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Coverage, Energy Consumption, Capacity, and Decision Sensitivity of LoRaWAN, NB-IoT, and Wi-Fi 6 for Battery-Powered IoT Deployments: A Simulation-Based Comparative Study

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ABSTRACT

Selecting a wireless technology for battery-powered sensing nodes requires consideration of more than coverage or nominal data rate. This paper presents a comparative evaluation of LoRaWAN, NB-IoT, and Wi-Fi 6 (IEEE 802.11ax with Target Wake Time) across four key performance dimensions: link-budget-based coverage under three propagation scenarios, energy consumption per uplink message, battery lifetime across reporting intervals ranging from 5 minutes to 24 hours, and network capacity. Representative datasheet-based radio parameters are used in a log-distance path-loss model with shadowing, a per-message energy model, a Monte Carlo simulation of LoRaWAN contention with capture effects, an Erlang-B model of NB-IoT random-access resources, and a TOPSIS-based multi-criteria decision analysis with weight-sensitivity evaluation. Under the urban outdoor propagation scenario, the estimated 90% availability ranges are 5.05 km for NB-IoT (deepest coverage level), 2.09 km for LoRaWAN (SF12), and 91 m for Wi-Fi 6. For a 20-byte uplink message, the estimated energy consumption is 11.4 mJ for LoRaWAN (SF7), 12.0 mJ for Wi-Fi 6 with TWT, and 343 mJ for NB-IoT under its best coverage class, decreasing to 165 mJ with release assistance. At a 15-minute reporting interval, the modelled battery lifetime of a 2400 mAh battery is 27 years for LoRaWAN, 3.5 years for Wi-Fi 6, and 1.9 years for NB-IoT. Adaptive Data Rate (ADR) increases the estimated capacity of a single LoRaWAN gateway from fewer than 500 nodes to approximately 4,746 nodes while maintaining 90% packet delivery across three channels. The multi-criteria analysis indicates that LoRaWAN ranks first in 90–98% of weight combinations for agricultural and conventional city-metering applications. For a managed-service application profile that assigns greater importance to infrastructure burden, NB-IoT and LoRaWAN achieve statistically comparable rankings. These findings are based on simulation and analytical models, and further field validation is required.

Keywords—LoRaWAN; NB-IoT; Wi-Fi 6; target wake time; LPWAN; link budget; battery life; network capacity; TOPSIS

1. Introduction

The number of battery-powered connected sensors is growing in agriculture, utilities, logistics and urban monitoring. Three connectivity families compete for these deployments. LoRaWAN offers a licence-exempt, long-range, low-rate radio with a simple star topology [1], [2]. NB-IoT is a 3GPP cellular technology that reuses licensed spectrum and operator networks and targets deep indoor coverage [3]. Wi-Fi 6 extends the ubiquitous local-area standard with features such as target wake time (TWT) intended to reduce the energy cost of keeping a station associated [4].

Existing comparative studies concentrate mainly on coverage and technology characteristics [5], [6], with some detailed work on LoRaWAN energy [7] and scalability [8], [9]. Two gaps motivate the present paper. First, coverage, energy and capacity are normally analysed separately, although a design decision involves all three at once: a technology that reaches a node only at its slowest, most energy-hungry setting is a different proposition from one that reaches it comfortably. Second, comparisons are rarely accompanied by a sensitivity analysis of the final ranking, so a reader cannot see how much the conclusion depends on the weights an author chose.

The contributions are: (i) a unified, parameterised model of link budget, per-message energy, battery life and capacity for the three technologies, with all parameters listed; (ii) a Monte Carlo and queueing-based capacity analysis showing how strongly protocol options (LoRaWAN adaptive data rate, NB-IoT connection release) change the answer; and (iii) a multi-criteria ranking for three application profiles with a weight-space robustness analysis and an explicit break-even weight at which the preferred technology changes.

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2. Background and Related Work

LoRaWAN. LoRa uses chirp spread spectrum, with the spreading factor (SF 7–12) trading data rate for sensitivity at a fixed 125 kHz bandwidth [1]. Adelantado et al. analyse the limits imposed by duty cycle, channel count and the asymmetry of the downlink [2]. Bor et al. showed by simulation that pure-ALOHA contention limits the scale of a LoRa cell unless data rates are adapted [8], which motivates the ADR comparison in Section 4.4. Casals et al. model the energy of LoRaWAN class-A devices from transmit, receive and sleep phases [7], the same decomposition adopted here.

