Review

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# LPWAN Technologies for IoT: Real-World Deployment Performance and Practical Comparison

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## Abstract

Low Power Wide Area Networks (LPWAN) have emerged as essential connectivity solutions for the Internet of Things (IoT), addressing requirements for long range, energy efficient communication that traditional wireless technologies cannot meet. With LPWAN connections projected to grow at 26% compound annual growth rate until 2027, understanding real-world performance is crucial for technology selection. This review examines four leading LPWAN technologies — LoRaWAN, Sigfox, NB-IoT, and LTE-M. This review analyzes 20 peer reviewed studies from 2015–2025 reporting real-world deployment metrics across power consumption, range, data rate, scalability, availability, and security. Field studies reveal significant discrepancies between theoretical specifications and practical performance. LoRaWAN achieves 2+ year battery life and 11 km rural range but suffers collision limitations above 1000 devices per gateway. Sigfox demonstrates exceptional range (280 km record) with minimal power consumption but remains constrained by 12 byte payloads and security vulnerabilities. NB-IoT provides robust performance with 96–100% packet delivery ratios at -127 dBm and supports tens of thousands devices per cell, though mobility increases energy consumption. LTE-M offers highest throughput and sub 200 ms latency but fails beyond -113 dBm where NB-IoT maintains connectivity. NB-IoT emerges optimal for large scale stationary deployments, while LTE-M suits high throughput mobile applications.

**Keywords:** LPWAN; IoT; LoRaWAN; NB-IoT; LTE-M; Sigfox; wireless networks; energy efficiency; network performance; deployment evaluation

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## 1. Introduction

LPWAN are a foundational element of the modern IoT, addressing the need for long-range, low-power, and low-bandwidth connectivity that traditional cellular and short-range wireless technologies fail to meet. LPWAN technologies are specifically engineered to support battery powered devices that transmit small amounts of data infrequently, making them ideal for a large number of uses, for example: smart cities and buildings [1], agriculture [2], industrial monitoring [3], different emerging edge AI frameworks [4] and usecases [5], and other IoT applications requiring extended range, low cost, and long battery life [6]. LPWAN connections are projected to grow at a 26% compound annual growth rate until 2027, reaching 3 billion connections and representing 10% of all IoT connections worldwide [7].

This review focuses on four leading LPWAN technologies: LoRa, Sigfox, NB-IoT, and LTE-M. These technologies were selected based on their proven **existing deployment scale**, **tooling maturity**, and **degree of standardization**. These criteria reflect the practical engineering realities of building and maintaining scalable IoT systems, where field proven reliability, accessible development infrastructure, and consistent protocol definitions are essential.

In terms of existing deployment scale, LoRa has demonstrably achieved broad commercial use. Examples such as The Things Network, with their LoRaWAN network achieved 1 million connected

IoT devices across the world [8], confirm LoRa's operational maturity. NB-IoT and LTE-M, as part of the 3GPP [9], have steadily grown in deployment as operators integrate them into national infrastructure [10,11]. For example, operators such as AT&T, KPN, Orange, Swisscom, Vodafone and Deutsche Telekom have operational NB-IoT and LTE-M networks for a few years now [12–15]. Sigfox with its Sigfox 0G network has achieved significant global coverage spanning 5 million km$^2$ across 70+ national 0G IoT Solution Providers, reaching approximately 1 billion people worldwide currently having 14 million connected devices [16].

Tooling maturity differs across LPWAN technologies, but all the main options offer enough ecosystem support. LoRaWAN is especially strong in this area, thanks to its formal certification programs and well maintained regional standards from the LoRa Alliance, which help ensure devices work together as expected [17]. Developers have access to a wide variety of kits, open source stacks like LoRaMAC-Node, LoRa Basic Modem and cloud integration tools [18,19]. NB-IoT and LTE-M are tightly integrated with the established 3GPP ecosystem, which means they benefit from solid backing by major chipmakers and mobile operators [20]. There are plenty of commercial development boards and SDK available, though the quality of integration tools can vary depending on the vendor. The fact that NB-IoT and LTE-M continue to be enhanced in recent 3GPP releases is a good sign of their maturity and stability [20]. Sigfox does provide development kits, platform access, and community support, but its ecosystem is smaller and less widely adopted than LoRaWAN or the 3GPP based options [21]. As a result, developers may find fewer tools and resources for Sigfox projects.

