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Choosing IoT-connectivity? A guiding methodology based on functional characteristics and economic considerations

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Abstract

Along with the growing market of Internet of Things (IoT), the set of IoT-connectivity networks is also continuously expanding. Large-scale deployments of the new low-power wide-area networks and announcements of new technologies prove this trend. Although these new technologies take care of some key IoT-challenges, such as communication cost and power consumption, careful consideration of the IoT-connectivity is still required since there is no one-size-fits-all solution. Typical comparisons of IoT-connectivity networks are based on technical characteristics but remain unpractical when it comes down to comparing functional characteristics. Questions on public network accessibility, ability for private network deployments, and cost considerations related to IoT-connectivity networks often remain unanswered. In this work, a 2-step methodology is proposed to guide IoT-developers in choosing an appropriate connectivity network. First, a questionnaire walkthrough eliminates IoT-connectivity networks based on mismatches between their functional characteristics and the functional requirements of the IoT-applications. In a second step, an evaluation of the main cost components related to IoT-connectivity indicates the most economical solution. As an illustration, we present 2 case studies: (1) deploying smart shipping containers in the port of Antwerp and (2) installing shop'n go parking spaces, which detect vehicle presence via a sensor.

1 | INTRODUCTION

The Internet of Things (IoT), a fast emerging technological wave, already finding its way in the market under the form of various applications such as pet trackers, parking sensors, and smart water meters, is about to flood our imagination. Various researchers report on market sizes of billions of devices within the next 5 years.[1]

Addressing 2 important challenges being (1) power consumption and (2) range of the connectivity network, the deployment of low-power wide-area networks (LPWANs) has been an accelerator for the development of IoT-applications. In recent years, numerous radio-based connectivity networks and protocols have been developed, all contributing to the reality of IoT.

Today, IoT-developers have a complete set of connectivity networks at their disposal, ranging from short-range networks such as Bluetooth to global connectivity via satellite networks, all spread over the radio spectrum. Physical characteristics, such as frequency, regulations, and technology used, result in an extensive set of connectivity networks, each with their own specific particularities.

These particularities translate in pros and cons when considering a specific connectivity network for an IoT-application. Since there is currently no "one-size-fits-all" or best solution, choosing a well-suited connectivity network that fits the needs of an IoT use case should be a careful trade-off between the ability of a technology to meet specific functional requirements and the connectivity-related costs occurring during the lifetime of the application.

Research is available that compares a set of typical connectivity networks.[2,3] Although these comparison charts sum up the core technical characteristics of these technologies, there remains a gap to their functional, strategical, and economic-related characteristics. Typical unaddressed and hard-to-answer questions in technological comparisons are as follows:

- Is there a public network available?
- Can a private network be deployed?
- What about manufacturer dependence?
- What would be the difference in costs when choosing for a network A vs network B over the lifetime of the application?

Therefore, the goal of this research is to guide IoT-developers in choosing the right connectivity network based on functional requirements of the IoT-application and their economic aspect rather than pure technical characteristics of connectivity networks.

We start this work traditionally by comparing technical characteristics of a range of available connectivity networks. Next, an elimination questionnaire is presented that reduces the choice set in case of a mismatch between functional requirements of the IoT-application or service and the characteristics of a particular connectivity network. The remaining available options are subjected to a life cycle-cost modeling methodology. This second step allows comparing the costs associated with the various suitable connectivity networks. This 2-step methodology is demonstrated via 2 specific IoT use cases.

1.1 | Radio-based connectivity networks for IoT

Different types of wireless or radio-based networks are suitable for IoT. In this work, focus is on following wireless network implementations:

1. Satellite (L-band)
2. Cellular (GSM–LTE-A)
3. LoraWAN
4. Sigfox
5. Weightless-P
6. Wi-Fi a/n/ac – b/g/n

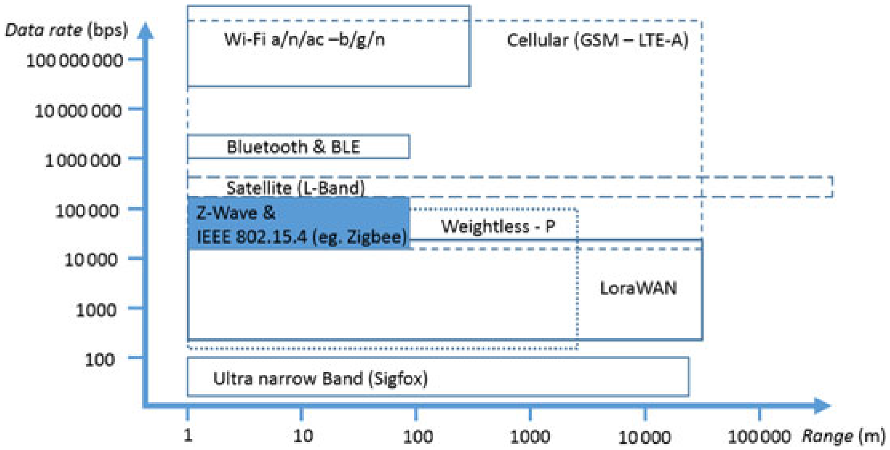

FIGURE 1 Wireless connectivity networks overview: data rate vs range. BLE, Bluetooth Low Energy

