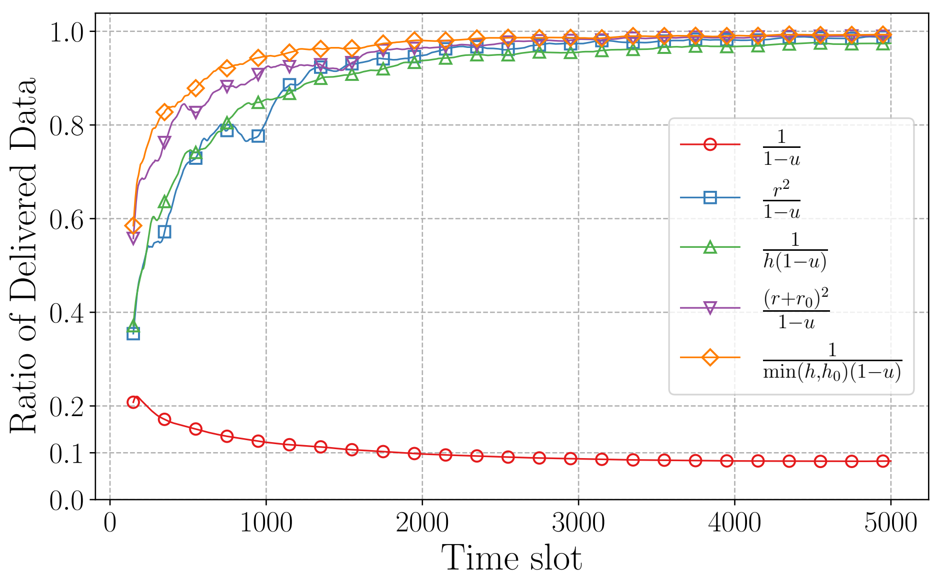

Figure 3: Ratio of total data delivered to all P2P destinations to total injected data per slot at total traffic arrival rate 100 **Mbps.**

As shown in Fig. 4, which presents the maximum queue length (in packets) across all network links, incorporating the utilization factor into routing metrics—especially through the offset and threshold methods—proves effective in achieving balanced load distribution. These offset metrics, *by design*, maintain a significantly lower maximum queue length compared to the other two methods, indicating more balanced load distribution across the network. This improvement results from their ability to leverage the diversity of the network topology and establish parallel transmission paths. Furthermore, offset methods reduce the number of hops and packets spend less time in the network, which translates to shorter queues and lower overall queuing delays. Moreover, as shown in Fig. 4, all four proposed metrics maintain a nearly constant maximum queue length, demonstrating that the utilization factor $1/(1-u)$ effectively balances network load, *by feedback*. Despite the highly complex topology—with 2000 nodes and potentially millions of links generating unpredictable traffic patterns—the simple yet robust feedback provided by the utilization metric prevents queues from reaching full capacity. This minimizes packet drops and retransmissions. This effectiveness stems from the distributed nature of the network: with many simultaneous traffic demands, there will be an even greater number of possible paths (the number of possible paths increases as the network expands), and consequently, load distribution occurs naturally. In distributed networks, even a basic traffic feedback like utilization enables efficient rerouting and load sharing, akin to how water in a wide river(where its width is always proportional to flow demand) easily disperses bursts of new flow. Thus, while large-scale distributed networking introduces significant complexity, it simultaneously offers new opportunities for efficient, scalable traffic management that are unavailable in centralized systems.