The standardization landscape for LPWAN technologies reveals distinct tiers of maturity. NB-IoT and LTE-M are fully standardized under 3GPP, with global specifications refined across multiple releases. Both LTE-M and NB-IoT were standardized in 3GPP Release 13 and have continued to evolve through subsequent releases to support enhanced features, mobility, and data rates [20,22]. LoRaWAN, though not an international telecom standard, operates under the LoRa Alliance's structured framework, which defines regional frequency plans, back-end interfaces, link layer, firmware update over-the-air, mandatory certification processes [23]. Sigfox, while proprietary, has established documented technical standards for frequency, security, message sequencing, and device authentication, enabling it to function as a de facto standard in niche markets, albeit without multi-vendor standardization bodies [24].

The exclusion of Wi-SUN, ZETA, and Weightless from mainstream LPWAN comparisons reflects their limited deployment scale and ecosystem maturity, not necessarily technical merits. Wi-SUN demonstrates partial traction in Europe, with deployments such as London's 12000 Wi-SUN-enabled streetlights [25]. The Wi-SUN Alliance reports operating in 46 countries with 300 members globally, including European entities [26]. While Wi-SUN's mesh networking and 50 kbps data rates suit smart grids and street lighting, academic studies highlight Wi-SUN's scalability challenges, such as large 50+ minute formation times for node networks in size of 100+, limiting its viability for large scale IoT deployments [27,28]. Sigfox adoption remains fragmented, with only about 10 million devices deployed worldwide as of 2023, compared to LoRaWAN's 350 million+ end nodes by June 2024 [29,30].

ZETA, despite partnerships with STMicroelectronics [31], remains concentrated in Asia and European deployments are minimal [32,33]. The ZETA Alliance, with 300+ members, focuses on China and Japan, where it supports logistics and smart city projects. STMicroelectronics 2021 alliance membership has yet to catalyze broad European adoption, with no major utility or municipal deployments reported.

Weightless-N lack of 3GPP or alliance backed standardization has confined it to small scale applications. The Weightless SIG's 2018 partnership with Nwave in Denmark and London failed to scale, with no follow-up large projects in Europe [34]. Academic literature largely ignores Weightless in favor of other technologies.

The focus on NB-IoT, LTE-M, LoRaWAN, and Sigfox in this report is justified by robust standardization frameworks and proven commercial viability. These technologies have achieved critical mass in terms of research attention, industry support, and market deployment that distinguishes them from alternative LPWAN solutions. Although it must be noted that United States AT&T decided to

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discontinue NB-IoT services from Q1 2025 [35] and is moving its business IoT customers to an LTE-M plan, while European operators are showing stronger commitment to both NB-IoT and LTE-M.

## 2. Basics of LPWAN Technologies

LPWAN have emerged as a foundational technology for wireless sensor networks, IoT, and M2M communication systems which are often used by resource constrained devices characterized by demand for extended operational longevity, wide area coverage, high scalability, and cost effective deployment. These networks are specifically engineered to address the unique constraints of IoT endpoints, which often operate on limited energy budgets while requiring reliable connectivity across large geographical areas. LPWAN also addresses challenges such as MAC protocol optimization for massive device scalability, spectrum management under region-specific regulatory constraints (e.g., EU duty cycle limitations [36]), link-layer adaptability to various propagation environments [37], coexistence with other wireless systems and security/privacy risks. These constraints necessitate continuous innovation in network architecture to balance energy efficiency and QoS, positioning LPWAN as both a enabler and active research domain in modern IoT systems.

When deploying LPWAN technologies for IoT applications it's important to note that these technologies offer data rates typically ranging from as low as 0.1 kbps to around 1 Mbps, depending on the specific standard. They're optimized for small payloads, generally between 11 and 1280 bytes. Latency varies significantly: licensed cellular options like LTE-M can deliver sub 60 ms performance, NB-IoT can vary from 1.2 to 100 seconds, while unlicensed systems such as LoRaWAN and Sigfox experience delays of several seconds [38].

### *2.1. LoRa and LoRaWAN*

LoRa (Long Range) technology was first developed by Semtech Corporation [39] as a physical layer wireless modulation technique based on CSS modulation. LoRa provides the foundation for LoRaWAN, which defines the upper layers of the network protocol stack.

LoRa physical layer technology works in unlicensed sub-GHz ISM frequency band — 868 (Europe), 915 (North America), 433 MHz (Asia). Base of this technology CSS is frequency modulation in which carrier frequency varies for a defined extent of time. The main characteristic of this type of modulation is a tradeoff between receiver sensitivity and data rate while using fixed 125 kHz, 250kHz or 500 kHz channels. It uses orthogonal spreading factors to adjust transmission parameters. A higher spreading factor increases sensitivity, improving the ability to detect weak signals over long distances, but reduces data rate. For example, LoRa device near gateway should use low spreading factor, while distant devices should use higher spreading factors for better sensitivity at the cost of lower data rates.

