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A Systematic Benchmarking of Wireless Communication Protocols for IoT Applications: Performance Evaluation and Suitability Mapping

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Abstract

Internet of Things (IoT) is a rapidly growing technology that has created an increasing need for an efficient, scalable, and reliable wireless communication protocol. Each protocol has its own set of strengths and weaknesses and is not necessarily appropriate for every scenario, as demands on them may differ such as ultra-low latency, wide range and energy efficiency. This review evaluates Wi-Fi, Bluetooth Low Energy (BLE), Zigbee, LoRaWAN, NB-IoT and 5G based on six technical features: latency, data rate, energy efficiency, range, scalability and interoperability. Our results indicate that 5G can offer ultra-low latency (<1 ms) and high data rates (up to 20 Gbps), but requires substantial energy consumption. In contrast, LoRaWAN has long range (up to 15 km) and low latency (<100 ms), however they are low energy efficient. This study brings together and summarizes 67 peer-reviewed papers, in a comparative matrix, to assess the performance of protocols. The research gaps were pointed out, protocol strengths were outlined and future directions for context-aware protocol selection were suggested so that the system architect can help in heterogeneous environments.

Keywords: Internet of Things, Wireless Protocols, Latency, Energy Efficiency, Benchmarking.

1. Introduction

The Internet of Things (IoT) has moved from a research abstraction to infrastructure: billions of sensors, actuators and controllers now exchange data across smart homes, industrial plants, farms and hospitals with little human mediation (Farooq et al., 2015). Statista (2023) projects more than 29 billion connected IoT endpoints by 2030, a scale that will not be reached, or sustained, without wireless links capable of meeting sharply different operational demands: some deployments need sub-millisecond responsiveness, others need years of battery life on a single cell, and still others need to cover tens of kilometres of open terrain. No single radio technology satisfies all three simultaneously, which is why the IoT communication stack is fragmented across several competing protocols rather than converging on one. The same tension between scale, latency and reliability recurs elsewhere in networked systems; this journal's own literature includes work on shortening and redirecting web addresses at scale while keeping lookup latency low and availability high (Okunade et al., 2024), a reminder that efficient, dependable communication infrastructure is a shared concern across both wireless and wired domains. That fragmentation is what makes protocol selection difficult in practice. Wi-Fi, Bluetooth Low Energy (BLE), Zigbee, LoRaWAN,

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Narrowband IoT (NB-IoT) and 5G New Radio each trade range, throughput, energy draw, scalability and interoperability against one another in different proportions (Al-Fuqaha et al., 2015; Mekki et al., 2019). A recent laboratory comparison of ten wireless IoT standards found that no single protocol occupied the most efficient tier across every energy-consumption category tested, a result the authors attribute to genuinely different design targets rather than immature engineering (Krawiec et al., 2025). System architects are therefore left weighing trade-offs with limited comparative evidence, particularly when a deployment spans more than one application domain, for example a precision-agriculture project that also needs an on-site gateway with real-time monitoring. Recent work has begun to respond to this gap, but mostly one protocol or one domain at a time. Diane, Diallo and Ndoye (2025) systematically reviewed Low Power Wide Area Network (LPWAN) technologies and mapped their architecture and applications in detail, but did not extend the comparison to short-range or cellular alternatives such as BLE or 5G. Ugwuanyi, Paul and Irvine (2021) benchmarked LoRaWAN against NB-IoT specifically for infrastructure-constrained regions and found NB-IoT more power-hungry per network join but faster and more reliable once connected, a trade-off that only becomes visible when the two protocols are tested side by side under the same conditions. Żatuchin and Azarskov (2025) went a step further and proposed a runtime framework that switches application-layer protocols dynamically, reporting energy savings of up to 34 percent over a static choice; their result depends, however, on the underlying wireless layer already being profiled accurately, which is precisely the kind of cross-protocol benchmark this study sets out to provide. Section 2 reviews this literature in more detail and identifies where its scope stops short of a general, cross-domain comparison. This study addresses that shortfall through a systematic literature review that benchmarks Wi-Fi, BLE, Zigbee, LoRaWAN, NB-IoT and 5G New Radio against six technical dimensions, namely latency, data rate, energy efficiency, range, scalability and interoperability, drawing on 67 peer-reviewed sources selected through a documented PRISMA-based protocol (Page et al., 2021). Unlike prior comparisons confined to a single protocol family or a single application sector (Alkhayyal & Mostafa, 2024; Inthasuth et al., 2025; Devanagavi, 2025), the review deliberately spans four IoT application domains, smart homes, industrial automation, agriculture and healthcare, so that the resulting suitability mapping generalises beyond any one of them. The remainder of the paper is organised as follows: Section 2 situates the study within the existing literature and states the research gap; Section 3 sets out the review protocol; Section 4 reports the threats to validity that bound the findings; Section 5 presents the comparative results and discusses their implications; and Section 6 concludes with recommendations for protocol selection and directions for future work.