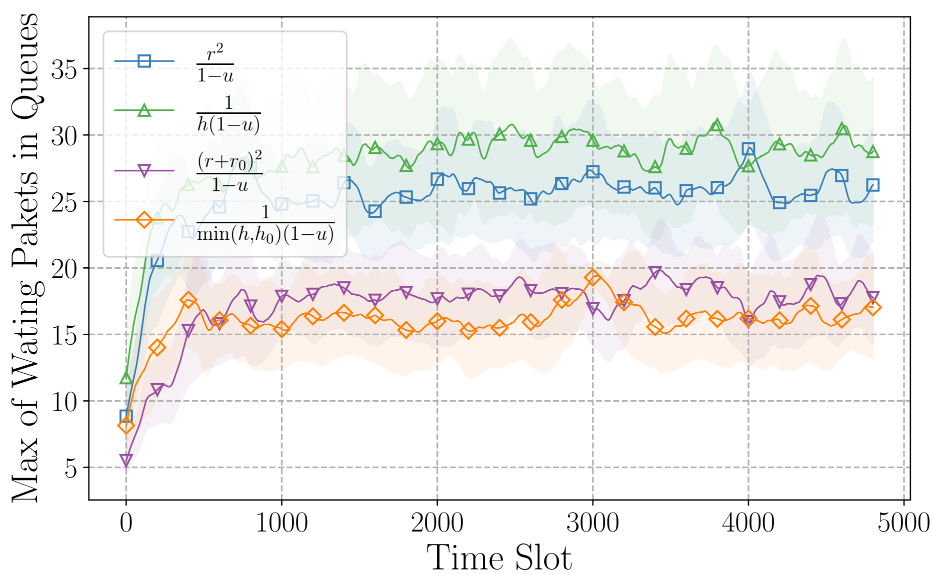

Figure 4: Maximum packet queue length across all links and its standard deviation (shaded) at link queue capacity 40.

Fig. 5 compares the distribution of P2P delay among delivered packets between four proposed metrics. Again, as shown in Fig. 5, the $1/(\min(h, h_0)(1-u))$ metric enables faster packet delivery compared to non-offset methods, primarily due to reduced queuing delays and a lower number of hops. The similar distribution patterns observed across all metrics reflect the influence of the underlying power-law parameter, which shapes the physical P2P connection lengths and, consequently, the distributions of hop count and end-to-end delay. Moreover, these results highlight the efficiency of the routing metrics: even in a fully decentralized network with $N = 2000$ nodes (representative of a small town population), operating without infrastructure and under limited frequency resources (40 MHz), it is possible to achieve robust end-to-end distributed communication. The overall end-to-end delay values are presented in Table 1, demonstrating that the observed quality of service—specifically, an end-to-end delay of approximately 50 ms—is ideal even for online video streaming. This performance is comparable to that achieved in 5G networks, which typically exhibit end-to-end delays in the range of 30 to 35 ms [16].

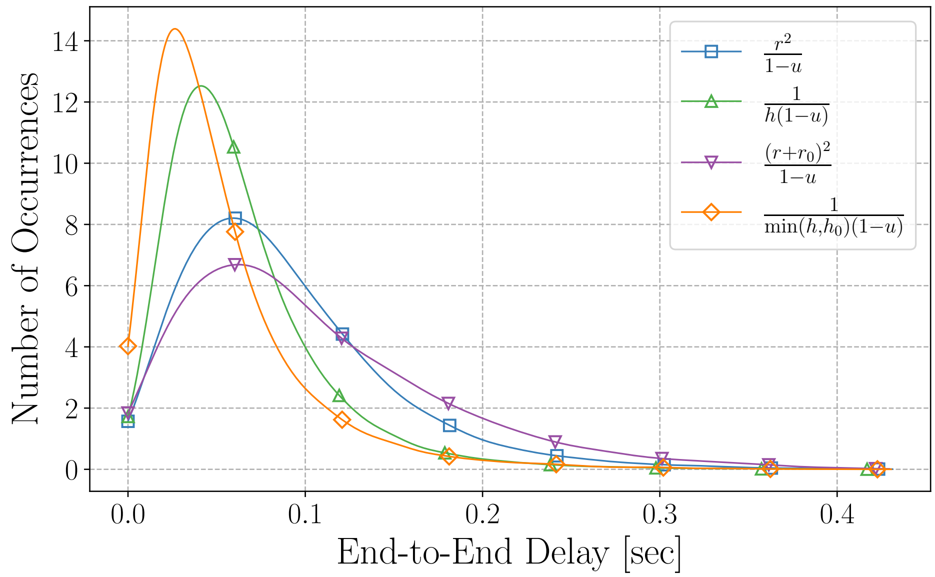

Figure 5: Distribution of end-to-end P2P delay for delivered packets; the vertical axis shows packet frequency.