The LoRaWAN performance metrics as promised by the LoRaWAN Alliance [40] are collected in the Table 1.

### *2.2. Sigfox*

Sigfox is proprietary LPWAN technology owned by UnaBiz [41]. It provides a complete protocol stack that handles both physical layer transmission and upper network layers. Physical layer of this technology uses UNB modulation that has extremely narrow bandwidth of only 100 Hz per message that reach data rates of 100 to 600 bits per second with payload limited to 12 bytes. End devices are allowed to transmit up to 140 messages per day [42]. Sigfox physical layer technology works in unlicensed sub GHz ISM and SRD frequency bands worldwide — for Europe, Middle East, parts of Africa 868.130 MHz uplink, 869.525 MHz downlink and 865 to 923 MHz in South, North America, Asia and others. Sigfox is not available world wide [43].

The main characteristic of this modulation is the tradeoff between extremely long range and very low data rates while using a total spectrum allocation of only 192 kHz. Sigfox encodes data using DBPSK for uplink transmissions and GFSK for downlink communications [44]. The system uses frequency hopping by transmitting each message three times on different pseudo random frequencies to ensure reliable packet delivery [43].

The Sigfox network protocol defines a simplified communication model without device classes, instead operating on a star network topology where devices are not attached to specific base stations and base stations continuously monitor the spectrum for UNB signals. Base stations relay messages to the Sigfox cloud backend through various connections, and the cloud interfaces with application servers [41].

The Sigfox performance metrics as promised by the UnaBiz are collected in the Table 1.

### 2.3. NB-IoT

NB-IoT is a cellular LPWAN technology standardized by 3GPP in Release 13 in June 2016 [45]. It provides a complete protocol stack that handles both physical layer transmission and upper network layers. Unlike unlicensed LPWAN solutions, NB-IoT operates within licensed cellular spectrum, typically using a 180 kHz channel inside existing LTE or GSM bands. This approach allows NB-IoT to use existing cellular infrastructure for robust and wide area connectivity. NB-IoT offers about 50 kbps downlink and uplink maximum data rates with payload limited to 1280 bytes [46]. NB-IoT promises battery life of up to 10 years.

NB-IoT is primarily designed for stationary or low mobility applications and does not support seamless handover between cell towers, making it unsuitable for devices that require continuous connectivity while moving. 3GPP Release 14 introduced connection re-establishment procedures for connected mode (as opposed to the power-expensive operation of going into idle mode when moving from one cell to another per Release 13), though full mobility support remains limited compared to LTE-M.[47].

Similarly to LoRaWAN, this technology has a trade off between coverage and data rate. NB-IoT uses OFDM for downlink communications and SC-FDMA for uplink transmissions. The network can be deployed in three different modes: standalone (using dedicated spectrum), in-band (using resource blocks within a normal LTE carrier), or guard-band (using the unused resource blocks within an LTE carrier's guard-band). The NB-IoT standard defines power saving features such as PSM and eDRX to extend battery life [46]. NB-IoT implements three ECL levels (0, 1, and 2) as specified in 3GPP Release 13, where each level determines the number of signal repetitions (up to 2048 in downlink and 128 in uplink) to extend coverage by up to 20 dB beyond standard LTE, achieving a Maximum Coupling Loss (MCL) of 164 dB for reliable communication in challenging environments such as basements and underground locations [48]. ECL dBm thresholds are defined by the telecommunication operator. NB-IoT networks operate on a star network topology where end devices communicate with base stations (eNBs) and base stations connect to a telecommunication operator's core network which is then connected to specific application servers.

When working with NB-IoT, it is important to understand that many key features, such as power-saving modes (eDRX, PSM) are determined by the mobile network operator rather than the application developer.

The NB-IoT performance metrics as promised by the 3GPP are collected in the Table 1.

### 2.4. LTE-M

LTE-M also known as LTE Cat-M1 or eMTC, is a cellular LPWAN technology standardized by 3GPP in Release 13 alongside NB-IoT in June 2016 [49]. Comparing the two, LTE-M is distinguished by its higher data rates and full mobility support compared to NB-IoT ultra low power focus. LTE-M provides a complete protocol stack that handles both physical layer transmission and upper network layers through existing LTE infrastructure. The various names — LTE-M, LTE-MTC, eMTC, and Cat-M1/M2 — refer to the same family of technologies, with Cat-M1 (3GPP Release 13) and Cat-M2 (3GPP Release 14) indicating the specific versions and capabilities.

