Wireless Personal Communications (2021) 121:887–903
https://doi.org/10.1007/s11277-021-08664-0

Comparison of LPWAN Technologies: Cost Structure and Scalability

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Accepted: 14 June 2021 / Published online: 7 July 2021

Abstract
Small-scale commercial rollouts of Cellular-IoT (C-IoT) networks have started globally since last year. However, among the plethora of low power wide area network (LPWAN) technologies, the cost-effectiveness of C-IoT is not certain for IoT service providers, small and greenfield operators. Today, there is no known public framework for the feasibility analysis of IoT communication technologies. Hence, this paper first presents a generic framework to assess the cost structure of cellular and non-cellular LPWAN technologies. Then, we applied the framework in eight deployment scenarios to analyze the prospect of LPWAN technologies like Sigfox, LoRaWAN, NB-IoT, LTE-M, and EC-GSM. We consider the inter-technology interference impact on LoRaWAN and Sigfox scalability. Our results validate that a large rollout with a single technology is not cost-efficient. Also, our analysis suggests the rollout possibility of an IoT communication Technology may not be linear to cost-efficiency.

Keywords Cost structure · LPWAN · Ultra-narrowband · Cellular-IoT · LoRaWAN · NB-IoT

1 Introduction

Internet of things (IoT) extends internet connections to physical devices like sensors and actuators. Physical devices are remotely communicating with each other and end-users via IoT platforms. For a multitude of application areas like smart cities, smart factories, vehicular, and surveillance services, experts identified IoT as the key to digital transformation. Hence, IoT has been a widely studied topic in the technology, economics, business, and policy management domain.

The commercial rollout of 5G and Cellular-IoT (C-IoT) networks began in 2020. However, according to Ericsson mobility report [1], already one-eighth of the IoT devices

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are connected worldwide through cellular networks using 2G, 3G, and 4G. The rollout of C-IoT systems, e.g., NB-IoT, LTE -M, and EC-GSM-IoT is expected to boost the IoT business of telecom operators. On the other hand, a plethora of low power extensive area networks (LPWAN) and low power local area networks (LPLAN) technologies like Sigfox, LoRaWAN, Weightless N/P, Z-Wave, Dash-7, BLE, Zigbee, LoRa, 802.11ah, and 802.15.4k are available to provide indoor and outdoor coverage. Currently, there are around twenty IoT connectivity solutions available in the market. Most importantly, the end-user device modules of these technologies are available in the market.

So far, most of these technologies, both C-IoT and non-cellular LPWAN technologies, are still at the pilot phase with a small area coverage and service provisioning. The cost-effectiveness of an IoT communication technology is not sure from an IoT service provider and communication service providers' perspective. The scalability and viability of these technologies are a concern. Researchers performed a number of studies on Network-Economics' studies on GSM [2], WCDMA [3, 4], and LTE [5–10]. Moreover, there are plenty of studies on IoT business modeling [11, 12] and value network [13, 14]. In [15], market research company Mobile Experts provides a return of investment (ROI) calculations predicted for LPWA and cellular-IoT solutions. To the best of our knowledge, IoT connectivity service scalability has not yet received the necessary attention in scientific research. Hence, there is currently a research gap related to understanding different architecture choices and their impact on IoT communication systems' scalability.

Furthermore, technical papers present intra-technology interference challenges in the unlicensed band [16–18]. In [16], a survey has been performed to identify the gap of LPWAN unlicensed band research. The study has identified the uncoordinated coexistence of devices as a key challenge that may affect the coexisting technologies' packet transmission performance. [17] shows the impact of cross technologies like camera, analog phone, FH phone, and microwave on IEEE 802.15.4. Interference impact between LoRa and IEEE 802.15.4 shows in [18]. Also, coexistence impact of LoRa and IEEE 802.11n (WiFi) is studied and presented in [19]. Due to the modulation scheme, LoRa is more resilient to interference than IEEE 802.11n and IEEE 802.15.4. Also, the paper points out the trade-off between bit rate and spreading factor that limits the data rate. A measurement base interference impact of sub-one GHz technologies in LoRa presented in paper [20]. The results show that Sigfox interference in the worst case can result in 28% losses. Similar observation is found in [21] for IoT devices in mobility. Till to date, no work assesses the coexistence impact of LoRaWAN and Sigfox. Also, the coexistence impact of LoRaWAN and Sigfox on each other's scalability is not investigated thoroughly.

Henceforth, this paper extends the discussion of [22] focusing on the deployment options and cost-structure of IoT communication service scalability. To do so, first, we investigate the coexistence impact of LoRaWAN and Sigfox on each other's scalability. Then we assess the cost-effectiveness of C-IoT and LPWA technologies. This paper aims to compare C-IoT and non-cellular LPWAN technologies' scalability advantages and disadvantages in terms of rollout cost. We study deployment options in Urban and Rural scenarios and using unlicensed and licensed bands. Overall, we check the cost structure of IoT communication systems to answer the overall question: 'What are the advantages and disadvantages of LPWAN technologies to build a network in different scenarios?'