7. Z-Wave
8. 802.15 4 (Zigbee)
9. Bluetooth
10. Bluetooth Low Energy

We refer to Elkhodr et al,[2] Sanchez-Iborra and Cano,[3] and Raza et al[4] and Mahmoud and Mohamad[5] for a technical overview of these network technologies suitable for IoT-connectivity. The provided list is certainly incomplete but is a good mix of the available choice set. Although satellite is an often overlooked type of connectivity network when it comes down to IoT, it is included since certain applications (cf ultra-remote or global tracking) have no viable alternative yet. Figure 1 maps these technologies on typical comparison characteristics, being spatial range and data rate. Various different technologies are overlapping but have complete different functional characteristics, all serving very dissimilar sets of applications.

Within this work, focus is only on a single radio link, meaning that only the link from end node to the nearest hub or Internet access point is discussed. When making use of bridging technologies, which accumulates and transmits data packets from one particular type of connectivity network to another (cf Zigbee end nodes communicating via Zigbee hubs, connected via Wi-Fi to the Internet), the proposed methodologies need to be applied to each different type of radio link.

1.2 | Technical characteristics relevant for IoT-developers

Various parameters describe the technical characteristics of connectivity networks or hardware-related specifications.[4] Often used characteristics are, for example, bandwidth, max nodes per gateway, modulation techniques, authentication and encryption technologies, collision detection techniques, and number of channels, and orthogonal signals.

Because of their direct impact on IoT-application performance or business model, the following relevant technical characteristics for IoT-developers are described:

- *Data rate:* The speed to transport data between transceivers.
- *Frequency band:* The interval or band within the radio-frequency spectrum, used to carry the radio signals.
- *ISM band:* Specific-frequency bands, reserved for industrial, scientific, and medical purposes. These parts of the radio spectrum are unlicensed, which means that anyone can use these bands for free when respecting a set of radio regulations to prevent interference and bandwidth monopoly. In contrast with ISM, there are also licensed frequency bands for which network operators have paid to manage. Using licensed bands often requires financial resources.
- *Mode of operation:* indicates whether the network is able to transmit data in both directions simultaneously (Full Duplex) or has to wait for transmitting until the message is received (Half Duplex).
- *Max. payload size:* maximum amount of bytes sent in one message.
- *Power profile:* Often an indication of typical lifetimes of IoT-applications using a certain connectivity network. Hard numbers on energy consumption have a very limited value since this parameter is affected by various technical and design decisions such as data rate, sleeping modes, transmit power, etc.
- *Typical Range:* The typical spatial range a radio link can bridge. A very disputable parameter since various technical and environmental parameters cause interference and affect the range. Maximum range is typically achieved in an outdoor environment and with clear line of sight. In urban and indoor environments, the range is usually much lower.
- *Standard:* Whether the connectivity network is based upon wide available standards or not (cf LoraWAN, etc).

Table 1 gives an overview of the technical characteristics of the selected connectivity networks. Although similar comparisons in tables[4,6] are often an important decision aid, their value is limited in the sense that they do not provide insights on functional characteristics of the connectivity networks. In the next section, we translate technical parameters to functional characteristics of each connectivity network.

2 | TWO-STEP METHODOLOGY LEADING TO CAREFUL TRADE-OFF BETWEEN THE ABILITY OF A TECHNOLOGY TO MEET SPECIFIC FUNCTIONAL REQUIREMENTS AND THE CONNECTIVITY-RELATED COSTS

Comparing pure technical characteristics has limited value when it comes down to describing and comparing functional characteristics of IoT-connectivity networks and matching it with functional requirements of the IoT-application. In this section, we propose a 2-step methodology to guide the IoT-developer when considering multiple connectivity networks in a comprehensive and accessible manner. First, the technological choice set will be reduced if IoT-connectivity networks

TABLE 1 Comparing a set of technical characteristics of IoT-connectivity networks

	Satellite (L - band)	*Cellular (GSM (lowest) to LTE-A (highest)*	*Spread spectrum –LoraWAN*	*UNB -Sigfox*	*Weightless - P*	*Wi-Fi a/n/ ac– b/g /n*	*z-Wave*	*802.15.4 (Zigbee)*	*Bluetooth*	*Bluetooth low energy (BLE)*
Data rate	200 kbps	14.4 kbps (GSM); 1 Gbps (LTE)	300 bps -50 kbps	100 bps	200 bps - 100 kbps	54–1300 Mbps	40–200 kbps	20/40/ 250 kbps	1–3 mbps	1 mbps
Frequency band	1–2 GHz	900/1800/ 1900/ 2100 MHz	868/915 MHz	868/915 MHz	169/433/470/ 780/868/915/ 923 MHz	2.4/5 GHz	868/915/ 2400 MHz	868/915/ 2400 MHz	2400 MHz	2400 MHz
ISM band	No	No	Yes	yes	yes	yes	yes	yes	yes	yes
Mode of operation	Full Duplex	Full Duplex	Half Duplex	Half Duplex	Half Duplex	Half Duplex	Half Duplex	Full Duplex	Full Duplex	Full Duplex
max. Payload size			256Bytes	12B	min. 10B		64B	127B	358B	47B
Power profile	High (weeks)	Medium (months)	Low (+years)	Low (+years)	Low (+years)	High (weeks)	Low (+years)	Low (+years)	Medium (+months)	Low (+years)
Typical Range (indoor/urban areas vs outdoor)	global	35 km	3–15 km	5–25 km	2 km urban 5 km outdoor	15–150 m	30-100 m	30-100 m	3-30 m	5-100 m
Standard	Proprietary (eg, Iridium)	GSM; GPRS; EDGE;HSPA; LTE; LTE-A	LoraWAN	Sigfox proprietary	Weightless SIG	IEEE 802.11 a/b/g/n/ac	z-wave proprietary	Zigbee (based on IEEE 802.15.4)	IEEE 802.15.1	IEEE 802.15.1