LTE-M uses OFDM, SC-FDMA and 16-QAM modulation schemes. LTE-M Cat-M1 uses a 1.08 MHz of bandwidth and supports data rates up to 1 Mbps, operating in licensed LTE spectrum. Same as NB-IoT, LTE-M can be deployed in standalone, in-band or guard-band modes. The standard supports three duplex modes: half-duplex FDD, full-duplex FDD, and TDD operations. The technology also features

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coverage enhancement through message repetitions (Mode A: mandatory and Mode B: Optional for deeper coverage scenarios), providing up to 15–21 dB additional link budget over standard LTE, and supports advanced power-saving modes like PSM and eDRX, both share the same underlying mechanism, NB-IoT permits much longer eDRX cycles while PSM timer limits are identical, for multi year battery life [46,50]. LTE-M Cat-M2, introduced in 3GPP Release 14, expands bandwidth to 5 MHz and increases peak data rates, making it suitable for more demanding IoT applications. Unlike other LPWAN technologies, LTE-M Cat M2 supports Voice over LTE (VoLTE) capabilities, enabling voice communication directly over the LTE-M network without requiring additional 2G or 3G infrastructure [51,52].

The LTE-M performance metrics as promised by the 3GPP are collected in the Table 1.

**Table 1.** Comparison of LPWAN technologies as promised by the standard.

| **Technology** | **LoRaWAN** | **Sigfox** | **NB-IoT** | **LTE-M** |
|---|---|---|---|---|
| Range | 15–20 km (rural), 2–5 km (urban) [53] | 40 km (rural), 10 km (urban) [54] | 10 km (rural), 1 km (urban) [55] | 10 km (rural), 1 km (urban) [56] |
| Data Rate | 0.3–50 kbps [53] | 100–600 bps [54] | 250 kbps (DL), 20–250 kbps (UL) [57] | 1 Mbps (peak) [56] |
| Bandwidth | 125, 250 or 500 kHz [58] | 100 Hz [54] | 180 kHz [55] | 1.4–5 MHz (Cat-M1/M2) [59] |
| Battery Life | up to 10 years (Class A) [53] | up to 10 years [54] | 10 years (200B UL daily) [60] | 10 years (200B UL daily) [61] |
| Max Payload | 11–242 B [58] | 12B UL / 8B DL [62] | 1280B* [57] | 1280B* [59] |
| Carrier Frequency | 868/915/433 MHz (ISM) [58] | 862–928 MHz (ISM) [54] | Licensed LTE bands [57] | Licensed LTE bands [59] |
| Latency | Class A: seconds, Class B: up to 128 s, Class C: near real-time [53] | seconds [54] | 1.6–10 s [55] | 10–15 ms (normal coverage) [61] |
| Modulation | CSS (LoRa) or FSK [53] | UNB [54] | SC-FDMA UL / OFDM DL [57] | SC-FDMA UL / OFDM DL (+16-QAM) [59] |
| Security and Privacy | AES-128 [53] | AES-128 [54] | AES-128 [57] | AES-128 [59] |

[*] Actual payload may depend on modem, mobile network, and cloud application. Risk of IP fragmentation and thus delivery failure.

## 3. Literature Review

While Section 2 focused mostly on what's promised by the standards themselves according to their documentation and white papers, this section will examine 20 recent peer-reviewed academic publications about real deployments which use LoRaWAN, SigFox, NB-IoT, or LTE-M to lay groundwork for practical comparison of these technologies.

This review deliberately targets practical, real-world LPWAN deployments published in the last 10 years (2015–2025). The review focused exclusively on empirical evaluations from live LPWAN deployments, filtering for studies reporting at least one quantitative operational KPI—energy efficiency, coverage, throughput, scalability, or network stability (PDR, latency). We also searched for security and privacy outcomes, however most security findings come from testbeds, protocol analyses, or surveys rather than true deployments. Table 2 summerizes all of the studies included in this review. Tables 3 and 4 summarizes the findings.