We answer the question from the IoT communication service providers' (CSPs) perspective. To answer this question, we consider IoT service deployments in the urban and rural context. In this study, we compare Sigfox, LoRaWAN, NB-IoT, LTE-M, and EC-GSM-IoT to understand the practicality of each technology under rural and urban use-cases. We analyze the inter-technology interference impact on the scalability of Sigfox and LoRaWAN.

Table 1 Specifications of technologies

	Sigfox	LoRaWAN	NB-IoT	LTE-M
Frequency band (MHz)	868	868	868	700
Spectrum (kHz)	200	1175	180	1080
Sub-channel BW (Hz)	100	125 k	15 k	18 k
Spacing (kHz)	0	200	3.75	15
Modulation	D-BPSK	FSS/CSS	OFDMA	OFDMA
Receiver sensitivity (dBm)	164	154	150	146
Device capacity/cell	100 k	10 k	40 k	50 k
DL payload (Bytes)	8	14	125	1 k
UL payload (Bytes)	12	51	125	1 k
Data rate (bps)	100	1760	50 k	1000 k
Duty cycle/ Tx restriction	140 msg/day	1%	–	–
Bi-directional	HD [1]	HD	HD	FDD, TDD, HD

The main contributions of this paper are: (1) the cost comparison of LPWAN in urban and rural deployments, (2) identification of the key cost drivers of LPWAN network rollout, (3) the impact of inter-technology interference on the LPWA scalability in the unlicensed band, and (4) extending understanding and motivation of the need for IoT communication technologies mix to optimize the profitability.

The paper is outlined as follows; Sect. 2 covers the overview of studied technologies. Section 3 describes the research approach and method. Section 4 elaborates the assumptions and considered scenarios. Section 5 illustrates the results. Findings and discussions are listed in Sect. 6, and conclusions are presented in Sect. 7.

2 Overview of LPWAN Technologies

This section describes the main characteristics of Sigfox, LoRaWAN, NB-IoT, LTE-M, and EC-GSM-IoT briefly. Table 1 illustrates the specifications of the selected IoT communication technologies. We have collected the technology specifications based on academic articles [23, 24, 28–30], standardization specifications [25, 26] and white papers [27, 28].

2.1 Sigfox

Sigfox is a proprietary ultra-narrowband (UNB) technology that operates in an unlicensed ISM band. In Europe, it operates at 868 MHz, and in North America, it operates at 915 MHz. Sigfox offers an end-to-end IoT connectivity solution in 45 different countries globally along with a connectivity platform service. Sigfox uses binary phase-shift keying (BPSK) modulation in the ultra-narrow band (100 Hz) that gives low noise level, low power consumption, and high receiver sensitivity. As a result, larger area coverage with a simple end-device antenna design is achieved with Sigfox. The simple end-device antenna design assures a longer battery lifetime but with the cost of throughput. Sigfox data rate is only 100 bps. Due to regulation, a device can transmit 140 messages per day and can receive eight messages per day. The transmission works in a 'fire and forgets' manner where a device transmits the message three times in different frequency and period, which reasonably assures the message delivery rate to 95%. The payload size is 12 bytes with 14 bytes of overhead. The more significant advantage of Sigfox is that the country operators only deploy and manage the radio networks where the OSS/BSS and platform are centralized and shared by all the operators in the world.

2.2 LoRaWAN

LoRaWAN is adapted from LoRa and modulates in the unlicensed SubGHz band. For modulation, it uses the proprietary chirp spread spectrum (CSS) techniques. LoRaWAN shares ISM Band 868 MHz in Europe and 915 MHz in North America along with Sigfox. It also supports the limited bi-directional transmission of a narrowband signal over broader channel bandwidth. LoRaWAN uses spreading factors (SFs) that give a trade-off between extended coverage area and bandwidth. Depending on different SF, the data rate can vary between 300 bps and 50 kbps. This means the cell edge user can transmit at 300bps, and the closer a device to the access point, the higher throughput a device can achieve through LoRaWAN [22]. Due to the regulation policy, LoRAWAN has 1% duty cycle, which can be translated to 36 sec/hour transmission per device per channel.

2.3 NB-IoT

Narrowband-IoT (NB-IoT) is standardized in 3GPP release-13. NB-IoT can be considered as another track dependent on the current 3GPP innovation particulars. NB-IoT can be deployed in Licensed (in-band, guard band. Standalone) and unlicensed band. In the licensed band, there are no limitations on the duty cycle. In the unlicensed band, the duty cycle depends on the spectrum regulation policy of the specific region. NB-IoT occupies one resource block of LTE systems, corresponds to 180 kHz in the frequency band. In NB-IoT new radio is introduced to optimize the battery efficiency and coverage [23]. NB-IoT provides extended coverage (164 dB) and can support a long battery lifetime (up to 15 years). Future NB-IoT will extend to include services like localization, and multicast, in the upcoming release [23].