fail to address the IoT-application requirements. In a second step, we provide a methodology that allows modeling the relevant capital and operational expenditures (CapEx and OpEx) associated with the different network types.

Step 1: Reducing the technological choice set in case of a mismatch between functional requirements of the IoT-application and functional characteristics of IoT-connectivity networks, using an elimination questionnaire

By means of an elimination questionnaire, the technological choice set will be narrowed down based on mismatches between the functional requirements of the IoT-application and the functional characteristics of the different IoT-connectivity networks. Four categories of questions have been identified:

- *Application requirements:* requirements concerning application environment and setting such as required signal penetration, application mobility requirement, and its geographical span.
- *Data or payload requirements:* requirements on data traffic streams, payload size, and frequency of the messages.
- *Device or end node-related questions:* specifications on power profiles and ability to address over-the-air updates.
- *Requirements concerning the business model:* clarifications on vendor dependencies, public accessibility, and ability for private network deployments.

Next to decisive or eliminating questions also suggestive answers can be a result, which do not eliminate but suggest a certain network or idea (eg, consider satellite-based connection in extreme remote areas when no Internet access point is available). The guiding process is a result of both technical and business-related limitations concerning a network. Table 2 presents the questions directed toward IoT-developers or providers. The former develops the IoT-application and hardware. The latter offers the IoT-application, not necessarily being the same party as the IoT-developer. Prioritizing the importance of the functional requirements is up to the IoT-providers since that depends heavily on the application. The formulation of the functional network characteristics is a result from recurring questions IoT-developers or providers are faced with. They are founded on technological and business-related properties of the considered networks, acquired via data sheets and research literature.[7-11]

The outcome of the elimination questionnaire is a set a feasible IoT-connectivity networks, which meet the functional requirements of the IoT-application.

Step 2: Life cycle cost comparison

In order to guide an IoT-developer to a well-suited connectivity network technology for a particular IoT- application, not only functional characteristics of the networks should match the requirements of the service.

Choosing a connectivity network is a trade-off between functionality and costs. Therefore, in this second step, a methodology is presented that compares life cycle costs of the network technologies, resulting from the previous step.

The model is a straightforward presentation of possible cost parameters likely to occur, depending on the setting. The magnitude of the costs is determined by cost drivers, variables scaling according to the specificities of the connectivity network. Capital expenditures are nonrecurring investments in technologies (eg, installation of base stations, which are the transceivers wirelessly connected with the end nodes and trafficking the data further to the Internet). In controversy, operational expenditures are the recurring expenses that results from operations.

At last, economic effects such as price erosion due to competition and maturing technology and market, and economies of scale can be taken into account if justified by the case. For example, it can be expected that the costs for the relatively new LPWAN- based communication chips (eg, Sigfox and LoraWAN) will decrease as the number of end nodes will increase over time and competitors will enter the market. Since cellular based chipset have been around for a while now, it is not realistic to say their price will decrease at the same rate of LPWAN-based chipsets. Also as the market and the competition in the IoT-connectivity landscape will grow, it is likely that today's subscription fee will no longer be competitive or realistic. As described in the work of Verbrugge et al,[12] learning curves are often used to model the effects of price erosion as the market matures.

In the presented methodology, figures of the listed cost parameters have not been provided since they depend on the use case, vary from country to country and are not always publically known. In addition, Weightless-P is excluded from the economic comparison of the different technologies because no reliable cost data is available.

Table 3 gives an overview of different CapEx and OpEx components and their related cost drivers. Having insights in each of these relevant cost categories and cost units associated with connectivity networks and their effect over the lifetime of the IoT-application, is key to make a profound decision on which technology to use.