NB-IoT. NB-IoT occupies a 180 kHz carrier with single-tone and multi-tone uplink options and repetition-based coverage enhancement, with a target maximum coupling loss of 164 dB [3], [10]. Its energy cost is dominated by connection setup and the inactivity tail, which release-assistance and early-data features aim to shorten. Lauridsen et al. compared the coverage of NB-IoT, LoRa and Sigfox over a large area [6].

Wi-Fi 6. IEEE 802.11ax adds OFDMA and TWT, a scheduling mechanism by which a station agrees wake times with its access point [4], [11]. TWT removes the need to wake for every beacon but requires the station to remain associated, and therefore to keep a state-retaining sleep mode with a current higher than deep sleep.

Multi-criteria selection. The technique for order preference by similarity to ideal solution (TOPSIS) ranks alternatives by relative closeness to an ideal point [12]. Its results depend on criteria weights, so this study repeats it over a sampled neighbourhood of weights.

3. Models and Parameters

3.1 Propagation and coverage

Path loss follows the log-distance model with log-normal shadowing [13]:

$$PL(d) = PL_0(f) + 10 \cdot n \cdot \log_{10}(d / 1\ \text{m}) + L_{pen} + X_\sigma \quad (1)$$

where PL_0 is the free-space loss at 1 m, n the path-loss exponent, L_{pen} an additional wall-penetration loss and X_σ a zero-mean Gaussian with standard deviation σ. Coverage range is defined at 90 % edge availability, so the shadowing margin is 1.28 σ. Three scenarios are used: *urban outdoor* (n = 3.3, σ = 8 dB), *rural open* (n = 2.7, σ = 6 dB) and *urban indoor* (urban parameters with an extra 14 dB penetration loss at sub-GHz frequencies and 18 dB at 2.4 GHz). Range is capped at 15 km to reflect the radio horizon, which affects the rural case only. Maximum path loss is the transmit power plus the receiver sensitivity (or, for NB-IoT, the coupling-loss target of each coverage class). Antenna gains are taken as 0 dBi and antenna-height effects are absorbed into n.

3.2 Radio and energy parameters

Table 1. Representative radio parameters used in the models (datasheet-class values; see Section 5.2 for limitations).

Parameter	LoRaWAN	NB-IoT	Wi-Fi 6 (TWT)
Carrier (MHz)	868	900	2400
Transmit power (dBm)	14	23	18
Sensitivity / max. coupling loss	−123 (SF7) to −137 dBm (SF12)	144 / 154 / 164 dB (CE0/1/2)	−97 dBm (1 Mb/s)
Maximum path loss (dB)	137 (SF7) – 151 (SF12)	144 – 164	115
Transmit current (mA)	44	220	250
Receive current (mA)	11.5	46	90
Sleep current (µA)	2	5 (PSM)	60 (TWT) / 8 (deep sleep)
Per-message overhead	2 class-A RX windows (12 symbols each)	Setup 0.5/1/2 s; tail 10 s (1 s with release assistance)	TWT: 15 ms wake + 25 ms sync; reconnect: 0.6 s at 110 mA
Uplink rate	5.5 – 0.29 kb/s (SF7–SF12)	15 kb/s ÷ repetitions (1/8/64)	1 Mb/s

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Values were chosen to be representative of widely used sub-GHz LoRa transceivers (e.g. SX1276 class [14]), NB-IoT modules in the 220 mA transmit class, and Wi-Fi 6 system-on-chips. They were not measured on a specific product, and individual products differ.

The energy of one LoRaWAN uplink is the sum of transmit and receive phases. Airtime follows the standard LoRa packet-time expression [14] with an 8-symbol preamble, explicit header, CRC and 13 bytes of LoRaWAN overhead:

$$E_{LoRa} = V \cdot (I_{tx} \cdot T_{air}(SF, PL) + I_{rx} \cdot 2 \cdot 12 \cdot T_{sym}), \quad T_{sym} = 2^{SF} / BW \qquad (2)$$

For NB-IoT, energy is the sum of connection setup, uplink transmission at the repetition-dependent rate, a downlink acknowledgement of 0.2 s and the connected-mode tail. For Wi-Fi 6, TWT energy is the wake, synchronisation and transmission energy; the comparison case without TWT reconnects for every report. Payload overhead is 20 bytes for NB-IoT and 100 bytes for Wi-Fi.