2.4 LTE-M

LTE-M, also known as LTE-MTC or LTE CAT-M, is a 3GPP Release-13 LPWAN series C-IoT communication technology. Like other LPWAN technologies, IoT service targeted LTE-M is designed to conserve battery power and can offer up to 10-years battery lifetime with 5 watt-hour battery[1]. The data rate may vary between 10 kbps and 1 Mbps. LTE-M can be deployed inband to LTE, where the LTE service can coexist within the same bandwidth. TTI bundling, repetition, and narrowband retuning are the key features to achieve extensive coverage ($\approx 164.7dB$) of LTE-M [30]. By reducing end-device design complexity, Cat-M devices' cost would be comparable to GSM devices. LTE-M can support positioning service with multicast and mobility. Additionally, the voice over LTE (VoLTE) service can be supported by LTE-M. LTE-M is expected to be deployed with a simple software upgrade in addition to the existing LTE's radio system but not backward compatible.

[1] Where the battery and lifetime are dependent on traffic and coverage needs.

2.5 EC-GSM-IoT

EC-GSM is the enhanced GSM that reuses GSM and CDMA technology with changes on the logical channel to enhance the coverage. Long battery life, low device cost relative to GPRS/GSM devices, extended coverage, and variable rates are all benefits of extended DRX with radio control level enhancements. In contrast to GSM, it can support a large number of devices while providing enhanced security. Release-14 enables the positioning, makes at least 3 dB MCL improvement for low power devices on all uplinks, and uses alternative mappings of blind physical layer transmissions for higher coverage classes [31]. This results in 20 dB coverage improvement. The expected battery lifetime for EC-GSM is more than ten years.

Additionally, EC-GSM delivers EDGE support, which provides instantaneous global coverage and allows the maximum throughput of 355 kbps. A simple software upgrade of existing GSM deployments should be enough to avail of such services. Also, due to the expiration of the device module patents, the module cost for EC-GSM is expected to be the lowest among the 3GPP-defined technologies [31].

3 Research Approach

This section describes the method, analytical approach, scenarios, and assumptions that are considered in this paper. We analyze the cost-capacity features of C-IoT and non-Cellular IoT systems. The analysis includes network dimensioning and costs analysis.[2]

3.1 Viability Assessment Method

The typical lifecycle of a network consists of three phases: planning, rollout, operation, and maintenance. The planning phase is critical for assessing the business viability of a deployment. This is the first step in determining how to realize and minimize the risk associated with a specific business goal or technology implementation. The aim is to lower the investment risk and understand how a specific technology will better meet a business goal with a specific technology. A thorough techno-economic analysis, which includes qualitative business analysis, technical performance analysis of the subject technology, and qualitative assessment of the technology, is required for the validity check.If all three parameters assessments suggest business scalability with positive cash flow, the CSPs then move to the second phase of the initial rollout. At year zero, a CSP invests a significant amount to network rollout.

Extend the investment over the years, first to ensure coverage and then to ensure service efficiency by continual operation and maintenance, followed by a continuous investment in technology and network extension, which is the third step, which operates almost parallel to the second. The second phase's investment is a considerable upfront investment typically considers as capital expenditure (CAPEX). Costs like the maintenance cost and electricity fees are considered as the regular incurring cost, known as an operational expenditure (OPEX).

[2] In terms of deployment cost and Net Present Value (NPV).

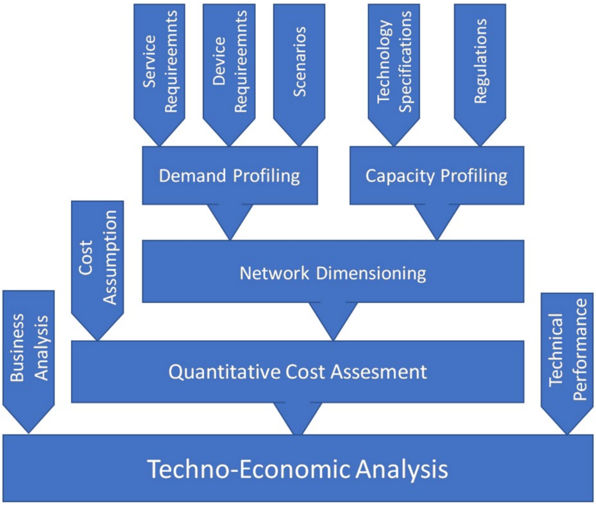


Fig. 1 Viability assessment framework

3.2 Network Dimensioning

Figure 1 illustrates the proposed assessment framework for IoT communication service providers. The demand profile is created here based on the service, device, and scenario requirements. The number of devices and their normalized duty cycle are a likely consequence of the IoT service case's demand. Capacity is calculated based on the technical specification like bandwidth, data rate, and modulation, along with regulations. For instance, technologies that are operating at the unlicensed band would face restrictions on the end-user activity pattern. The required number of sites is estimated using the framework explained in [22], based on the demand and capacity profile. We consider four key parameters for the capacity trade-offs:

1. Coverage: number of the site to area coverage
2. Device capacity per site
3. Data capacity per site per day
4. Message transmission capacity per site per day based on the 'time on-air' calculation

Network dimensioning gives the required number of equipment, fronthaul, and backhaul bandwidth.