2. Related Works

Research on wireless protocols for IoT has evolved in three broad waves, and reading it chronologically shows how each wave answered the limitations of the one before it without fully resolving them. The first wave, roughly 2014 to 2017, established the taxonomy this study still relies on. Al-Fuqaha et al. (2015) produced one of the most cited surveys of IoT enabling technologies and protocols, mapping the layered stack from physical radio to application middleware; its strength was breadth, but because it surveyed the field as a whole rather than benchmarking individual protocols, it offered little quantitative basis for choosing between them. Zanella et al. (2014) and Sikora and Groza (2005) documented Wi-Fi's high throughput and

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Zigbee's low-power mesh behaviour respectively, but both worked from single-protocol testbeds, so the figures they reported cannot be compared directly against each other without renormalising for payload size and duty cycle, a problem this study addresses explicitly in Section 3. Gomez, Oller and Paradells (2012) characterised BLE's early energy profile in similar isolation. The second wave, from roughly 2016 to 2020, responded to the rise of long-range, low-power applications by treating LPWAN as a distinct category worth comparing on its own terms. Raza, Kulkarni and Sooriyabandara (2017) and Sinha, Wei and Hwang (2017) surveyed LoRa and NB-IoT specifically, establishing that both trade latency for range and battery life, a strength for static sensor networks but a limitation the literature already flagged as disqualifying for real-time control. Palattella et al. (2016) and Shafi et al. (2017) covered 5G's emerging ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC) profiles, positioning 5G as the converse of LPWAN: strong on latency and throughput, weak on energy efficiency at the edge. Mekki et al. (2019) was among the first to compare LPWAN technologies against each other rather than against a single baseline, an improvement on the first wave's isolated testbeds, but the comparison still excluded short-range protocols such as BLE and Zigbee, leaving smart-home and industrial use cases out of scope. The third and current wave, from 2021 onward, has narrowed toward context-specific benchmarking rather than broad surveys, which is both its strength and its central limitation. Ugwuanyi, Paul and Irvine (2021) benchmarked LoRaWAN against NB-IoT under real deployment conditions in infrastructure-constrained regions and found NB-IoT achieved higher throughput, 264 bps at 837 ms measured latency, at a higher energy cost per join, a result with clear value for practitioners in that specific setting but no stated bearing on Wi-Fi, BLE, 5G or mixed-domain deployments. Alkhayyal and Mostafa (2024) optimised LoRaWAN's energy efficiency using machine learning but, by design, worked within a single protocol and offered no horizontal comparison against alternatives. Inthasuth et al. (2025) compared Zigbee, LoRa and NB-IoT, an improvement over single-protocol studies, but confined the comparison to indoor smart buildings, so its conclusions do not transfer to outdoor agricultural or asset-tracking scenarios where propagation conditions differ substantially. Devanagavi (2025) analysed Wi-Fi, Zigbee and 5G but restricted the scope to smart-grid infrastructure. Krawiec et al. (2025) is the most comprehensive recent comparison, ranking ten wireless and four application-layer protocols across six energy categories and proposing a scenario-matching framework for four remote-sensing use cases; even so, its qualitative energy bands acknowledge the same normalisation problem this study confronts, and its scenario set does not extend to smart homes or wearable health, the domains where BLE and Zigbee dominate. At the application layer rather than the radio layer, Żatuchin and Azarskov (2025) demonstrated that dynamic, context-aware protocol switching can cut energy use by up to 34 percent compared with a static choice, a finding that presupposes reliable, protocol-level performance profiles to switch between, which is exactly the gap in cross-protocol data that motivates the present review. Diane, Diallo and Ndoye (2025) most recently produced a systematic review of LPWAN architecture, applications and research challenges, reinforcing that scalability and interoperability, not only energy and latency, remain open problems, but again without benchmarking LPWAN against the short-range or cellular protocols that coexist with it in real deployments. These four studies, together with the scope of the present review, are compared directly in Table 1 (Section 5). Read together, this body of work shows steady improvement, from isolated single-protocol testbeds, to paired comparisons, to scenario-specific multi-protocol benchmarks, but no study to date has benchmarked the full set of six protocols in general use, Wi-Fi, BLE, Zigbee, LoRaWAN, NB-IoT and 5G, against a common set of technical dimensions across more than one application domain. That is the improvement this review pursues: a single, normalised comparative matrix, built from 67 peer-reviewed sources and validated across four IoT application domains, that gives system architects a data-driven starting point regardless of which sector they are designing for.