In Fig. 6, we present the distribution of power consumption for all routing metrics. All four proposed routing metrics not only outperform the hop count metric in terms of power consumption but also deliver significantly higher traffic volumes, as shown in Fig. 3. This improvement results from the controlled selection of link lengths—and, consequently, channel gains—in our proposed metrics (Fig. 2), in contrast to hop count routing, which often selects longer links that consume more power. However, a closer examination of Fig. 6 underscores the importance of practical routing metrics. Although the link length square metric typically selects much shorter links than the inverse channel gain metric, as shown in Fig. 2, it does not necessarily achieve better channel conditions or lower power consumption, since it ignores fading effects. In contrast, the channel gain metric captures the cumulative impact of all key factors—including link length and fading—leading to a selection of links that require, on average, nearly 20 dB less power, which is a remarkably significant improvement. For context, the average power consumption in the $1/\min(h_k, h_0)(1-u)$ metric not only delivers the best end-to-end traffic rate (Fig. 3) and minimum delay (Fig. 5), but also stays below an upper bound of 50 μW, as presented in Table 1. With 2000 nodes at an aggregate P2P rate of 100 Mbps, the total energy required to deliver one bit is $2000 \times 4.1 \times 10^{-5}/10^8 = 0.82\,\text{nJ/bit}$. This value is dramatically lower than even the best reported scenarios for 5G downlink (20 nJ/bit [23]) and LTE (70 nJ/bit [23]). In another perspective, the average power consumption for the $1/\min(h_k, h_0)(1-u)$ metric is 4.1×10^{-5} W, compared to 3.3×10^{-3} W for hop count metric, while the corresponding data delivery ratio is around 0.08 (see Fig. 3). Consequently, the power efficiency of the $1/\min(h_k, h_0)(1-u)$ metric for delivering the same amount of data exceeds that of hop count routing by roughly 1000 times. In practical terms, this translates to an energy consumption of approximately 0.27 mAh (at 3.7 V) per day per node, which is less than 0.1% of a typical smartphone's daily battery capacity.

Table 1: Overall Performance comparison of routing metrics.

Routing Metric	Avg. Power Consumption (mW)	Avg. End-to-end Delay (ms)	Delay Standard Deviation (ms)
$1/(1-u)$	3.3	-	-
$r^2/(1-u)$	1.6	88.2	58.3
$1/(h(1-u))$	$\mathbf{3}\times10^{-2}$	63.6	**42.2**
$(r+r_0)^2/(1-u)$	2	103	71
$1/(\min(h,h_0)(1-u))$	4.1×10^{-2}	**52.8**	45.2

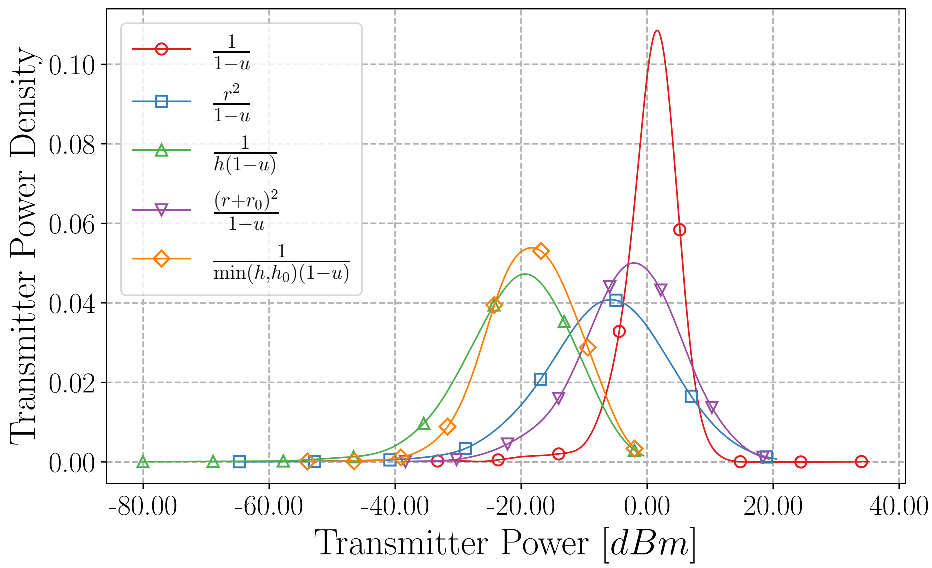

Figure 6: Distribution of per-node power consumption, averaged over time.