In addition, as seen in Fig. 2, we found three different types of cell patterns. Omni-directional, null sector, and sectorized cell are relevant patterns for meeting certain performance criteria. For example, Sigfox uses 3-RAT null-sector strategy where there is no sector within a cell. If a device transmits a payload, all the nearby receivers receive the message. Then, forward the message to the core. OSS/BSS then detects and discards the duplicate packets if the core network receives multiple packets. In such a way, the network can increase the link availability and accessibility performance rate. However, this strategy potentially wastes lots of radio resources and may become a barrier to scale up the cell capacity where the sectorized cell is suitable for capacity densification. Omni-directional antenna takes less rollout cost as we can potentially deploy a single antenna per cell.

Table 2 Coverage area and re-usable sites

	Urban		Rural	
	Coverage (km^2)	Re-usable sites	Coverage (km^2)	Re-usable sites
Sigfox	1.296662	40	36.47679	1
LoRaWAN, SF=9	0.570355	20	18.57258	2
NB-IoT	0.69244	15	24.33866	2
LTE-M	0.466199	10	15.49615	2
EC-GSM	0.430936	15	16.08256	2

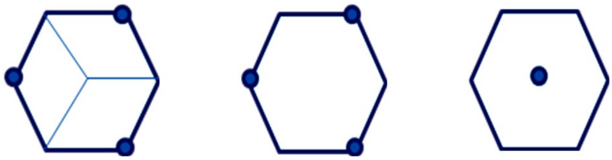


Fig. 2 Three different types of sites (omnidirectional, 3-RAT null-sector, three-sector)

Furthermore, we consider the coexistence impact of LoRaWAN and Sigfox in the unlicensed band. We evaluate the scalability limits of LoRaWAN and Sigfox to meet the 95% packet delivery rate. In section V, we present the result of our simulations in detail. According to the simulation results, we show that LoRaWAN and Sigfox can coexist with slide performance deprivation. In coexistence case, packet loss for Sigfox and LoRaWAN is around 3% and 4.5%, respectively.

To calculate the required number of sites for area coverage, first, we estimate the cell range from path loss. The path-loss is calculated using the sensitivity of the receivers, transmit power, antenna gain, and transmitter parameters. Then, for urban outdoor to indoor attenuation and rural outdoor attenuation, we use the Okumura-Hata propagation model. The derived cell range of different technologies can be found in Table 2. In this calculation, we consider all the sensor devices have an antenna gain of 3 dB, and the receiver antenna gain at the base station is set to 6 dB.

3.3 Cost Module

CAPEX and OPEX elements directly linked to the IoT radio access technologies (RATs) deployment are considered as the total cost of ownership. The parameter considered in the CAPEX and OPEX equations as shown in Fig. 3. Table 3 Lists the cost assumptions that are taken from three primary sources. We took the NB-IoT, LTE-M cost assumptions from METIS-II [24, 31]. Sigfox, and LoRAWAN from [7, 24].

The net present value (NPV) analysis is applied to account for the investment and operation cost. In this study, we only calculate NPV based on the cash flow related to network deployment-related costs with a discount rate of 10%. The NPV for N years is calculated as,

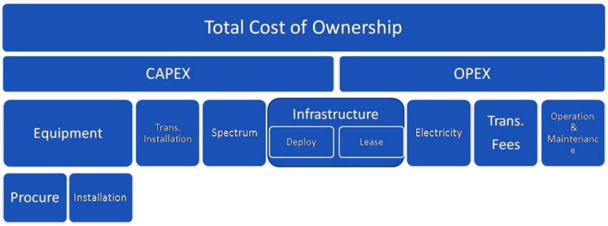


Fig. 3 Cost module

Table 3 Cost assumptions

	Sigfox	LoRaWAN	NB-IoT	LTE-M	EC-GSM
Equipment cost (K€)	4	1	3-10	6	8
Installation cost (K€)	6	2	10	10	10
Spectrum cost (K€/kHz/site)	0	0	0.001	0.001	0.001
Site build cost (K€)	10	2	20	20	20
Site lease (K€/year)	0.8–1	0.4–1	3.5–8	3.5–8	3.5–8
Transmission installation cost (K€)	0.5	1	0	0	0
Electricity cost (K€/year)	1	0.1	1	1	1
Transmission cost (K€/year)	0.12	0.1	0.1	0.1	0.1
Operation and maintenance cost (relative to CAPEX)	15%	20%	10%	10%	10%

$$NPV = \sum_{yr=0}^{N} \frac{C_{yr}}{(1+R)^{yr}} \quad (1)$$

where C_{yr} is the annual total cash flow for the year yr. R is the discount rate, and yr is the network operation period in years. Also, we assumed that the maintenance cost is increasing at a rate of 5% per year.