TABLE 2 Elimination questionnaire

Category		Questions	Response_ID	Answer	Action	Reason
App	1	Do you want connectivity with end nodes in extreme remote areas or overseas?	1.A	Yes	If there is no Internet access point available, consider a satellite based uplink	Deployment of other types of IoT-connectivity networks may be impossible or very costly
			1.B	No	-	
	2	What geographic span is required	2.A	International	exclude Wi-Fi a/n/ac– b/g/n; z-Wave; 802.15 4 protocol; Bluetooth; BLE	Limited Range or uncertain access to public networks
			2.B	National	exclude Wi-Fi a/n/ac – b/g/n; z-Wave; 802.15 4 protocol; Bluetooth; BLE	Limited Range or uncertain access to public networks
			2.C	Local	-	
	3	What is the magnitude of the required range between base station and end node?	3.A	+ 10 m	-	
			3.B	+ 100 m	exclude Bluetooth; BLE	Limited Range
			3.C	+ km	exclude Wi-Fi a/n/ac – b/g/n; z-Wave; 802.15 4 protocol; Bluetooth; BLE	Limited Range
			3.D	global	consider a satellite based connectivity network	Only satellite networks eliminate the need for on ground installed base stations
	4	What level of connectivity penetration is required?	4.A	outdoor	-	
			4.B	Indoor (moderate signal-strength-reduction)	Exclude satellite	Insufficient radio link budget
			4.C	deep indoor (strong signal-strength-reduction)	exclude satellite; Cellular; Wi-Fi a/n/ac– b/g/n; z-Wave; 802.15 4 protocol; Bluetooth; BLE	Insufficient radio link budget
	5	End node mobility is a requirement?	5.A	Yes - high speed	exclude Lora, Sigfox	Currently too much packet loss
			5.B	Yes - low speed (<20 km/h)	Exclude Wi-Fi a/n/ac – b/g/n; z-wave,802.15 4 protocol; Bluetooth; BLE	Handoff performance insufficient
			5.C	No	-	
	6	Localization of end nodes is needed?	6.A	Yes	Exclude Sigfox	Currently not able to localize an end node. However, triangulation is on the localization via roadmap of Sigfox.
			6.B	No	-	
Data	7	What kind of data traffic is required	7.A	Video streaming	Exclude satellite L-band; LoraWAN; Sigfox; z-wave; 802.15.4 (Zigbee); BLE	Insufficient data rate
			7.B	Audio streaming	Exclude satellite L-band; LoraWAN; Sigfox; z-wave; 802.15 4(Zigbee)	Insufficient data rate
			7.C	No streaming	-	
	8	Messages from BS to end node required? (= downlink traffic)	8.A	Yes	Exclude Sigfox	Very limited downlink capability
			8.B	Yes - but very rare	-	
			8.C	No	-	

TABLE 2 (Continued)

Category	Questions		Response_ID	Answer	Action	Reason
	9	What is the size of the message (= payload)?	9.A	> 12 bytes	Exclude Sigfox	Max. Payload per message: 12 bytes
			9.B	< 12 bytes	-	
	10	Number of messages sent per day?	10.A	> 140	Exclude Sigfox (LoraWAN allows more messages at a lower spreading factor)	Regulated duty cycle (airtime) does not allow more messages per day.
			10.B	< 140	-	
Device	11	What is the required order of magnitude for the battery lifetime of the end nodes? (assuming identical batteries, and amount of messages sent). In case of energy harvesting (eg, devices solar powered sensors), this question may be irrelevant.	11.A	#days - weeks	-	
			11.B	#months	Exclude satellite; Wi-Fi a/n/ac – b/g/n	Power profiles of the technologies are too high
			11.C	#years	Exclude satellite; cellular; Wi-Fi a/n/ac – b/g/n; Bluetooth	Power profiles of the technologies are too high
	12	Over-the-air firmware updates of the end nodes?	12.A	Yes	Exclude Sigfox	Downlink capability not sufficient for firmware updates
			12.B	No	-	
Business model (BM)	13	Private network deployment or subscribing to a public network?	13.A	Public access only	Exclude z-wave; Zigbee; Bluetooth; BLE	No public deployments available
			13.B	Private deployment only	Exclude satellite; cellular; Sigfox	Licensed spectrum or business strategies do not allow private deployments
			13.C	Must be able to allow both access to a public network or deploy it privately	Exclude satellite; Sigfox, z-wave; Zigbee; Bluetooth; BLE	No public deployments available available or business strategies do not allow private deployments
			13.D	Not clear yet, it depends on the costs	-	Do not exclude a technology if it is unclear which technology will be chosen.
Remarks	14	Be aware of some vendor or network operator dependencies	14.A	Lora	Currently there is a vendor lock-in, only Semtech can produce the Lora chips.	
			14.B	Sigfox	Currently only one network provider per country.	
	15	International access to public IoT-networks can lead to additional roaming fees.	15.A	Cellular	Additional roaming fees or international subscriptions required.	
			15.B	LoraWAN	Depending on the LoraWAN-network provider, international connectivity can require additional roaming fees.	

1) *CapEx components*

- *Communication chip costs:* Depending on the technology, the newness of it, vendor lock-in or monopolies, etc, significant differences exist in the chip cost. This cost is a product of the unit cost of a chip and the amount of nodes needed.