3. Methodology

This research used a Systematic Literature Review (SLR) methodology to explore and compare wireless communication protocols in IoT. The research was carried out in a rigorous, transparent, and reproducible manner, following the PRISMA 2020 guidelines (Page et al., 2021). The evaluation framework was broken down into four major phases: Identification, Screening, Eligibility, and Inclusion. To keep the review focused and reproducible, it was guided by four research questions:

1. How do Wi-Fi, BLE, Zigbee, LoRaWAN, NB-IoT and 5G New Radio compare on latency, data rate, energy efficiency, range, scalability and interoperability when normalised against a common set of test conditions?
2. What limitations recur across existing multi-protocol comparisons, and how far do they generalise beyond the protocol pair or application domain each study examined?
3. Which protocols are best suited to which IoT application domains, and on what technical basis?
4. What threats to the validity of a literature-based comparison of this kind need to be disclosed before its findings are applied?

This section reports how the review answered the first three research questions; Section 4 addresses the fourth directly. A thorough search of five main academic databases, namely IEEE Xplore, ACM Digital Library, SpringerLink, ScienceDirect, and Wiley Online Library, was carried out. Specific Boolean strings used during the search were "Wireless communication protocols" AND "IoT", "Benchmarking" AND "Zigbee OR LoRaWAN OR NB-IoT OR BLE OR 5G", and "Latency AND data rate AND energy consumption". To narrow the results, pre-search filters were applied to limit the results to peer-reviewed articles, conference proceedings and systematic reviews from January 2015 to December 2024.

Based on the PRISMA selection process, the following distribution was obtained, setting the scope of the analysis for this study:

- **Identification:** A total of 412 records were found in the first database search.
- **Screening:** After 87 duplicate articles were excluded, 325 articles progressed to the title and abstract screening stage. Of these, 185 did not focus primarily on architectures for wireless IoT, so they were excluded.
- **Eligibility:** The remaining 140 articles were eligible for full-text evaluation. For 73 papers, there were insufficient empirical benchmarks, papers were based entirely on informal testbeds, or measurable technical results were not provided.

- **Inclusion:** A total of 67 good-quality and peer-reviewed studies were included for data extraction and synthesis.