3.4 Techno-Economic Analysis

The techno-economic analysis is based on the qualitative results of the NPV, technical performance, and business aspects, meaning the targeted IoT services and market share is considered in this analysis. This is important because some technologies may come out cost-efficient from a business perspective, but the technology is not viable. For example, if we see that technology is viable for small-scale operations but not cost-effective for large-scale operations, lacking the business aspect like a business goal and strategy, we can make a partial argument that may not be accurate for all cases. In this case, the business case assumptions are reflected in terms of market share and growth rate.

Table 4 Traffic assumptions

Scenario	Area	Operator		Device density	Market share	Msg/day	Packet size
SC1	Urban	Incumbent	High	57,552	0.6	300	100
SC2			Low	1550	0.25	5	12
SC3		Entrant	High	57,552	0.15	300	100
SC4			Low	1550	0.05	5	12
SC5	Rural	Incumbent	High	70,000	0.6	300	100
SC6			Low	400	0.25	5	12
SC7		Entrant	High	70,000	0.15	300	100
SC8			Low	400	0.05	5	12

4 Assumptions

4.1 Scenario Description

We consider a large urban city and rural area in our use cases wherein urban city services like smart home, smart metering, and smart city are the key focus. For rural areas, services like forestry, farming industry monitoring, remote smart home, and smart elderly monitoring services are considered. We consider an urban city area of 300 km^2 and a rural city area of 10000 km^2. We considered the incumbent or brownfield and new market entrant or greenfield scenarios. In each case, we analyzed the scenario in both extremely high and low device density cases. Additionally, we analyze the site builds and leasing cost in all cases. The incumbent operators reuse the existing site for LPWAN rollout. We consider the unlicensed sub-GHz band is used by LoRaWAN and Sigfox, and licensed band by NB-IoT, LTE-M, EC-GSM-IoT.

4.2 Traffic Demand

Table 4 elaborates on the assumption of traffic demand of our considered use cases. Stockholm's population density is considered as baseline for the urban use-case, which is 3597 $people/km^2$. The device penetration is 16 sensors per person in the high-density case and 50% of population density for the low-density case. For a rural area, the highest density of trees per km^2 in Sweden, which is 69967 $trees/km^2$ is considered. However, when it comes to population density in rural areas in Sweden, it can be as low as 25 $people/km^2$. In this study, we take a normalized average, which is 100 $people/km^2$. Now for the high-density traffic case, it is assumed that the forestry monitoring services will be the key service, and monitoring the trees will be the essential Industrial-IoT service for the Swedish timber industry. This paper assumes that 70000 $trees/km^2$ will be under monitored by the end of 10 years of operation. Also, it is assumed that the devices' growth rate is 50% in greenfield cases and 35% in brownfield cases.

5 Results and Cost Analysis

In this section, first, we present a simulation-based inter-technology interference impact on Sigfox and LoRaWAN scalability. Then we use this understanding to analyze the deployment cost structure.

Table 5 Simulation parameters

Parameters	Values
No of sigfox devices	1000 (with step size 10)
No of LoRaWAN devices	100 (with step size 1)
LoRaWAN SF	6-12
LoRaWAN bit rate	0.293-5.468 kb/s
Sigfox frequency span	200 kHz
LoRaWAN frequency span	125 kHz
LoRaWAN channel	6
No of packet transmission (Sigfox)	3
No of packet transmission (LoRaWAN)	1
Payload	25 bytes

5.1 Simulation Assumption

We perform a MATLAB-based simulation where one gateway per technology is considered. The cell range for Sigfox and LoRaWAN is taken from Table 2. Both technologies can use the maximum allowed transmit power defined by ETSI. We consider different sensitivity levels for different SF values. We assume each device generates one payload per day. We only consider the performance over 1 min transmission. The details of the assumptions are listed in Table 5.

5.2 Scalability in Unlicensed Band

Figure 4 shows the scalability limits of LoRaWAN and Sigfox in an unlicensed band coexistence case. As one can see on the left subfigure of Fig. 4, LoRaWAN coexisting with Sigfox on average can gain four packet collisions per minute with a 4.5% packet error rate. As we did not consider the packet error recovery mechanism in detail, the error rate and the failed transmission are equal. Some study has shown that depending on the collision location, the recovery of the payload is possible. In such a case, the collision rate will reduce from this observation. For simplicity and high-level understanding, we take into account this error rate. So, where there are around 700 Sigfox devices, around 5% packet will be erroneous.