Therefore, the $1/\min(h_k, h_0)(1-u)$ metric not only maximizes P2P throughput, but also operates as an *exceptionally energy-efficient* routing metric. The physical rationale for this remarkable efficiency can be likened to the concept of channel diversity in Multi Input Multi Output (MIMO) systems—yet here, the diversity gain emerges at the network level. In distributed multi-hop communication, multiple alternative paths can connect source and destination pairs, and minimizing the sum of inverses of channel gains along a path naturally prioritizes links with superior conditions. Due to the inherent randomness of wireless fading, this routing approach harnesses diversity, frequently allowing higher-quality links to be chosen compared to distance-based metrics that do not account for channel variability. Thus, the connectivity in distributed wireless networks essentially forms a massive ensemble of alternative paths, providing inherent opportunities for extremely low power consumption and robust, sustainable communication—a property unique to distributed wireless architectures. Conversely, in centralized architectures such as 4G and 5G, the presence of fixed access points forces users to select from a limited set of routing paths, preventing them from leveraging the inherent path diversity of a distributed network. Moreover, since all users must connect to one of these few access points, the resulting spatial correlation significantly increases the likelihood of cross-interference, thereby limiting the potential for resource reuse. In contrast, a distributed network allows each P2P communication pair to independently and unconditionally select its own optimal path from a vast set of possibilities. This flexibility minimizes both cross-interference and power consumption. As a result, even with simple omnidirectional antennas, distributed networks can achieve substantially higher energy efficiency compared to centralized systems like 4G and 5G, despite the latter's advanced physical-layer technologies.

Overall, these simulations—conducted under realistic network settings and accounting for multi-layer practical aspects—demonstrate the superiority and performance of structural routing metrics, not only in theory but also in practice. Both the channel gain and link length square metrics operate very efficiently in large-scale, complex distributed wireless networks from the most fundamental aspects of distributed wireless networks, including P2P data delivery, energy efficiency, reliability, latency, and scalability. However, for practical urban deployments, the channel gain metric proves to be more accurate, convenient, and extremely energy efficient. Indeed, the link-length-square metric directly yields the theoretical optimal solution for ideal network environments, whereas in non-line-of-sight (NLOS) wireless environments, link length alone provides only partial information about the underlying channel conditions. In contrast, the channel gain metric not only approximates the spatial occupancy of each link but also incorporates comprehensive information for optimizing power consumption related to channel fading. In other words, channel gain is a more robust and informative metric, as it accounts for both the physical length of the link and environmental factors such as fading. This makes channel gain a more effective choice for routing decisions in practical urban wireless networks. However, in free-space environments, the link length square metric may perform comparably to the channel gain metric.

5 Conclusion and future work

In this work, we analytically derived optimal routing metrics for maximizing P2P traffic volume and enabling scalable distributed wireless networks. Notably, these metrics also yield optimal solutions for minimizing power consumption and ensuring reliable paths, resulting in a unified multi-objective metric. Such efficient metrics play a critical role in deploying large-scale distributed solutions from all fundamental perspectives, including throughput, reliability, delay, energy efficiency, and scalability. Our simulations further confirm that the proposed methods exceptionally outperform the conventional minimum hop count routing approach in all aforementioned aspects. This work highlights that many limitations of classical hop-count-based routing stem not from protocol design, but from metric structure. By grounding routing metrics in network-wide resource constraints rather than local path length alone, scalable multi-hop communication becomes feasible even in interference-limited wireless environments.

In future work, these routing strategies alongside with their network overhead could be evaluated under more diverse network scenarios, including mobility. Additionally, developing a version of this metric that does not rely on routing tables or link-level state information—thus supporting true scalability—would be an interesting direction for enabling city-scale distributed network deployments.

References

[1] Bahador Amiri, Hamid R Sadjadpour, and Jose Joaquin Garcia-Luna-Aceves. Outage optimum routing for wireless networks. In 2011 7th International Wireless Communications and Mobile Computing Conference, pages 1–6, 2011.

[2] Bita Azimdoost, Hamid R Sadjadpour, and JJ Garcia-Luna-Aceves. Capacity of wireless networks with social behavior. IEEE Transactions on Wireless Communications, 12(1):60–69, 2012.

[3] Lars Backstrom, Eric Sun, and Cameron Marlow. Find me if you can: improving geographical prediction with social and spatial proximity. In Proceedings of the 19th international conference on World wide web, pages 61–70, 2010.

[4] C Balasubramanian and R Lal Raja Singh. Iot based energy management in smart grid under price based demand response based on hybrid fho-rernn approach. Applied Energy, 361:122851, 2024.