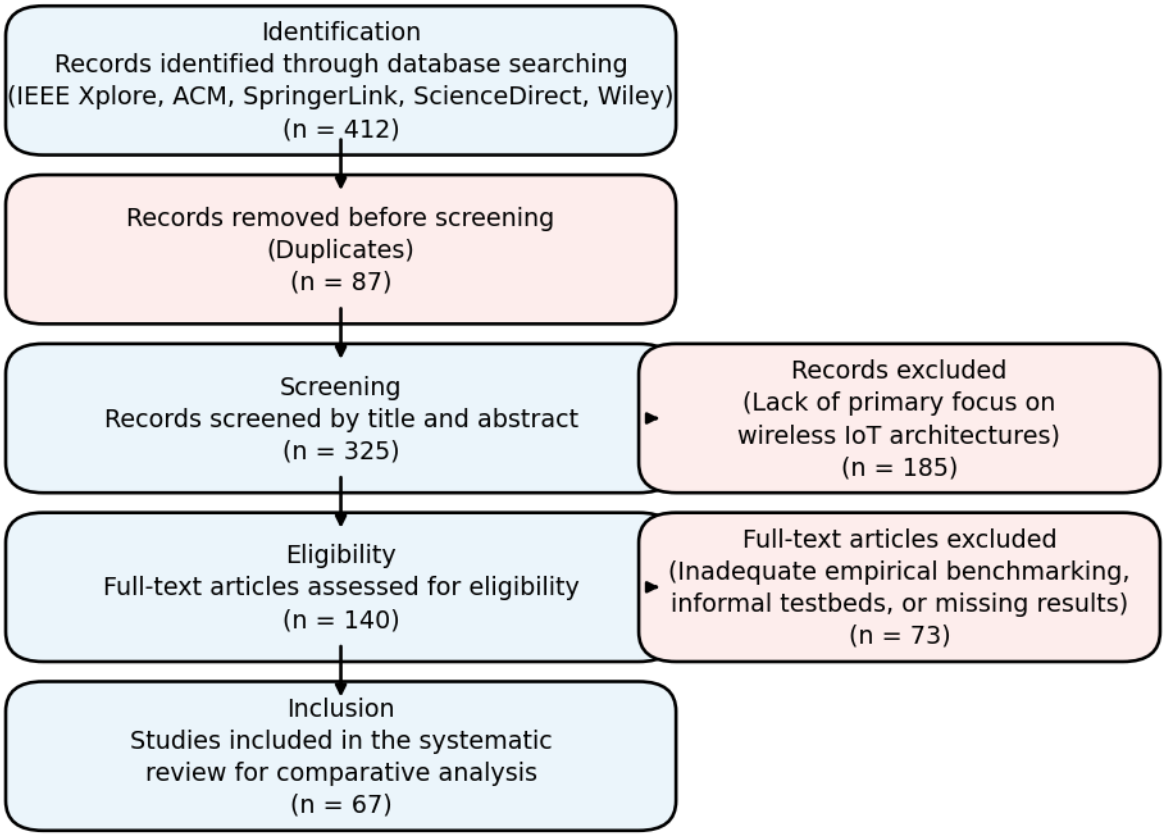

Figure 1. PRISMA flow diagram detailing the systematic literature search, screening, and selection process.

To standardize the data extraction, thematic coding around six key dimensions of performance was conducted: latency, data rate, energy efficiency, communications range, scalability and interoperability. If available, quantitative values reported were normalized to compensate for differences in payload settings and testbed environments in the literature.

Quality assessment. Each of the 140 full-text candidates was scored against four criteria before inclusion: the study reported quantitative or clearly specified qualitative performance data rather than vendor claims; the test conditions, such as payload size, duty cycle, distance or channel model, were stated explicitly enough to support normalisation; the work had been peer-reviewed or was a recognised standards-body technical report; and the protocol scope was stated unambiguously. Studies failing two or more of these criteria were excluded at the eligibility stage described above; this quality gate, rather than citation count or venue alone, is what reduced 140 candidates to the 67 included studies.