- *Network installation: Base station cost:* The costs for base stations (BS) depends heavily on the network technology, IoT-application environment (eg, outdoor vs indoor) and the amount of BS required. Main characteristics affecting the amount of BS are the covered range and the amount of connected devices. The latter one can be a constraint when deploying a private network in areas that are heavily populated with end nodes such as city environments or industrial sites. Starting from the total area to be covered and the range of a BS, one can map the theoretical covered area per BS, which will indicate the order of magnitude of the number of BS required. This is a simplification and could be an underestimation of the required amount because of path loss and interference.
- *Network installation; Base station setup cost:* This cost parameter should not only consider the physical installation of each BS, which heavily depends on the IoT-application, but also on the development of required firmware for the BS (eg, synchronization of BS)

2) *OpEx components*

- *Network subscription fee:* Access to public networks is often granted under the form of a network subscription. Pricing schemes can be based on the amount of data sent per end node or a fixed monthly fee per end node connected. Subscribing to a public network is an important consideration since it leads to recurring expenses and scales with the number of end nodes connected.
- *Battery replacement; Handling cost:* Battery-only powered IoT-applications will eventually die if batteries are not charged (eg, via energy harvesting techniques such as solar power) or replaced periodically. Important parameters affecting the replacement frequency are the power consumption of the end node and the energy capacity of the batteries. In addition, the number of end nodes to take care for and the handlings needed to change the batteries (eg, parking sensors vs sensors installed on power pylons) are important parameters to model the complete costs of the process and transport time.
- *Network operation; Network operation and maintenance:* Networks require periodic maintenance, both physical replacements and software updates. Often operational and maintenance costs are modeled as a percentage of the installation costs of the network.[13] The more BS installed, the more maintenance required, hence the number of installed BS as driver for this cost component. When subscribing to a public network, this cost is incorporated in the subscription fee.
- *Network operation; Base station site rental:* Lastly, often together with the installation of a base station also site rental comes into play.

Not all categories are relevant for all connectivity networks. For example, most local networks such as Wi-Fi or z-Wave, etc, do not require subscription costs, except as they are offered as a public service. Also network installation and operation costs do not have to be addressed by IoT-providers when subscribed to a public available network such as Sigfox, for example.

It should be stressed that the required lifetime of the IoT-application is a key driver for all abovementioned costs. For instance, it might not be worth it to install a private network at first glance, but eventually it could become the favorable option because of the recurring subscription fees resulting from the public network access.

Combining the elimination approach from step 1 with the cost considerations listed in step 2 will guide the IoT-developer not only to a connectivity network that meets the IoT-application requirements, but also to the most economical alternative.

In order to determine and quantify the total life cycle costs associated with IoT-connectivity networks, one must have access to relevant data on unit costs and cost drivers such as: amount of BS, base station costs, subscription costs, installation costs, etc. Since these parameters are not always available or are uncertain, a sensitivity analysis could be performed.[12] This type of analysis determines how the outcome, in this case life cycle cost, is affected by the uncertain parameters. For instance, an applied example question could be: ‘What is the impact on the total life cycle cost if 15 BS are required instead of 10?’

3 | USE CASES

In this section, the suggested 2-step methodology is applied to 2 use cases. The first case is about container monitoring at the port of Antwerp. A second case describes the deployment of a smart parking system in a city environment.

TABLE 3 Overview of most important cost components and their drivers

Category	Cost unit	Cost driver
CapEx		
Communication chip		• Amount of end nodes
Network installation	Base station cost	• Amount of base stations (secondary cost drivers: range of the base station and area to cover)
	Base station setup cost	• Amount of base stations
OpEx		
Subscription fee		• amount of end nodes • amount of data sent • Pricing model of network operator • Lifetime of IoT-application
Battery replacement	Handling cost	• Amount of end nodes • Energy consumption of the end node • Installation difficulties • Energy capacity of the batteries
	Battery costs	• Amount of end nodes
Network operation	Maintenance costs of base stations Base station location rental	• amount of base stations

Abbreviation: IoT, Internet of Things.

3.1 | Use case 1: smart containers to improve the in-port operations

The port of Antwerp wants to increase its process efficiency by using smart containers. Not only the location (area-based) of the containers should be available but also door openings need to be monitored, humidity, indoor temperature (via air vents), and acceleration. In total, about 100 000 containers need to be temporarily provided with IoT-end nodes whilst they are on the site. The total area of the site covers 120 km^2. A real-time data connection is not required, but threshold alerts will trigger a send event. Although devices are not installed permanently in the containers; thus, port-personnel could change or charge the batteries so now and then, the desired lifetime is at least 5 years to reduce handling costs.

Step 1: Elimination questionnaire

Starting from the functional requirements of the IoT-application, we learn that a LoraWAN- based connectivity network is suggested by the elimination questionnaire (see Table 4).

If it was not for the localization requirement and the required battery lifetime, Sigfox and Cellular would still be possible options. One could argue on that because the accuracy of the localization capability of the LoraWAN-based networks is not clear yet and heavily depends on some unknown variables such as the impact of metal containers on signal quality, amount of BS or gateways installed, etc. The alternative is to install an additional GPS receiver in each end node. However, because of the power hungriness of this module, the needed connection time when awaking from sleep mode, the additional costs and the many signal blocking elements, this is a suboptimal solution.