Battery life uses a 2400 mAh cell with 85 % usable capacity at 3.3 V. Average consumption includes the message energy, technology-specific sleep current and a self-discharge equivalent of 1 % of capacity per year (2.7 µA). Lifetimes above roughly 15 years therefore indicate only that the cell's calendar life, not the radio, is the limiting factor.

3.3 Deployment cases

Battery life is evaluated in the urban outdoor scenario for three node distances: 50 m (reachable by all technologies), 1.5 km (beyond Wi-Fi) and 4 km (beyond Wi-Fi and LoRaWAN). Each node uses the least costly configuration that satisfies the link budget with the 90 %-availability margin: the lowest LoRaWAN spreading factor and the lowest NB-IoT coverage class that fit. Payload is 20 bytes unless stated.

3.4 Capacity models

LoRaWAN. Nodes are placed uniformly in a disc of radius 1.8 km around one gateway, each with its own shadowing draw. With ADR each node takes the lowest SF with at least 3 dB of margin; the comparison case fixes SF12 for all nodes. Every node sends one 20-byte uplink per 15 minutes at a uniformly random phase with ±5 s jitter, on one of 3 channels (the default India sub-GHz channel set) or 8 channels. Four simulated hours are evaluated per run. Two packets collide if they overlap in time on the same channel and SF; the packet survives if its received power exceeds that of every overlapping packet by at least 6 dB (capture). SFs are treated as orthogonal. There are no retransmissions and no downlink traffic. Nodes with insufficient link margin for SF12 are counted as uncovered and reported separately from the packet-delivery ratio (PDR).

NB-IoT. The 12 single-tone uplink resources of one 180 kHz carrier are modelled as 12 servers. Each report occupies one for the setup plus transmission time of its coverage class. Requests arrive at rate $N/900$ s^{-1} and blocked requests are lost, giving the Erlang-B blocking probability [15]; capacity is the N for which blocking reaches 10 %.

Wi-Fi 6. Airtime is negligible at this traffic level, so capacity is set by the access point's association limit, assumed to be 128 stations. This is an assumption about a typical access-point configuration, not a standard-defined limit.

3.5 Multi-criteria ranking

Seven criteria are used: range (urban outdoor, maximum configuration), battery life (15-minute interval, 50 m case), capacity, peak application throughput, module cost, recurring connectivity cost and infrastructure burden on the owner. The first four are benefits (log-scaled before normalisation), the last three are costs. Module cost (USD 6, 12 and 4 for LoRa, NB-IoT and Wi-Fi 6) is indicative. Recurring cost and infrastructure burden are ordinal scores from 1 to 5 chosen by the author (recurring: 1, 4, 1; burden: 4, 1, 3) and are therefore subjective. Three weight profiles are defined (Table 9). Robustness is tested by drawing 10 000 weight vectors from a Dirichlet distribution centred on each profile (concentration 20) and counting how often each technology ranks first. A final sweep raises the infrastructure-burden weight from 0 to 0.9, rescaling the other weights of the agriculture profile proportionally.

4. Results

4.1 Coverage

Table 2. Range at 90 % edge availability (rural values capped at 15 km).

Scenario	LoRaWAN SF7	LoRaWAN SF12	NB-IoT CE0	NB-IoT CE2	Wi-Fi 6 (1 Mb/s)
Urban outdoor	785 m	2.09 km	1.25 km	5.05 km	91 m
Rural open	4.30 km	14.18 km	7.60 km	15.00 km	310 m
Urban indoor	296 m	785 m	471 m	1.90 km	26 m

NB-IoT at its deepest coverage class reaches 5.05 km in the urban outdoor case, 2.4 times the range of LoRaWAN at SF12 (2.09 km), the difference reflecting its higher transmit power and repetition gain (Table 2, Fig. 1). Wi-Fi 6 reaches 91 m, about one twenty-third of the LoRaWAN range. With wall penetration the ranges fall to 1.90 km, 785 m and 26 m. The NB-IoT advantage is therefore largest in exactly the indoor and underground cases that motivate the

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technology. The 14 dB sub-GHz and 18 dB 2.4 GHz penetration losses are typical textbook assumptions; real buildings vary widely.