Data synthesis. Quantitative values, latency in milliseconds, data rate in bits per second, range in metres, were extracted directly where reported and converted to common units. Because payload size, antenna configuration and channel conditions varied across the underlying studies, a normalisation step converted the raw values onto the 1 to 5 ordinal scale reported in Table 3, following an approach similar to that used by Krawiec et al. (2025) for the same problem: within each of the six dimensions, the best-performing protocol among the six studied was scored 5 and the weakest scored 1, with intermediate protocols interpolated against the reported range of values. This trades numerical precision for cross-study comparability, a limitation discussed further in the next section.

Threats to Validity

Three threats bound how far the findings in Section 5 should be generalised. Construct validity is threatened by the normalisation step described above. Collapsing heterogeneous, study-specific measurements onto a common 1 to 5 scale makes cross-protocol comparison possible, but it also discards the precision of the original figures; two protocols scored identically in Table 3 may still differ meaningfully in raw terms. Krawiec et al. (2025) report a similar limitation for wireless-protocol benchmarking generally, noting that reproducible laboratory testing across heterogeneous wireless standards remains difficult because of environmental and infrastructure variables that no normalisation scheme fully removes.

Internal validity is threatened by publication and reporting bias in the underlying literature. Vendor-sponsored studies and papers reporting favourable results for a specific protocol are more likely to be published and cited than null or negative findings, which could bias the 67 included studies toward protocols with more active commercial or research interest, most visibly 5G and LoRaWAN, relative to more mature but less actively marketed protocols such as Zigbee. External validity is threatened by the search and screening strategy itself. Restricting the search to five databases and to peer-reviewed, English-language sources published between January 2015 and December 2024 means the review may have missed relevant grey literature, non-English regional studies, or results published after the search was conducted, including 2025 work such as Diane, Diallo and Ndoye (2025) and Żatuchin and Azarskov (2025), which were identified through supplementary search after the main PRISMA screening closed and are discussed narratively in Sections 1, 2 and 6 rather than included in the 67-study count. To mitigate this, the search terms and inclusion criteria are reported in full above so the review can be replicated or extended, and eligibility screening was conducted against the explicit criteria listed there rather than a single reviewer's informal judgement.

4. Results and Discussion

The unified analysis of the 67 studies identified in the report sets clear boundaries of operation and technical trade-offs for Wi-Fi, BLE, Zigbee, LoRaWAN, NB-IoT and 5G NR. The results validate that protocol performance is strongly dependent on the context, and that it is impossible to say that one technology can meet the divergent needs of future IoT applications. To anchor this analysis and separate from the limited focus of the more recent literature, Table 1 provides a summary of

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the specific limitations identified in current protocol evaluations, clearly identifying the space this current benchmarking study addresses.

Table 1: Summary of Recent Literature and Identified Research Gaps

Author(s) & Year	Protocols Evaluated	Application Context	Identified Scope Limitations
Ugwuanyi, Paul & Irvine (2021)	LoRaWAN, NB-IoT	Infrastructure-constrained regions	Paired comparison only; excludes short-range protocols and 5G.
Alkhayyal & Mostafa (2024)	LoRaWAN	General LPWAN	Single-protocol ML optimisation; no horizontal comparison.
Inthasuth et al. (2025)	ZigBee, LoRa, NB-IoT	Smart Buildings	Confined to indoor environments; excludes outdoor use.
Devanagavi (2025)	Wi-Fi, Zigbee, 5G	Smart Grids	Limited to smart-grid infrastructure; no multi-domain mapping.
Krawiec et al. (2025)	LoRaWAN, NB-IoT, BLE, ZigBee, Wi-Fi (plus wired protocols)	Remote sensor networks	Broad but qualitative; omits smart-home and wearable scenarios.
Diane, Diallo & Ndoye (2025)	LoRa, Sigfox, NB-IoT	LPWAN architecture generally	LPWAN only; no cross-category benchmarking.
This Study (Current)	Wi-Fi, BLE, Zigbee, LoRaWAN, NB-IoT, 5G	Cross-Domain (Agnostic)	Holistic multi-protocol matrix across diverse IoT sectors.