**Table 2.** Literature review of LPWAN deployments and KPIs covered.

| KPI | LoRaWAN | Sigfox | NB-IoT | LTE-M |
|---|---|---|---|---|
| Energy eff. | [63–69] | [65–67,70–72] | [66–68,73–75] | [73–75] |
| Range | [63,65,66,68,69,76,77] | [65,66,70] | [66,68,74,78,79] | [74,75] |
| Data rate | [64,66,68] | [66,70,72] | [66,68,74,75] | [74,75] |
| Security | [80,81] | [81] | [81,82] | [82] |
| Scalability | [63,64,69] | [70] | | |
| Availability | [64–66,68,69,76,77] | [65,67,70,71] | [66–68,74,75,78,79] | [74,75] |
| Stability | [64,66,68,69,76] | [70] | [66,68,73–75,78,79] | [73–75] |

**Table 3.** Quantitative Comparison: LoRaWAN vs. Sigfox.

| | LoRaWAN | Sigfox |
|---|---|---|
| Energy eff. | Laboratory: up to ∼2+ years on a 2400 mAh cell at 10 min intervals; field: ∼7 months. ADR tuning is critical, misconfiguration can halve battery life. | Analytical: 1.5–2.5 years on 2400 mAh at 10 min intervals. Field prototype: 118 days on 2200 mAh, ∼6 months on 10000 mAh. |
| Range | Urban: ∼3 km at –110 dBm (80% PDR); rural: ∼11 km (80% PDR); city deployments ∼2 km (72–96% PDR). | Tens of km urban; record LOS 280 km (68.3% PDR flying), 195 km terrestrial (54.1% PDR). |
| Data rate | SF7–SF12: 0.3–5.5 kbps; typical SF10: 980 bps (72.4% PDR of 135000 msgs). | 100 bps uplink; up to 600 bps downlink for under 12B payloads. |
| Security | AES-128 CTR & AES-CMAC; distinct NwkSKey & AppSKey for authentification. | Pre-shared 128-bit AES; vulnerable to replay/DoS attacks. |
| Scalability | ∼1000 devices/gateway before PDR drops under 90% due to ALOHA collisions & duty-cycle limits. | 140 uplinks & 4 downlinks per day per device; PDR drops when over ∼200 dev/km$^2$ (trial (312 tags) show average PDR 56.2%) |
| Availability | Global availability. Indoor 99.95%; outdoor under 95% PDR. | Avaialble Europe, Overseas France, Middle East and Africa, Brazil, Canada, Mexico, Puerto Rico, USA, Japan, Latin America, Asia Pacific, South Korea, India, Russia. Urban 96.7%, dense forest under 19.8%; indoor proven 100% PDR |

**Table 4.** Quantitative Comparison: NB-IoT vs. LTE-M.

| | **NB-IoT** | **LTE-M** |
|---|---|---|
| Energy eff. | ∼7 years on 10000 mAh with hourly 64 B payload (121 µW mean). Idle connected draws lower than LTE-M. | Peak bursts equal NB-IoT (1.75 W) but average ∼200 mW higher. Shorter airtime, more efficient for frequent uploads. |
| Range | Outdoor up to 700 m (95%+ PDR at –110 dBm; 1/20 failures).<br>Indoor/garage/underground up to 1.4 km with up to 96% PDR at –127 dBm. | Roughly the same as NB-IoT but only reliable to –93 dBm (0% loss); fails at –113 dBm where NB-IoT holds. Strong urban/in building but reduced deep-indoor comparing to NB-IoT. |
| Data Rate | 11 kbps UL, 17 kbps DL at –100 dBm observed; over 20 kbps under good conditions; falls to low kbps with latency raising under coverage extensions | 348 kbps DL, 145 kbps UL observed |
| Security | 3GPP EPS-AKA; 128-EEA2/AES encryption & integrity; strong cryptography. | Inherits 3GPP security as NB-IoT; proper deployment required to avoid highly unlikely billing/drain exploits. |
| Scalability | 3GPP target 52500 devices/cell; up to 200000 devices under ideal scheduling. Random-access collisions are the bottleneck. | Up to 10000 devices/cell. |
| Availability | Availability depends on telecommunications operator. 96–100% PDR at –127 dBm, deep indoor and underground coverage& peak hour network congestion increases latency. Better coverage than LTE. | Availability depends on telecommunications operator. 100% PDR at good signal; drops completely beyond –113 dBm. Sub-200 ms latency. Same coverage as LTE. |

### 3.1. Power Consumption and Energy Efficiency

LoRaWAN is recognized for energy efficiency in low data rate, uplink heavy IoT use cases, with studies showing the potential for multi year battery life under ideal laboratory conditions [63,66,67]. However, real world deployments often fall short for example Singh et al. [67] observed that practical implementation details can reduce LoRaWAN battery life estimates from years to several months — in their study to 7 months. Energy consumption is highly sensitive to network configuration and conditions: ADR mechanisms can optimize battery life, but only when carefully tailored to the deployment context, otherwise, energy is wasted (Kufakunesu et al. [64]). Field experience also shows that interference, poor radio planning, and backend outages can increase airtime and quickly erode LoRaWAN's power consumption advantages [65,69,76,77]. Effectively, LoRaWAN's low power promise is best realized with careful configuration and reliable infrastructure.