In this case, the challenge is to determine what the most economical solution is in the long run: (1) deploying a private LoraWan-based network or (2) subscribing to Lora, a public LoraWan-based network offered by Proximus, a Belgian network provider.[14] Therefore, these 2 variants are being analyzed in the next step.

Step 2: Life cycle cost comparison

In order to compare the life cycle cost of a privately installed and maintained network versus the costs resulting from a network access subscription within the same technology, we do not need to consider the difference in communication chip cost and the costs for battery replacement because they will be same in the 2 alternatives. This brings down the comparison to the following 3 cost components: (1) Network installation, (2) Subscription costs, and (3) Network operations.

TABLE 4 Elimination questionnaire applied to use case 1

Response_ID of elimination questionnaire (see Table 2)	Action
1.B	-
2.C	-
3.C	Exclude Wi-Fi a/n/ac – b/g/n; z-wave; 802.15 4 protocol; Bluetooth; BLE
4.C	Exclude satellite; cellular; Wi-Fi a/n/ac – b/g/n; z-wave, 802.15 4 protocol; Bluetooth; BLE
5.B	Exclude Wi-Fi a/n/ac – b/g/n; z-wave, 802.15 4 protocol; Bluetooth; BLE
6.A	Exclude Sigfox
7.C	-
8.B	-
9.B	-
10.B	-
11.C	Exclude satellite; cellular; Wi-Fi a/n/ac – b/g/n; Bluetooth
12.B	-
13.D	-
14	No problem
15	No problem

1) Network installation
   The CapEx has 2 components; the costs for the BS and their installation and setup requirement. Mapping out the covered area per BS in a nonurbanized area indicates that 3 BS could theoretically suffice. However, because of gateway limitations, being max. 8000 connected end nodes in this case, at least 13 gateways or BS need to be installed. Current prices for industrial grade BS and equipment vary between 600 and 1500 EUR.
   Based on input from IoT-application developers, installing a BS will require 2 hours (50 EUR per hour) on average. Additionally one extra hour (50 EUR per hour) is foreseen per BS for the network and activation setup component to join the gateways in one managed network. This leads to an investment of 19.5 kEUR, an installation cost of 1.3 kEUR and a network setup and management cost of 0.65 kEUR. All data are summarized in Table 5.
2) Subscription costs
   In a privately owned network, no subscription fees are required. However, to have access to a public IoT-connectivity network, typically a monthly subscription fee per end node must be paid. Typical prices for LPWAN network access range from 0.3 to 1.5 euro per month per end node, depending on the number of messages sent per day by the end node (uplink messages), and the number of messages sent to the end nodes (downlink messages). This adds up to total monthly fee between 30 to 150 kEUR. Since the LPWAN market is still in a nascent phase and current prices are likely to decrease due to growing competition and a maturing market,[12] a price erosion is modeled via the extended learning curve with parameters $Q_0 = 10\%$, $K = 0.9$, $\Delta t = 8$ year, as described in the work of Olsen and Stordahl.[15]
3) Network operations
   Deploying a private network comes with the responsibility of network maintenance, which includes both hardware and software-related upgrades. To model this, a yearly recurring cost of 10% of the total CapEx is taken into account. This results in a yearly fee of 0.975 to 2.145 kEUR, depending on the chosen BS.
4) Total cost overview
   All costs are modeled over a 10-year period. Communication chip costs are not taken into account in the cost comparison since both alternatives rely on the same IoT-connectivity network technology, which would result in the same cost components. However, at a cost of 2 to 10 EUR for a LoraWan communication chip, this cost component would contribute 200 to 1000 kEUR to the overall CapEx of this use case, independently of the choice of private or public LoraWAN access. Also for this hardware cost, price erosion can be expected.

TABLE 5 Overview of relevant data and cost components for lorawan private deployment vs public network subscription (use case 1)

Category	Data
LoraWAN private deployment	
# BS units	13
BS and equipment cost/BS [EUR/BS]	1500
Subtotal CapEx: BS purchase [EUR]	*19.5 kEUR*
Installation cost/BS [EUR/BS]	100 (2 hr x 50 EUR/hr)
Subtotal CapEx: BS installation [EUR]	*1.3 kEUR*
Network setup and management [EUR/BS]	50 (1 hr x 50 EUR/hr)
Subtotal CapEx: Network setup [EUR]	*0.65 kEUR*
Total CapEx	***21.45 kEUR***
Network operations and maintenance (10% of total CapEx)	2.145 kEUR/year
Total OpEx	***2.145 kEUR/year***
Access to public LoraWAN network	
# end nodes	100 000
Network access subscription cost [EUR/month/end node]	0.3
Total OpEx	***360 kEUR/year***

Table 6 gives the summary of the cost components taken into account and their evolution over time. The results indicate that deploying a private LoraWAN network is the most economical solution, given the current market prices. The subscription fee cannot compete with a subscription free private network.

If this use case should be deployed globally, currently a GPS-based solution in combination with a globally deployed connectivity network (satellite or cellular) could be proposed. However, such a solution comes with challenges concerning power consumption and economic feasibility due to the IoT-connectivity subscription costs.