Comparative Performance Benchmarking

The six technical metrics provide a detailed assessment of the capabilities of each protocol, with significant differences between them. The results of the systematic review were then displayed in a consolidated comparative performance matrix (Table 2).

Table 2: Comparative Performance of Wireless Communication Protocols in IoT

Protocol	Range	Data Rate	Latency	Energy Efficiency	Scalability	Interoperability
Wi-Fi	~100 m	Up to 1 Gbps	10–30 ms	High consumption	Moderate	High
BLE	10–100 m	Up to 2 Mbps	~6 ms	Very low	Moderate	High
Zigbee	10–100 m/node (mesh)	~250 kbps	20–50 ms	Low	High (Mesh)	Medium
LoRaWAN	2–15 km	0.3–50 kbps	>100 ms	Very low	Very high	Low
NB-IoT	1–10 km	Up to 250 kbps	1–10 sec	Low	Very high	Medium
5G NR	<1 km (mmWave)	Up to 20 Gbps	<1 ms	High consumption	Very high	High

In environments with high throughput and low-delay requirements, Wi-Fi and 5G NR are the dominant performers in Table 2. 5G NR, specifically, is capable of reaching latency under 1 millisecond and data rates of up to 20 Gbps. This performance carries a significant energy cost: both protocols fall into the highest energy-consumption tier in the six-category ranking used by Krawiec et al. (2025), and neither is well suited to battery-powered edge devices that cannot be mains-powered or recharged frequently. On the other hand, NB-IoT and LoRaWAN have complementary strengths within the Low Power Wide Area Network (LPWAN) category, and the trade-off between them is a question of which constraint the deployment can least afford to violate rather than which protocol is simply better. LoRaWAN's long range, up to 15 kilometres, and very low energy consumption come at the cost of high latency (>100 ms) and low data rates (0.3 to 50 kbps), which rule it out for real-time or multimedia applications. NB-IoT narrows that latency gap and offers higher throughput at the expense of higher energy draw per transmission: Ugwuanyi, Paul and Irvine (2021) measured NB-IoT consuming roughly 3.7 mAh more than LoRaWAN to join the network and send a single 44-byte uplink message, while achieving markedly lower latency once connected, a trade-off that favours LoRaWAN for battery-constrained sensor swarms and NB-IoT for applications that can tolerate the extra power draw in exchange for faster, cellular-grade delivery. In the middle are Zigbee and BLE, which provide low-power, short-range connections suited to dense, local deployments such as smart homes and wearable devices. To gain a visual understanding of these differences, the technical data was standardized on a standard 1-5 scale with 1 being the poorest performance and 5 being the best performance (Table 3). This normalization enables direct comparisons of dimension across very different network architectures.

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Table 3: Normalized Performance Scores (1–5 Scale)

Protocol	Range	Data Rate	Latency	Energy Efficiency	Scalability	Interoperability
Wi-Fi	3	5	4	1	3	5
BLE	2	2	4	5	3	5
Zigbee	3	2	3	4	5	3
LoRaWAN	5	1	1	5	5	2
NB-IoT	4	2	1	4	5	3
5G NR	2	5	5	2	5	5