For the Sigfox case, as illustrated on the right subfigure of Fig. 4, where 100 LoRa devices are active, Sigfox devices encounter around 100 failed transmissions with 700 collisions. However, due to the 3-packet transmission in different times and channels, the packet error rate is maximum around 3%. So, in the case of the best-effort transmission assurance case, both the technology can coexist without hindering each other's scalability. Due to the duty cycle restriction and channel planning scope, we can assume that the LoRaWAN and Sigfox devices experience negligible interference from each other's transmission in small traffic conditions.

5.3 Cost Analysis

This section presents the results and analyzes the cost of Urban and Rural deployment.

Figure 5 depicts the number of sites require to meet the coverage and device requirements. Due to extensive coverage, Sigfox usually requires fewer sites than other

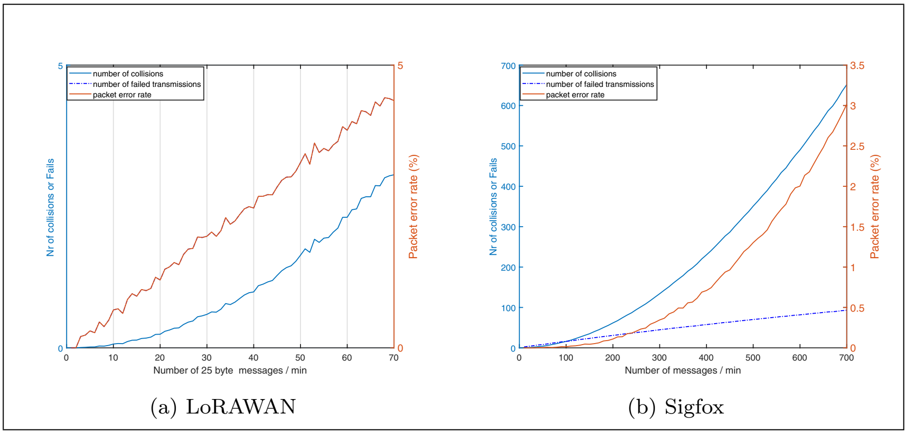


Fig. 4 Scalability performance

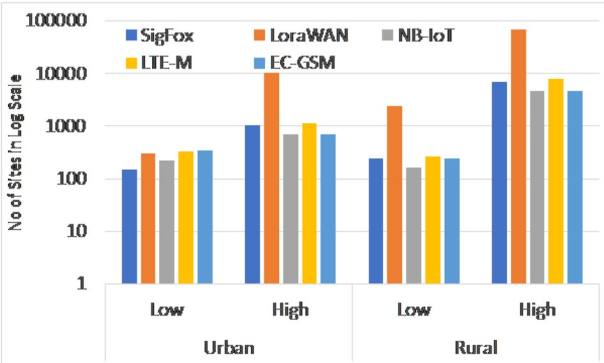
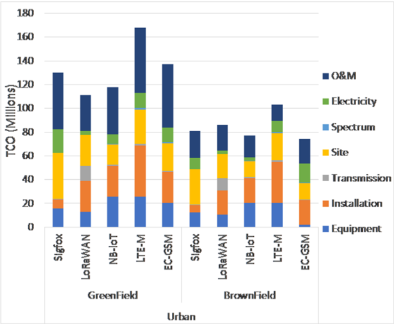


Fig. 5 Number of required sites

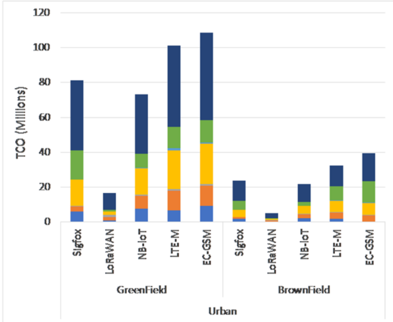
technologies. However, when the device density is high in both Urban and Rural cases, NB-IoT and EC-GSM- IoT requires less cell if C-IoT is deployed in the 3-cells sector. In all cases, LoRaWAN requires many cells to meet the device density.

When it comes to greenfield to brownfield deployment, one can observe from the subfigures of Fig. 6 that greenfield deployment is more costly than brownfield deployment. As the deployment cost includes new sites' acquisition cost, equipment cost, new deployment always takes up more costs than an upgrade of existing sites. It is interesting to note that greenfield actors need to invest a substantial amount in capturing a small market share than brownfield actors. On the other hand, brownfield actors can reuse their infrastructure to deploy the LPWAN networks, which are cost-efficient and viable. We can see a similar trend in the other three figures as well.