An alternative scenario of this use case is that management of the port of Antwerp decides to monitor only the containers that require more attention (for instance, in case of suspicious shipments such as drugs or weapons, or in case of containers that contain toxic gasses).

In this case, only 1000 containers, scattered all over the port area will simultaneously be monitored via the integrated sensors. Therefor the CapEx and OpEx for the private LoraWAN network will remain the same, as described in Table 5. However, the yearly total subscription fee for connecting the sensors with the public Lora network will be 3.6 kEUR per year (1000 sensors at 0.3 EUR/month per sensor). The cost comparison for this use case scenario is presented in Figure 2.

From the cost comparison, it is clear that subscribing to public Lora network is the most favorable solution. This is due to the high cost for deploying a private LoraWAN network that covers the total area of the port of Antwerp when compared to subscribing to a public available Lora network.

3.2 | Use case 2: deployment of a smart parking system

A company that provides both the hardware and a management platform to municipalities to enable them in offering and managing public parking lots, wants to introduce the concept of “shop'n go” parking places. These parking spots allow people to park their car free of charge for a maximum period of 30 minutes. Via sensors integrated in the parking spots, they will register the time of arrival and the time of departure. In case the maximum time is exceeded, a message will be sent to a parking officer. He then can issue a parking fine to the owner.

The sensors need to have a lifetime of at least 5 years. It is expected that no more than 50 shop'n go parking places will be scattered in area of maximum 1.5 km^2. In this use case, a midsized city will have in total 6 of these areas spread across the city. In total 300 shop'n go parking places will be foreseen.

Although the option of using a public IoT-network will be considered, there exists the option to install a base station with a cellular uplink in a parking meter nearby the shop'n go parking places when no reliable IoT-network is available publicly. Downlink capability is not required for the sensors.

TABLE 6 Cost evolution and comparison of LoraWAN private deployment vs public network subscription

kEUR	**Year**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
LoraWAN private network deployment												
CapEx	BS and equipment cost	19.5	0	0	0	0	0	0	0	0	0	0
	BS installation cost	1.3	0	0	0	0	0	0	0	0	0	0
	Network setup and management	0.65	0	0	0	0	0	0	0	0	0	0
OpEx	Network operations and maintenance	0	2.145	2.145	2.145	2.145	2.145	2.145	2.145	2.145	2.145	2.145
	Total cost in year i	21.45	2.145	2.145	2.145	2.145	2.145	2.145	2.145	2.145	2.145	2.145
	Cumulative cost	***21.45***	***23.595***	***25.74***	***27.885***	***30.03***	***32.175***	***34.32***	***36.465***	***38.61***	***40.755***	***42.9***
LoraWAN public network access												
OpEx	Subscription cost	0	360	360	360	360	360	360	360	360	360	360
	Price erosion for subscription cost (ext. learning curve)	0	100%	93%	87%	82%	78%	76%	74%	72%	72%	71%
	Cumulative cost	***0***	***360***	***694.7***	***1007.9***	***1303.5***	***1585.4***	***1857.3***	***2122.3***	***2382.8***	***2640.6***	***2896.7***

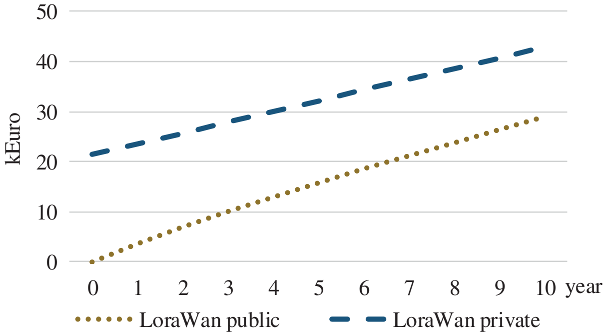

FIGURE 2 Cumulative cost comparison LoraWan public subsription vs private deployment use case scenario: 1000 containers

TABLE 7 Elimination questionnaire applied to use case 2

Response_ID of elimination questionnaire (see Table 2)	Action
1.B	-
2.C	-
3.C	Exclude Wi-Fi a/n/ac – b/g/n; z-wave; 802.15 4 protocol; Bluetooth; BLE
4.B	Exclude satellite
5.C	-
6.B	-
7.C	-
8.C	-
9.B	-
10.B	-
11.C	Exclude satellite; cellular; Wi-Fi a/n/ac – b/g/n; Bluetooth
12.B	-
13.D	-
14	No problem
15	No problem

Step 1: Elimination questionnaire

Based on the limited requirements provided for this use case, the outcome of the elimination questionnaire (see Table 7) suggests that both Sigfox and LoraWAN are feasible solutions.

In case Sigfox and LoraWan are publicly available, in total, 3 options need to be compared: (A) subscribing the sensors to a public LoraWAN network, (B) subscribing to the Sigfox network, or (C) deploying a private network. When none of these 2 types of LPWANs are publicly available, the suggested option is then to integrate a base station in a parking meter nearby and set up a private LoraWAN network.

Step 2: Life cycle cost comparison

Because 2 different IoT-network technologies will be compared in this use case, also the costs for the communication chips for the 2 different technologies must be taken into account when considering the CapEx.