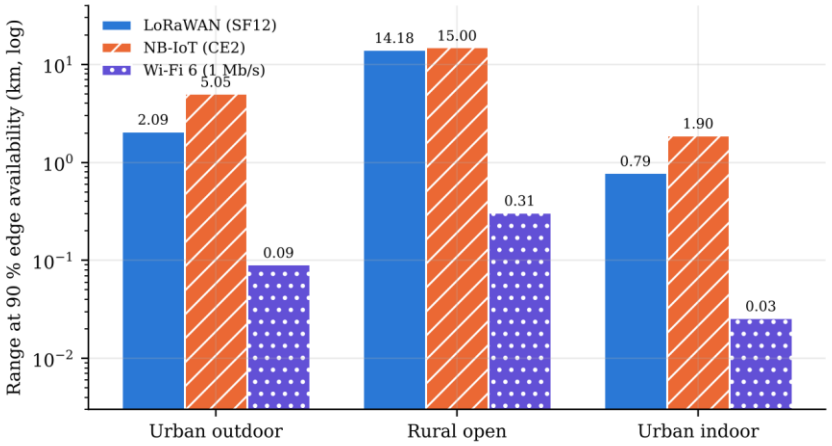

Fig. 1. Range at 90 % edge availability for the longest-range configuration of each technology in three scenarios (logarithmic axis; the rural NB-IoT value is capped at 15 km).

4.2 Airtime and energy per message

Table 3. LoRaWAN airtime and energy per uplink for each spreading factor.

Spreading factor	Airtime (ms), 20 B	Energy (mJ), 10 B	Energy (mJ), 20 B	Energy (mJ), 100 B
SF7	72	9.9	11.4	28.5
SF8	134	18.3	21.3	51.0
SF9	247	33.6	39.6	93.1
SF10	453	61.3	73.2	168.3
SF11	987	134.5	158.3	372.4
SF12	1810	245.1	292.7	673.4

LoRaWAN airtime grows from 72 ms at SF7 to 1.81 s at SF12 for a 20-byte payload (Table 3), and energy per message rises 26-fold from 11.4 to 293 mJ. The spreading factor is therefore the main lever on LoRaWAN battery life and is itself set by distance.

Table 4. Energy per uplink message (mJ) versus application payload.

Technology / configuration	10 B	20 B	50 B	100 B
LoRaWAN SF7	9.9	11.4	18.1	28.5
LoRaWAN SF12	245	293	435	673
NB-IoT CE0	339	343	354	374
NB-IoT CE0, release assistance	161	165	176	196
NB-IoT CE2	1,368	1,616	2,359	3,598
Wi-Fi 6 TWT	11.9	12.0	12.2	12.5
Wi-Fi, reconnect each time	219	219	219	219

Table 4 and Fig. 2 compare the technologies directly. For short payloads Wi-Fi 6 with TWT (12.0 mJ) and LoRaWAN at SF7 (11.4 mJ) are practically equal and about 30 times cheaper than NB-IoT at CE0 (343 mJ). The NB-IoT figure is dominated by the 10 s connected-mode tail (about 198 mJ of the 343 mJ); with release assistance it falls to 165 mJ. At SF12 LoRaWAN (293 mJ) uses less than NB-IoT at CE0 but exceeds it once the payload grows beyond roughly 30 bytes. Without TWT, Wi-Fi spends 219 mJ per report on reconnection, 18 times more than with TWT. Payload size matters little for Wi-Fi and NB-IoT at CE0, where fixed overheads dominate, but strongly for LoRaWAN at high SF and NB-IoT at CE2.