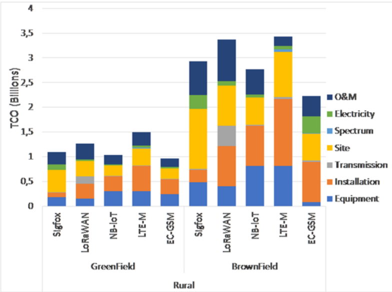
Figure 6 a and b illustrates the total cost breakdown of considered technologies deployment and operations in an urban scenario. Figure 6a shows the cost breakdown of deployment scenarios, SC1 and SC3 (see Table 4 for the scenario details). The brownfield and greenfield represent SC1 and SC3, respectively. From the figures, we can say



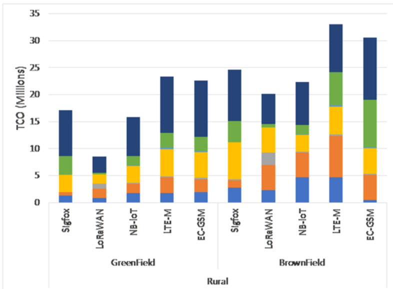
(a) SC1 (Urban, Brownfield), SC3 (Urban, Greenfield)



(b) SC2 (Urban, Brownfield), SC4 (Urban, Greenfield)



(c) SC5 (Rural, Brownfield), SC7 (Rural, Greenfield)



(d) SC6 (Rural, Brownfield), SC8 (Rural, Greenfield)

Fig. 6 TCO of different deployment options

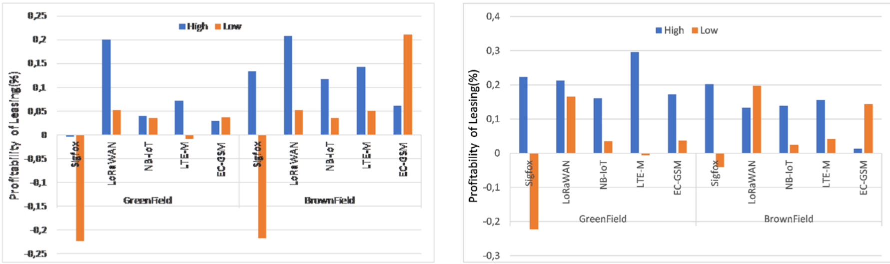
that NB-IoT and EC-GSM take less investment for SC1, and for SC3, LoRaWAN meets the low-cost requirements with less TCO than other technology options.

From Fig. 6b. one can see, LoRaWAN is cost-efficient in both SC2 and SC4 (see Table 4) when the device density is low. This is because the required number of equipment to meet the service demand is low. At the same time, the equipment pricing of LoRaWAN is assumed to be lower than other technologies equipment.

Figure 6c and d depicts the cost breakdown for rural deployment scenarios. For SC5 and SC7(see Table 4), EC-GSM is the most cost-effective solution (see Fig. 6c) in rural high traffic scenarios. From Fig. 6d, we can say that LoRaWAN is the most cost-efficient solution, like Fig. 6b.

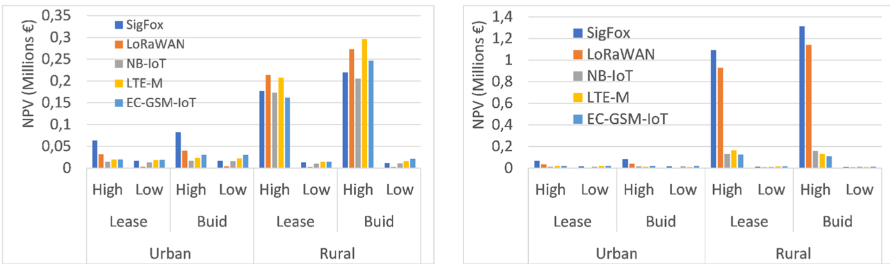
We can summarize the results of Fig. 6 by saying that LoRaWAN is cost-effective for low device density scenarios where EC-GSM is cost-effective for large area and high-density cases like in this case for rural coverage. Four key cost drivers of LPWAN deployments are site, electricity, management, and installation cost. OPEX is the most significant and dominant cost driver of LPWAN.

Figure 7 illustrates the effectiveness of infrastructure leasing vs. deployment. As shown in Fig. 7a and b, site leasing is not profitable for Sigfox with a low density of devices. This study assumes that Sigfox infrastructure cost and leasing cost are similar



(a) Site Build to Site Leasing ratio (Urban) (b) Site Build to Site Leasing ratio (Rural)

Fig. 7 Site build versus site leasing profitability



(a) Overall network costs of New Entrant (b) Overall network costs of Incumbent

Fig. 8 NPV

to C-IoT devices costs. As the Sigfox base station's device capacity and coverage range are higher, it requires the majority of the investment at the initial phase and then does not need to invest in those deployed cells. Hence, the recurring leasing cost turnouts expensive than building own site. On the other hand, LoRaWAN requires massive site deployments over years of operation. As a result, leasing turnouts profitable than deploying their infrastructure under yearly gradual rollout of LoRaWAN.