Other CapEx components that will be quantified are the cost of a LoraWAN base station, installation costs and network setup costs (cost data as described in Use case 1).

The operational costs include the subscription fee for access to both Sigfox and Lora, and the maintenance costs for the private LoraWAN network. Due to the higher number of daily transmitted messages, the subscription fee will be higher compared to the previous use case. Battery replacement costs can be excluded in this use case since both technologies will result in a similar sensor lifetime when fed by an identical battery. An overview of all relevant data of the use case and costs is provided in Table 8.

TABLE 8 Overview of relevant data and cost components for comparing LoraWAN private, Lora oublic and Sigfox (use case 2)

Category	**LoraWAN private**	**Lora public**	**Sigfox public**
# end nodes	300		
Communication chip cost [EUR/end node] (unit price for 100 pieces)	4.56 (SX1272 – Semtech)	4.56 (SX1272 – Semtech)	3.19 (CC120 - Texas Instruments)
Subtotal CapEx: Comm. Chip [EUR]	*1368*	*1368*	*957*
# BS units	6	-	-
BS and equipment cost/BS [EUR/BS]	1500		
Subtotal CapEx: BS purchase [EUR]	*9000*	-	-
Installation cost/BS [EUR/BS]	100		
Network setup and management [EUR/BS]	50	-	-
Subtotal CapEx: BS installation and network setup [EUR]	*900*	-	-
Total CapEx [EUR]	***11 268***	***1368***	***957***
Network operations and maintenance (10% of total CapEx of network) [EUR/year]	990	-	-
Subtotal OpEx: Network maintenance [EUR/year]	*990*	-	-
Network access subscription cost [EUR/month/end node]	0	1	0.9
Total OpEx [EUR/year]	***990***	***3600***	***3240***

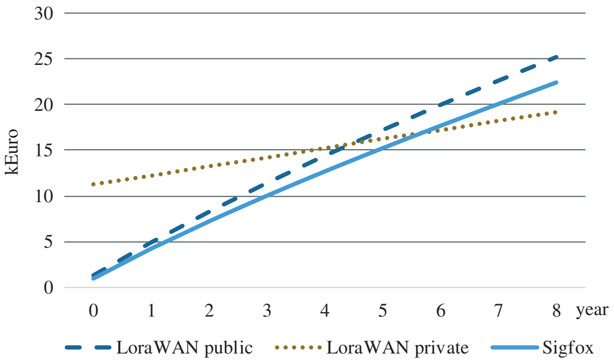

FIGURE 3 Cumulative cost comparison LoraWan public vs LoraWAN private deployment vs Sigfox

Since it is uncertain that all 6 shop'n go parking areas are located close to each other (within the range of a BS), this model assumes 6 different private LoraWAN networks with each 50 sensors nodes.

The total life cycle cost of the different options will be modeled over a period of 8 years. Also for this use case, a price erosion for the network subscription costs is modeled via the extended learning curve with (see use case 1: Subscription costs) to model the effect of a maturing market with more competition. The total undiscounted cumulative costs for the 3 options are visualized in Figure 3.

Even with an upfront investment, which is almost 10 times higher than the alternative options, the results suggest that deploying a private LoraWAN network is the economically preferred solution. This conclusion would not be affected when considering the total life cycle cost of only one shop'n go parking area (with 50 sensors) instead of 6.

4 | CONCLUSIONS

Together with the continuous expansion of the IoT-market, also the number of IoT-connectivity networks grows. We believe many of them will serve the market in parallel since no technology offers a one-size-fits-all solution for the wide variety of IoT-applications.

So the challenge for an IoT-developer or IoT-provider, if they are not the same actor, is to make a well-considered decision on the network technology. In response, we present a 2-step methodology to guide IoT-developers or IoT-providers toward a feasible set of network technologies based on the match between the functional requirements of the IoT-application and functional characteristics of the IoT-connectivity networks (first step of the methodology) and economic consideration associated with this set (second step of the methodology). Hereby complementing pure technical comparisons of connectivity networks with a more bottom-up approach.

The proposed 2-step methodology has been applied to 2 different use cases. The first use case describes a large-scale IoT-deployment in the port of Antwerp, Belgium to track the location, movement, acceleration, temperature, humidity and gasses within shipping containers. The second use case situates itself in the scope of smart cities. A parking system integrator wants to deploy “shop'n go” parking places, which can detect the presence of vehicles via a sensor to optimize the parking management processes.

Finally, it should be noted that together with the enormous opportunities and potential of the IoT- market place, the set of connectivity network technologies and providers is continuously expanding. Traditional network providers are responding to the IoT-market with new LPWAN technologies such as NB-IoT and LTE cat. M1. It can be expected that competition will be driven by quality of service, costs, network availability, and technical characteristics. Therefore, we acknowledge that the set of connectivity networks treated in this paper is incomplete. Many technologies (such as NB-IoT, LTE-M1, DASH7, Wi-Fi.ah (Halow), and ultra-wide band networks) currently in development or gaining interest should be added in the future. Additionally, as the market evolves, data on specific network-related costs will become available and could be added to further detail the cost comparison between the different networks.

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