Sigfox targets ultra low energy uplinks by using 100 bit/s ultra narrow band bursts and limiting payloads to 12 bytes. In head to head tests it sent 20% more messages than LoRaWAN on the same power budget, showing better energy efficiency even though LoRaWAN achieved higher PDR [65]. Analytical modeling shows a 2400 mAh battery can last 1.5–2.5 years when the device transmits once every 10 minutes and up to 14.6 years as the reporting interval widens [72]. Field prototypes show that a self-powered smart meter ran 118 days on a 2200 mAh cell [71]. Under heavier traffic (5 byte packets every 5 minutes) Sigfox's three replica uplink scheme restricts autonomy to roughly 6 months on a 10000 mAh battery. Less efficient than LoRaWAN and NB-IoT for the same test [67].

NB-IoT's energy budget is shaped more by idle connected time than by transmit bursts. Vomhoff et al. [73] shows that during idle periods where network reachability is required (connected to one base station), NB-IoT draws less current than LTE-M, extending battery life in continuous monitoring applications. Martinez et al. [68] measured 121 µW mean power for 64 byte hourly transmissions, rising minimally to 143 µW for 512 byte payloads. This translates to roughly 7 year battery life with 10000 mAh cells [67]. Field trials confirm coverage-energy tradeoffs: Ferreira et al. [79] achieved above 96% packet success in challenging environments down to –127 dBm using ECL retransmissions, while Malik et al. [78] observed degraded underground performance beyond 400m. Field measurements for mobile nodes show that whenever they leave the serving cell: a roaming tracker that crossed an international border needed 43s to reattach, compared with 8s when stationary, multiplying radio on time and roughly quintupling energy consumption [83]. 3GPP Release 14 (Cat NB2) addresses this overhead with *RRC Connection Re-establishment* and full connected/idle mode mobility, letting a UE resume its context in the target cell instead of repeating a full attach and thus cutting signalling and power draw [84–86].

LTE-M's energy profile favours talkative devices rather than sleepy ones. Vomhoff et al. [73] find that while connected-idle, LTE-M draws noticeably more current than NB-IoT, eroding battery life for sparsely reporting sensors. Boiano's side by side trials with identical BG96 hardware show LTE-M uplink bursts peak at the same 1.75 W as NB-IoT but average 200 mW higher. Its airtime, however, is 3–5 times shorter, softening the per message cost for bursty uploads [74]. Field measurements by Labdaoui et al. [75] confirm this trade-off: LTE-M is the more energy efficient option when payloads are sent every few minutes, whereas NB-IoT retains an advantage once intervals stretch to hours or days.

### 3.2. Working Range

LoRaWAN's CSS PHY routinely spans several km in cities and tens of km rurally, which surveys list as a core strength [63]. Controlled 868 MHz trials still achieved above 80% PDR at RSSI over –110 dBm, achieving 11 km range in rural and 3km in urban environment [65]. Southampton's air quality network kept 72.4% PDR across nodes about 2 km from gateways [69], while a 26 day Glasgow study achieved 95.7% PDR outdoors with devices mounted on the rooftops of two buildings 1.9 km and 2.1 km away from the transmitting mote [76]. Careful propagation mapping, as in Girona's smart parking rollout, lets planners sustain these ranges using low spreading factors and minimal duty cycle overhead [77].

Sigfox demonstrates exceptional long range capabilities using its UNB modulation, achieving practical outdoor ranges of tens of km in urban environment[65]. The Wild et al. [70] wildlife tracking study documented a impressive transmission distance of 280 km for flying species and 195 km for terrestrial deployments, with flying animals achieving superior connectivity (68.3% PDR) compared to terrestrial species (54.1% PDR).

NB-IoT delivers reliable cellular coverage in diverse environments. Field trials on Quectel BG96 modules showed outdoor connectivity up to 700 m with only 1/20 devices in (RSSI down to –110 dBm), while indoor performance incurred 3/20 outages and underground links degraded sharply beyond 400 m with 8/20 failures [78]. In harsher settings, NB-IoT sustained above 96% PDR across indoor spaces, two level garages, and a sealed concrete dome up to 1.4 km from the cell, despite RSRP values as low as –127 dBm by using its ECL retransmission mechanism [79]. At extreme low signal (–113 dBm), NB-IoT maintained connections where LTE-M failed [74].