Figure 8 a and b illustrate the overall network costs of the technologies in different deployment options. We consider CAPEX and OPEX over time using NPV calculation. Also, we assume that all the technologies have an equal discount rate, which is assumed 10%, in this case. As the figures represent the NPV based on the investment over the years, the technology that gets the lower value is the cost-effective solution for any deployment scenario.

Figure 8 a shows that NB-IoT is cost-effective in the SC3(Greenfield-Urban-High) scenario when the device density is high. In SC4 (Greenfield-Urban-Low), when the device density is low, LoRaWAN is cost-effective among the considered RATs. In the rural case for SC7 (Greenfield-Rural-High) when the device density and traffic density are considered at the upper bound, EC-GSM is cost-effective for site leasing and

NB-IoT is cost-effective for site deployment case. For SC8, LoRaWAN is viable in both leasing and sites deploy strategy.

Figure 8b shows that for SC1 (Incumbent-Urban-High), NB-IoT is cost-effective with leasing, and LTE-M is cost-effective in site build case. This means NB-IoT and LTE-M are more cost-effective than other technologies for existing operations. LoRaWAN is viable for low device density case SC2 (Incumbent-Urban-Low). Similarly, in SC6 (Incumbent-Rural-Low), LoRaWAN is cost-effective in both leasing and building strategy, and EC-GSM is cost-efficient in both leasing and site-building of SC5 cases.

6 Discussion and Findings

This analysis compared the network deployment options of five LPWAN technologies in urban and rural areas. We studied the scalability impact of Sigfox and LoRaWAN in a coexistence scenario. According to our observation, LoRaWAN and Sigfox can coexist with minor performance degradation in the sub-GHz unlicensed band. It is important to note that we did not consider any other technologies impact in this study. We partially address the coexistence issue, but the question about the assurance of the service availability and the impact of coexistence of other technologies is not guaranteed. The existence of more technologies can further degrade performance.

Coming to the question, 'What are the advantages and disadvantages of LPWAN technologies to build a network in different scenarios?' The cost analysis indicates that LoRaWAN is cost-efficient in scenarios where the device density is low. In the case of the high density of devices for urban areas, NB-IoT and LTE-M are cost-efficient. For rural areas, EC-GSM-IoT is cost-efficient. If we consider a Greenfield CSP business goal that targets a small customer base with nominal market share, in such settings, we can say that LoRaWAN with site leasing is plausible for such CSP as they can concentrate on one technology for service provisioning. In [15], the author compared the NB-IoT and LoRaWAN deployment cost structure in terms of TCO. In the report, the economic analysis also shows a similar trend for nationwide deployment cases. We can say, LoRaWAN will give new entrant CSPs the roam to invest more in market penetration and sales strategy.

Now, even though we showed the coexistence impact is limited due to the duty cycle bindings. We can argue that LoRaWAN cannot provide a service guarantee, limiting the CSP's service provisioning rage in IoT service offerings.

Although in our considered use cases, Sigfox is not the cost-efficient solution, Sigfox, today, can provide end-to-end service provisioning and complete connectivity solution regardless they have proprietary technology. However, Sigfox is offering open and standard API and making many of the patents public, eventually reducing the device module price. Additionally, Sigfox has a ready and running platform and API ecosystem, which in many ways can be beneficial for an IoT service provider.

Furthermore, LTE-M can provide IoT services and enable voice over LTE (VoLTE) service. This can bring big motivation for operators as VoLTE can reduce and simplify today's hierarchical network by entailing quality assured voice service for users. Hence, cost-effectiveness may play a crucial role, but it may not be the primary role at the beginning of the deployment. However, we can say it will draw attention when scalable service provisioning is required for IoT communication services.

Future research should extend the unlicensed band technologies' coexistence impact on each technology's scalability and packet delivery performance, which may change our findings with more realistic performance metrics.

7 Conclusion

This paper presents an inclusive framework for analyzing the cost structure of an LPWAN technology rollout. We argue that the quantitative cost analysis is not enough for the viability analysis of the LPWAN rollout. Instead, we need to consider business requirements, technological performance, and cost-efficiency to analyze and select cost-effective and credible LPWAN solutions. Moreover, our study on the coexistence of LPWA technologies shed light on the concern of Sigfox and LoRaWAN coexistence. Thanks to the duty cycle regulation, the coexistence of Sigfox and LoRaWAN can still meet 95% packet delivery rate requirements. Furthermore, the cost-benefit analysis results suggest that CSPs may achieve cost-efficient deployment with single technology base rural and urban rollouts in a low density of devices. However, this is decidedly case-specific and limited to scenarios and traffic conditions. For instance, LoRaWAN is cost-effective to deploy in rural and urban areas when the device density and device activity rate are low. In all other cases, different technologies proved to be cost-efficient in different scenarios. So, if an operator wants to achieve a broader market share with extensive coverage, the single technology-based rollout may not be cost-effective. Also, our results suggest that leasing is not always cost-effective for all IoT communication service rollout.

Funding Open access funding provided by Royal Institute of Technology.

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