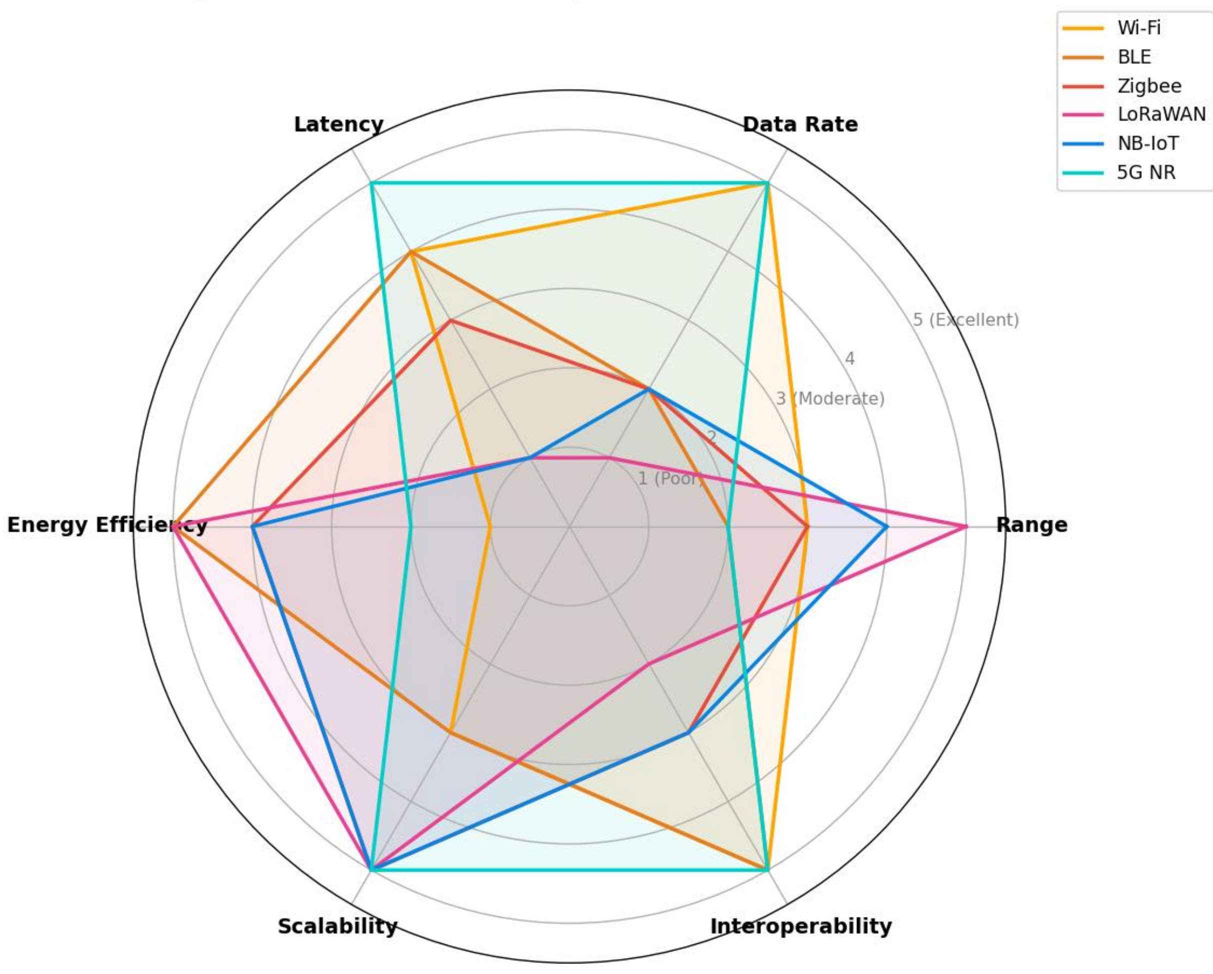

Figure 2: Radar Chart of Comparative Performance Scores.

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Application-Specific Suitability Mapping

None of the above-mentioned protocols have a normalized score that is equal across all dimensions, so system architects should take into account metrics according to application context. These protocols are then systematically mapped to the different domains of IoT, which shows the need for purpose-driven network design (Table 4).