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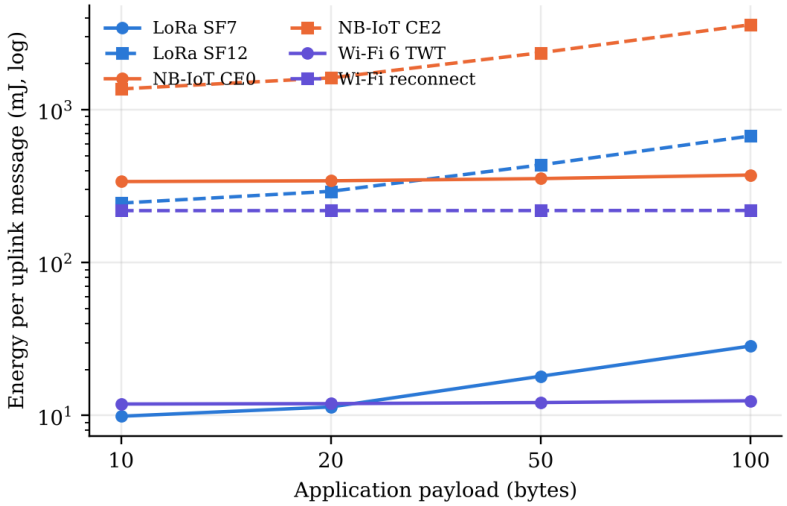

Fig. 2. Energy per uplink message against payload for each technology and configuration (logarithmic axis).

4.3 Battery life

Table 5. Modelled battery life (years) of a 2400 mAh cell, 20-byte reports. † exceeds 15 years: calendar life limits the cell.

Case / technology	5 min	15 min	1 h	6 h	24 h
A: 50 m					
LoRaWAN (SF7)	14.3	>15†	>15†	>15†	>15†
NB-IoT (CE0)	0.7	1.9	6.4	>15†	>15†
NB-IoT (CE0, release assist.)	1.3	3.7	10.8	>15†	>15†
Wi-Fi 6 (TWT)	3.1	3.5	3.7	3.7	3.7
Wi-Fi (reconnect)	1.0	2.8	8.0	>15†	>15†
B: 1.5 km					
LoRaWAN (SF11)	1.4	4.0	12.9	>15†	>15†
NB-IoT (CE1)	0.4	1.2	4.3	>15†	>15†
NB-IoT (CE1, release assist.)	0.6	1.7	6.0	>15†	>15†
C: 4 km (LoRaWAN and Wi-Fi out of range)					
NB-IoT (CE2)	0.1	0.4	1.6	7.7	>15†
NB-IoT (CE2, release assist.)	0.2	0.5	1.8	8.3	>15†

At 50 m and a 15-minute interval the modelled lifetimes are 27 years (LoRaWAN, flagged †), 3.5 years (Wi-Fi 6 with TWT), 2.8 years (Wi-Fi with reconnection) and 1.9 years (NB-IoT), improving to 3.7 years for NB-IoT with release assistance (Table 5, Fig. 3). The ordering changes with the interval. Wi-Fi 6 with TWT is almost flat at 3.1–3.7 years because its 60 µA sleep floor dominates at all but the shortest intervals, and in the model it is overtaken by NB-IoT with release assistance at an interval of about 15 minutes and by plain NB-IoT somewhere between 15 minutes and one hour. The reconnect strategy has a lower sleep current (8 µA) but a large per-report cost; the model gives a break-even interval of 20 minutes between the two Wi-Fi strategies, so TWT is advantageous only for intervals shorter than that. This crossover depends directly on the assumed 60 µA retention-sleep current and would move with a better or worse part.

At 1.5 km LoRaWAN needs SF11 and its 15-minute lifetime drops to 4.0 years, still above NB-IoT at CE1 (1.2 years). At 4 km only NB-IoT at CE2 is available and lasts 0.42 years at 15-minute reporting but 7.7 years at 6 hours. Interval and distance together thus separate the technologies more than either does alone.