[5] Mohammed Banafaa, Ibraheem Shayea, Jafri Din, Marwan Hadri Azmi, Abdulaziz Alashbi, Yousef Ibrahim Daradkeh, and Abdulraqeb Alhammadi. 6g mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities. Alexandria Engineering Journal, 2022.

[6] Simon Elias Bibri, Alahi Alexandre, Ayyoob Sharifi, and John Krogstie. Environmentally sustainable smart cities and their converging ai, iot, and big data technologies and solutions: an integrated approach to an extensive literature review. Energy Informatics, 6(1):9, 2023.

[7] Douglas SJ De Couto, Daniel Aguayo, John Bicket, and Robert Morris. A high-throughput path metric for multi-hop wireless routing. In Proceedings of the 9th annual international conference on Mobile computing and networking, pages 134–146, 2003.

[8] Hanqiang Deng, Jian Huang, Quan Liu, Tuo Zhao, Cong Zhou, and Jialong Gao. A distributed collaborative allocation method of reconnaissance and strike tasks for heterogeneous uavs. Drones, 7(2):138, 2023.

[9] Rohit Dube, Cynthia D Rais, Kuang-Yeh Wang, and Satish K Tripathi. Signal stability-based adaptive routing (ssa) for ad hoc mobile networks. IEEE Personal Communications, 4(1):36–45, 1997.

[10] Matej Fitoš, Juraj Ďuďák, Gabriel Gašpar, Juraj Machaj, and Peter Brida. Leo: An innovative metric for energy-efficient routing in wireless sensor networks. Internet of Things, 29:101472, 2025.

[11] Andrea Goldsmith, Michelle Effros, Ralf Koetter, Muriel Médard, Asu Ozdaglar, and Lizhong Zheng. Beyond shannon: the quest for fundamental performance limits of wireless ad hoc networks. IEEE Communications Magazine, 49(5):195–205, 2011.

[12] Piyush Gupta and Panganmala R Kumar. The capacity of wireless networks. IEEE Transactions on information theory, 46(2):388–404, 2000.

[13] Reza Khalvandi and Brunilde Sansò. Revisiting scalability of distributed wireless networks: A multi-hop communication perspective. IEEE Transactions on Network Science and Engineering, pages 1–21, 2025.

[14] Sung-Ju Lee and Mario Gerla. Load-aware routing in ad hoc wireless networks. Computer Communications, 24(15-16):1577–1588, 2001.

[15] Alex Murray, Dennie Kim, and Jordan Combs. The promise of a decentralized internet: What is web3 and how can firms prepare? Business horizons, 66(2):191–202, 2023.

[16] AA OLUWALEKE. Performance metrics evaluation and technical comparative analysis of 5g and fibre optics networks technology for real-time video streaming. Journal of Engineering Research and Development, 2025.

[17] Vu Khanh Quy, Nguyen Tien Ban, Vi Hoai Nam, Dao Minh Tuan, and Nguyen Dinh Han. Survey of recent routing metrics and protocols for mobile ad-hoc networks. J. Commun., 14(2):110–120, 2019.

[18] Yiftach Richter and Itsik Bergel. Optimal and suboptimal routing based on partial csi in random ad-hoc networks. IEEE Transactions on Wireless Communications, 17(4):2815–2826, 2018.

[19] Yiftach Richter and Itsik Bergel. Opportunistic routing based on partial csi in mimo random ad-hoc networks. EURASIP Journal on Wireless Communications and Networking, 2021(1):131, 2021.

[20] Suresh Singh, Mike Woo, and C.S. Raghavendra. Power-aware routing in mobile ad hoc networks. Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom), pages 181–190, 1998.

[21] C-K Toh. Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks. IEEE Communications Magazine, 39(6):138–147, 2001.

[22] Zhiqing Wei, Huici Wu, Xin Yuan, Sai Huang, and Zhiyong Feng. Achievable capacity scaling laws of three-dimensional wireless social networks. IEEE Transactions on Vehicular Technology, 67(3):2671–2685, 2018.

[23] Dongzhu Xu, Ao Li, Xiaojiang Guo, Jiacheng Liu, Yuefeng Zhang, Xinyu Xie, Yu Wu, Xuanzhe Zhang, Kai Liu, Zhi-Li Liu, and Yunxin Liu. Understanding operational 5g: A first measurement study on its coverage, performance and energy consumption. In Proceedings of the ACM SIGCOMM 2020 Conference, page 479–494, 2020.