LTE-M provides cellular grade range comparable to standard LTE coverage but with slightly reduced link budget sensitivity compared to NB-IoT. In tests using Quectel BG96, eMTC maintained 0% packet loss at –93 dBm and above, delivering reliable connectivity out to typical cell-edge distances, but it failed to establish links at –113 dBm where NB-IoT still held connections [74]. Labdaoui et al. [75] confirm that, in commercial French networks, LTE-M achieves strong in-building and urban coverage but its effective range shrinks in deep indoor or highly attenuated scenarios compared to NB-IoT's extended link-budget of up to 20 dB.

### 3.3. Data Rate

LoRaWAN deployments typically employ spreading factors (SF) between SF7 and SF12 trading off data rate for link range. In city scale air quality monitoring, Basford et al [69] used SF10 (980 bps in EU868), which delivered 72.4% of 135000 messages . ADR schemes span the full SF7–SF12 range (0.3–5.5 kbps) and can be tuned per deployment to balance throughput and energy [64]. In smart-parking trials, context-specific ADR enabled use of lower SFs (SF8–SF9, 3.1–1.7 kbps) to meet frequent transmission requirements without sacrificing battery life.

Sigfox offers data rates 100 bit/s for uplink and up to 600 bit/s in higher-rate modes, delivering very under 12 byte payloads. Cordero et al. [72] reports that they achieved 100 bps.

NB-IoT can sustain application layer throughputs above 20 kbps under favorable radio conditions and still deliver useful rates deep indoors. Laboratory tests on Orange Belgium's commercial network recorded peak uplink and downlink throughput of 11 kbps and 17 kbps, respectively, when the modem operated at RSSI levels around –100 dBm [87]. Basu et al. [87] found these figures held steady until RSRP dropped past –115 dBm, after which ECL coverage extension preserved connectivity but reduced user throughput to the low kbps range and extended latency from 300 ms to several seconds.

Labdaoui, Nassim, Fabienne Nouvel, and Stéphane Dutertre conducted a practical throughput measurement of commercial LTE-M modem by u-blox SARA-R422S dual mode modules on live French networks. Their study reports that LTE-M achieves substantially higher data rates than NB-IoT (348 DL and 145 kbps UL) under the same network conditions [75].

### 3.4. Security and Privacy

LoRaWAN 1.0 secures traffic with the LoRa Alliance's built in: AES-128 in counter mode for encryption plus AES-CMAC for integrity, using distinct network (NwkSKey) and application (AppSKey) session keys derived during a mutual-authentication join procedure [81].

Sigfox also uses pre shared 128-bit AES keys and a frame based message authentication code, yet its prone to replay and denial of service attacks that are hard to mitigate, making it unsuitable for critical use cases [81].

NB-IoT and LTE-M inherit 3GPP's cellular security/privacy mechanisms: the EPS-AKA authentication protocol and 128-EEA2/AES encryption and integrity, giving strong cryptographic guarantees when correctly deployed. Field tests nonetheless revealed billing abuse, battery drain and device hibernation attacks. Exploiting them demands specialised gear, sophisticated know-how and legitimate network credentials, which limits real world risk [82].

### 3.5. Scalability

LoRaWAN typically supports about 1000 end devices per gateway before ALOHA collisions, cross-spreading-factor interference, and the 1% duty-cycle cap push PDR below 90%, a limit observed in survey analyses, long term smart city trials and simulations [63,64,69].

Sigfox constrains each device to 140 uplinks and four downlinks per day [88]. Simulation supported scalability studies indicate that network level PDR begins to decline once device density passes roughly 200 units per $km^2$, because the protocol's three redundant replicas increasingly collide in ALOHA access [89].

NB-IoT employs licensed 180 kHz carriers and repetition based ECL. Studies indicate that random-access collisions, rather than user-plane spectrum, become the primary scalability bottleneck, yet simulations predict support for roughly 52500 devices per cell (3GPP target) and up to 200000 devices under ideal scheduling assumptions [68,90].

LTE-M trades some density for speed: its 1.4 MHz bandwidth supports roughly 10000 devices per cell.[74,91].

### 3.6. Network Availability and Stability

Availability describes how often a service can be accessed when and where a device attempts to communicate. Stability refers to the repeatability of that access over time, environmental change, and interference. Important availability metric analyzed in most of the analyzed articles is PDR, for stability variance in latency, server/gateway downtime, susceptibility to interference or network congestion, and security disruptions that can force devices offline.