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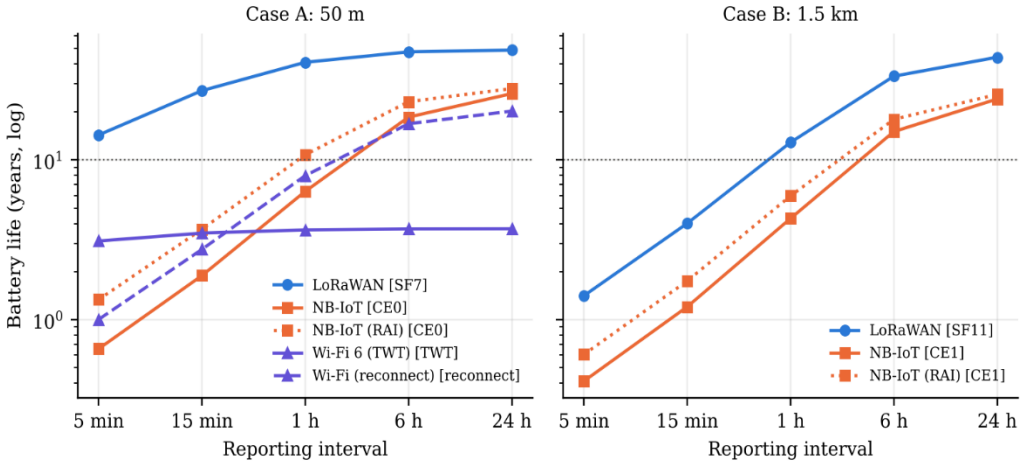

Fig. 3. Modelled battery life versus reporting interval for the 50 m (left) and 1.5 km (right) cases. The dotted line marks 10 years. Wi-Fi 6 is out of range in the right panel.

4.4 Capacity

Table 6. LoRaWAN packet-delivery ratio of covered nodes (one gateway, 15-minute reports, 20-byte payload).

Nodes per gateway	ADR, 3 ch	ADR, 8 ch	Fixed SF12, 3 ch
500	98.7 %	99.5 %	64.4 %
1,000	97.6 %	98.9 %	44.9 %
2,000	95.4 %	98.3 %	24.0 %
5,000	89.5 %	95.8 %	8.1 %
10,000	80.0 %	91.9 %	3.6 %
20,000	64.9 %	84.6 %	1.8 %

Table 6 and Fig. 4 show how strongly protocol configuration drives LoRaWAN scale. With all nodes at SF12 the delivery ratio is already 64 % at 500 nodes and 8 % at 5 000, because every packet occupies the channel for about 1.8 s. With ADR, 60 % of nodes in the 1.8 km disc use SF7 (72 ms airtime) and the same three channels sustain 90 % delivery up to roughly 4,746 nodes. Eight channels extend this to about 12,578. About 4 % of nodes in the disc fall outside SF12 coverage because of shadowing and are not counted in the delivery ratio. The capacities are interpolations between simulated node counts and are subject to Monte Carlo variation, and the simulation ignores downlink traffic and acknowledgements, which would reduce capacity in practice.

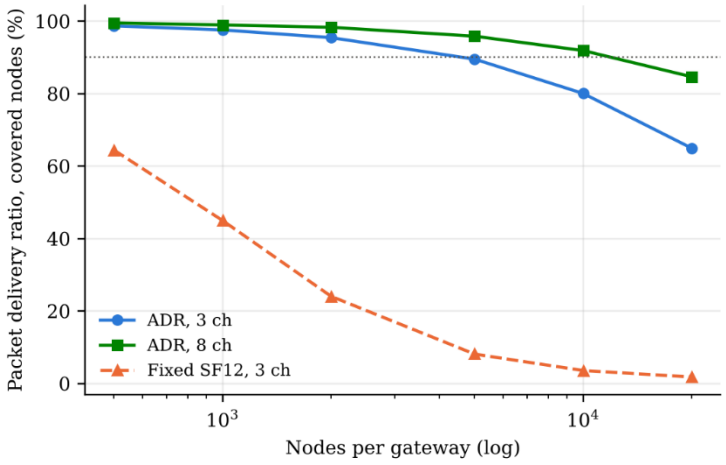

Fig. 4. LoRaWAN delivery ratio versus number of nodes per gateway. The dotted line is the 90 % target.

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Table 7. NB-IoT capacity of one 180 kHz carrier (12 single-tone resources, 15-minute reports; Erlang-B model).