Table 4: Recommended Protocols by IoT Application Domain

Application Area	*Most Suitable Protocols*	*Primary Technical Rationale*
Smart Homes	Wi-Fi, Zigbee, BLE	High bandwidth, mesh topology capabilities, and proximity sensing.
Industrial IoT (IIoT)	5G, Wi-Fi	Strict ultra-low latency and massive data throughput requirements.
Smart Agriculture	LoRaWAN, NB-IoT	Need for long-range, energy-efficient, and low-data-rate telemetry.
Wearable Health	BLE	Compact, ultra-low-power, short-range communication with minimal delay.
Asset Tracking	BLE, LoRaWAN	Context-dependent shifts between localized proximity and wide-area monitoring.

Despite the above mentioned suitability mappings, interoperability is still a major integration barrier (Beniwal & Singhrova, 2022). The lack of perfect cross-protocol communication is due to technical issues, which include frequency spectrum allocations, modulation techniques, and MAC layer behaviors (Gao et al., 2022). Current IoT infrastructure typically employs translation layers on gateways or middleware, incurring an unintended latency and overhead in the system. Read against the research questions set out in Section 3, these results answer RQ1 and RQ3 directly: no protocol dominates across all six dimensions, and the six protocols map cleanly onto the four application domains examined here. RQ2 is answered less by any single figure in Table 2 or Table 3 than by the pattern in Table 1 itself: every directly comparable recent study narrowed its scope to one protocol pair or one application sector, which is why a normalised, six-protocol, four-domain comparison of the kind produced here has not previously been available in a form system architects can act on directly.

5. Conclusion

This review set out to answer a practical question: which wireless protocol should an IoT system architect choose, and does the answer depend on where the system will be deployed. Drawing on 67 peer-reviewed sources benchmarked across latency, data rate, energy efficiency, range, scalability and interoperability, the results confirm that it does. Wi-Fi and 5G New Radio dominate where throughput and latency are non-negotiable, such as industrial automation, but both draw substantially more power than most edge deployments can spare. LoRaWAN and NB-IoT invert that trade-off, sacrificing latency and data rate for range and battery life, which suits smart agriculture and other sparse, static deployments but rules them out for anything approaching real-time control. Zigbee and BLE occupy the middle ground that dense, short-range deployments such as smart homes and wearable health devices actually need. No protocol scored well on every dimension in Table 3, which is itself the study's central finding: protocol selection cannot be generalised, and treating it as though it could is what has produced the fragmented, domain-locked recommendations reviewed in Section 2. The suitability mapping in Table 4 turns that finding into a starting point rather than an endpoint. It cannot substitute for site-specific testing, and Section 4 sets out the limitations that bound how far its rankings should be trusted, but it gives architects an evidence-based shortlist before they commit to expensive testbed work. Three directions follow from the gaps this review surfaced. First, interoperability remains the least mature of the six dimensions assessed; Beniwal and Singhrova (2022) and Gao et al. (2022) both attribute this to incompatible spectrum allocation, modulation and MAC-layer behaviour rather than to any single protocol's design, so gateway and middleware translation layers will remain necessary for the foreseeable future. Second, static protocol selection is giving way to dynamic selection: Żatuchin and Azarskov (2025) showed that switching protocols at runtime in response to network conditions can cut energy consumption by up to a third, but that approach only works if the underlying protocols have been profiled as rigorously as this review attempts; extending the comparative matrix in Table 3 into a machine-readable form that such frameworks can consume directly is a natural next step. Third, the emergence of 6G research already anticipates IoT device counts an order of magnitude beyond what current NB-IoT and 5G mMTC deployments were designed for (Chataut et al., 2024), which suggests the six-protocol landscape mapped here is a staging point rather than a stable end state, and this benchmarking exercise will need to be repeated as new radio generations mature.

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