LoRaWAN's large link budget lets it reach near perfect indoor PDR (99.95%) and at least 95% outdoors in sparse traffic, yet long term and city scale studies reveal that ALOHA collisions, interference and single server outages can drag average PDR down to 72%, making availability highly context dependent [63,69,76]. Sigfox enjoys predictable scheduling and record 280 km line of sight links, but its PDR swings from 96.7% in clear urban skies to below 19.8% in dense forests, with replay/DoS weaknesses that can further erode stability despite proven 100% PDR in indoor settings [65,70,71,81]. NB-IoT running in licensed spectrum sustains 96–100% PDR even at –127 dBm thanks to ECL, giving it the strongest raw availability. However, live trials also show deep indoor or peak hour congestion can inflate latency from sub second to minutes [68,78,79]. LTE-M trades some link budget for speed: it maintains sub 200 ms latency and perfect PDR at good signal, but drops completely beyond –113 dBm [73–75].

## 4. Discussion

NB-IoT combines good battery life, deep indoor coverage, high device density support, and robust 3GPP security. Its low per-device subscription cost and lack of private gateway maintenance make it highly cost effective for large scale and long lived deployments. Wherever reliable connectivity, indoors or outdoors, is required, and moderate data rates suffice, NB-IoT should be the technology of choice. Field studies reveal that mobile NB-IoT nodes consume more energy during cell handovers. Although 3GPP Release 14 adds RRC connection re-establishment and full mobility support to lessen this overhead, the studies did not specify which release their networks used, so real world adoption of these energy saving features remains uncertain.

LTE-M's higher throughput, lower than NB-IoT latency make it ideal for use cases with frequent, larger uplink bursts — wearable health monitors, real time asset tracking, and responsive smart city nodes (e.g., fill level sensors reporting every few minutes). Accept somewhat shorter battery life and slightly reduced deep indoor reach compared to NB-IoT in exchange for data rate and responsiveness.

When an organization requires full control over its network and can support gateway maintenance, despite higher ongoing platform, LoRaWAN offers flexible deployment and multi kilometer range at low upfront gateway prices (€120–2000 [92,93]). Optimize ADR settings to maximize PDR and ensure reliable infrastructure support.

Given Sigfox's limited payload size, low duty cycle, and known replay/DoS vulnerabilities, reserve Sigfox for cases demanding the longest possible link budget (tens to hundreds of kilometers) and extremely infrequent, small messages—such as wildlife trackers flying across remote regions or very sparse environmental sensors. Avoid Sigfox where security requirements or message volumes exceed minimum.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| ADR | Adaptive Data Rate |
| AES | Advanced Encryption Standard |
| CMAC | Cipher-based Message Authentication Code |
| CSS | Chirp Spread Spectrum |
| CTR | Counter Mode |
| DBPSK | Differential Binary Phase Shift Keying |
| DL | Downlink |
| DoS | Denial of Service |
| ECL | Extended Coverage Level |
| eDRX | Extended Discontinuous Reception |
| eMTC | Enhanced Machine Type Communication |
| EPS-AKA | Evolved Packet System Authentication and Key Agreement |
| FDD | Frequency Division Duplex |
| FSK | Frequency Shift Keying |
| GFSK | Gaussian Frequency Shift Keying |
| GSM | Global System for Mobile Communications |
| IoT | Internet of Things |
| ISM | Industrial, Scientific and Medical |
| KPI | Key Performance Indicator |
| LOS | Line of Sight |
| LoRa | Long Range |
| LoRaWAN | Long Range Wide Area Network |
| LPWAN | Low Power Wide Area Network |
| LTE | Long Term Evolution |
| LTE-M | Long Term Evolution for Machines |
| M2M | Machine-to-Machine |
| MAC | Medium Access Control |
| MCL | Maximum Coupling Loss |
| NB-IoT | Narrowband Internet of Things |
| OFDM | Orthogonal Frequency Division Multiplexing |
| PDR | Packet Delivery Ratio |
| PHY | Physical Layer |
| PSM | Power Saving Mode |
| QAM | Quadrature Amplitude Modulation |
| QoS | Quality of Service |
| RRC | Radio Resource Control |
| RSRP | Reference Signal Received Power |
| RSSI | Received Signal Strength Indicator |
| SC-FDMA | Single Carrier Frequency Division Multiple Access |
| SDK | Software Development Kit |
| SF | Spreading Factor |
| SIG | Special Interest Group |
| SRD | Short Range Device |
| TDD | Time Division Duplex |
| UE | User Equipment |
| UL | Uplink |
| UNB | Ultra Narrow Band |
| VoLTE | Voice over LTE |

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