NB-IoT configuration	Resource time per report (s)	Devices per carrier at ≤10 % blocking
CE0	0.52	16,355
CE1	1.17	7,284
CE2	3.37	2,534
CE0 + EDT (t_occ=0.3 s)	0.30	28,422

The NB-IoT model (Table 7) gives 16,355 devices per carrier when all devices are in the best coverage class, falling to 2,534 when all are in the deepest, because repetitions multiply the time each report occupies the carrier. An early-data style shortening of the resource time to 0.3 s would increase capacity to 28,422. A realistic cell holds a mixture of classes, so the practical capacity lies between the first two rows. The Wi-Fi 6 value of 128 is an association-limit assumption, and the three numbers are not strictly equivalent: LoRaWAN is for one gateway with three channels, NB-IoT for one carrier, and Wi-Fi 6 for one access point.

4.5 Multi-criteria ranking and sensitivity

Table 8. Decision matrix used in the TOPSIS analysis.

Criterion	LoRaWAN	NB-IoT	Wi-Fi 6 (TWT)	Type
Range, urban outdoor (m)	2,086	5,054	91	benefit
Battery life, 15 min (years)	27.2	1.9	3.5	benefit
Capacity (devices)	4,746	16,355	128	benefit
Peak throughput (kb/s)	5.5	15.0	1,000.0	benefit
Module cost (USD, indicative)	6	12	4	cost
Recurring cost (1–5, subjective)	1	4	1	cost
Infrastructure burden (1–5, subjective)	4	1	3	cost

Table 9. TOPSIS closeness (higher is better) with the percentage of 10 000 sampled weight vectors in which each technology ranks first.

Profile	Weights (range, battery, capacity, throughput, module, recurring, infrastructure)	LoRaWAN	NB-IoT	Wi-Fi 6
Smart agriculture	0.25, 0.30, 0.08, 0.04, 0.10, 0.15, 0.08	0.81 (98 %)	0.28 (1 %)	0.41 (1 %)
Smart-city metering	0.12, 0.25, 0.25, 0.08, 0.05, 0.13, 0.12	0.70 (89 %)	0.36 (6 %)	0.41 (5 %)
Managed-service metering	0.20, 0.20, 0.20, 0.05, 0.05, 0.05, 0.25	0.52 (49 %)	0.53 (49 %)	0.32 (2 %)

For the agriculture profile LoRaWAN has a closeness of 0.81 against 0.41 for Wi-Fi 6 and 0.28 for NB-IoT and ranks first in 98 % of weight draws (Tables 8–9, Fig. 5). For conventional city metering the order is the same, with LoRaWAN first in 89 % of draws. The result changes for the managed-service profile that places 25 % of the weight on infrastructure burden: NB-IoT and LoRaWAN have closeness 0.53 and 0.52, and each ranks first in about half of the draws (49 % and 49 %), i.e. they are statistically tied. Wi-Fi 6 never leads in more than 5 % of draws, mainly because of its short range and modest capacity.

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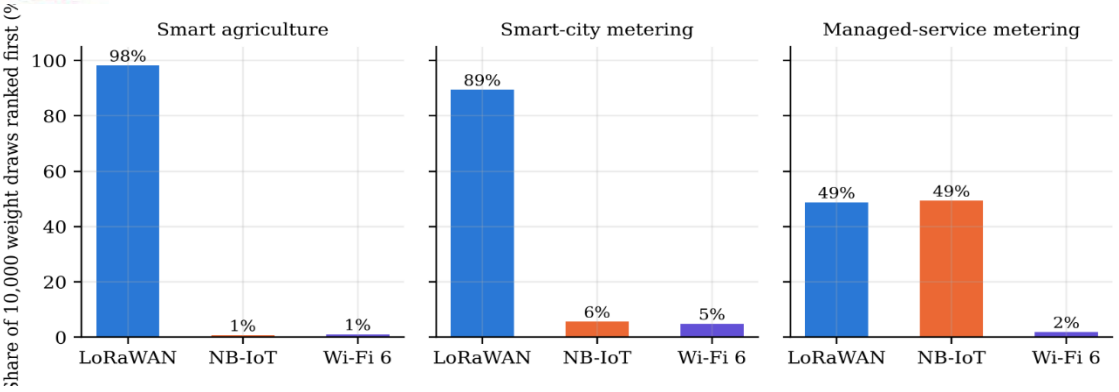

Fig. 5. Share of 10 000 sampled weight vectors in which each technology ranks first, for the three application profiles.

Increasing the infrastructure-burden weight in the agriculture profile shows when the preference flips (Fig. 6). NB-IoT overtakes LoRaWAN once that weight exceeds about 0.35, against a baseline of 0.08. In other words, a decision-maker must care about not operating any network infrastructure roughly four times more than the baseline profile does before the recommendation changes. This threshold is a transparent statement of the one subjective judgement that most affects the outcome and is more informative than the ranking itself.

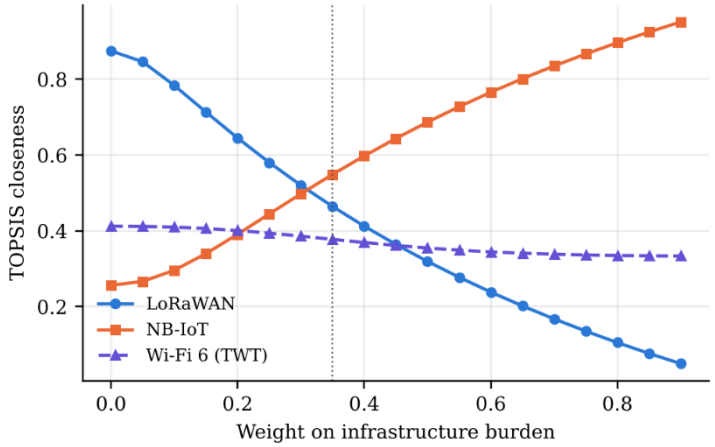

Fig. 6. TOPSIS closeness versus the weight placed on infrastructure burden (agriculture profile, other weights rescaled). The dotted line marks the point at which NB-IoT overtakes LoRaWAN.

5. Discussion

5.1 Main observations

Four conclusions follow from the models. First, no technology dominates: NB-IoT leads on coverage and cell capacity per carrier, LoRaWAN on battery life and on cost of connectivity, Wi-Fi 6 on throughput and per-message energy at short range. Second, protocol features are worth as much as the radio: NB-IoT release assistance roughly halves energy per message, LoRaWAN ADR multiplies capacity roughly tenfold, and Wi-Fi TWT lowers per-report energy by a factor of eighteen against reconnection. Third, the benefit of TWT is limited by the sleep current needed to remain associated, and above an interval of about 20 minutes deep sleep with reconnection can be preferable in the model. Fourth, the final recommendation is sensitive to weight on infrastructure ownership far more than to the radio parameters.

5.2 Limitations

This is a model-based study. Radio and energy parameters are representative values and not measurements; propagation uses a single statistical model per scenario; the LoRaWAN simulation has one gateway, ideal SF orthogonality, no downlink or retransmission traffic and no regulatory duty cycle; the NB-IoT model treats random access and scheduling as a single Erlang loss system and ignores paging and tracking-area updates; the Wi-Fi capacity is an assumed association limit; battery self-discharge and temperature effects are simplified; and costs and infrastructure burden in the decision matrix include subjective ordinal scores. TOPSIS is also subject to rank reversal when alternatives are added. Absolute values (years, kilometres) should therefore be read as indicative, and the

relative behaviour and break-even points as the useful output. Validation with a field testbed of each technology is the obvious next step.

6. Conclusion

A unified model of link budget, message energy, battery life and capacity was used to compare LoRaWAN, NB-IoT and Wi-Fi 6 for battery-powered nodes. In the urban case NB-IoT reaches 5.05 km, LoRaWAN 2.09 km and Wi-Fi 6 91 m. LoRaWAN and Wi-Fi 6 TWT need about 11–12 mJ per report against 343 mJ for NB-IoT without release assistance, yet the Wi-Fi advantage disappears over long intervals because of its sleep current. LoRaWAN capacity depends on ADR by an order of magnitude, and NB-IoT capacity on the coverage-class mix. A TOPSIS analysis with sampled weights places LoRaWAN first for agriculture and standard metering, with NB-IoT competitive once infrastructure ownership carries more than about 35 % of the weight. The study offers a transparent framework that practitioners can re-run with their own parameters.

Declaration. The study is simulation-based and uses no field measurements. Any use of AI-based writing or coding assistance must be disclosed in accordance with the target journal's policy.

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