Low Cost Connectivity for Household Appliances using Low Power Wide Area Network (LPWAN)

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Household appliances are transitioning to be connected to the Internet as technology advances. Most of the currently available household appliances already have a feature that enables connectivity to retrieve the system's data using the end-customers (appliance owner) internet connection. However, this is not desirable as the customers (appliance suppliers) desire to have an internet connection independent system to minimize ongoing maintenance costs, enable a reliable connection, and enable a secured connection to retrieve the system's data. Among the currently available wireless technologies, Low Power Wide Area Network (LPWAN) is the most promising one. This paper firstly investigates the business use cases enabled by LPWAN and the corresponding technology requirements, then compares the most frequently used LPWAN technologies thoroughly, including Long Range Wide Area Network (LoRaWAN), Sigfox, and NarrowBand IoT (NB-IoT). LoRaWAN is selected based on the comparison results and its performance is further evaluated in a real-life scenario. It is found that LoRaWAN is practically usable under specific conditions because the performance differs from the technical specifications, which needs to be investigated more in future research.

Additional Key Words and Phrases: LPWAN, IoT, Household Appliance, Cloud Computing

1 INTRODUCTION

1.1 Background

Household appliances, such as refrigerators, washing machines, and air conditioners, are becoming increasingly "smart" due to the rise of Internet-connected appliances, also known as the Internet of Things (IoT). Most of the current household appliances that are sold in the market are able to connect appliances to the network server in order to retrieve the system's data to be processed using the end customer (appliance owner) internet connection, namely WiFi, and the appliances depend on end customer infrastructure. The current system architecture is depicted in Figure 1. However, this is not desirable as the customer (appliance supplier) desire to have an internet connection independent system to minimize ongoing maintenance costs, enable a reliable connection, and enable a secured connection. Thus, a specific solution to the problem needs to be explored.

In order for the customers to achieve the goals of having an independent system of the end customer, a technology that could transmit data rates for long distances efficiently at a relatively cheap end device cost is investigated. The current state-of-the-art wireless communication technologies to enable connectivity are using radio transmission technologies (e.g. WiFi, Bluetooth, and NFC) and cellular communications (e.g. 2G, 3G, and 4G) [4]. Radio transmission technologies transmit high data rates efficiently but are not suitable for long-range communications. On the other hand, cellular communication is suitable for long-range high data rates but requires high power to transmit the data. Hence, none of the current state-of-the-art technologies satisfies the product's requirements.

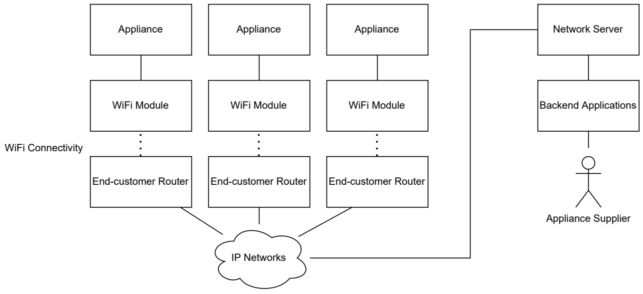

Fig. 1. Current system architecture

The specified product's requirements caused an emergence of a new technology named Low Power Wide Area Network (LPWAN), a new specification of wireless communication technology via radio frequency that has different characteristics from the current state-of-the-art technology. The different characteristics include its feature of a long transmission range that could reach up to 5 km in urban zones and 40 km in rural zones [4] accompanied with a low power consumption which could last at least 10 years using battery [20]. Long transmission range is achieved by using modulation that uses higher receiver sensitivity, up to -130 dBm, which trades off for lower data rates while low power consumption is achieved by employing a one-hop star topology which allows end devices to continuously be in the sleep mode [20]. It also offers an affordable cost, with the LPWA module ranging from 4-6€ and the connectivity cost for each device ranging from 0.5-1.5€ [22]. Recent experimental studies have been driven by these properties which makes them highly suitable for IoT application use cases [2, 9, 26].

Currently, the most frequently used LPWAN technologies are Long Range Wide Area Network (LoRaWAN), Sigfox, and NarrowBand IoT (NB-IoT). In 2022, the number of LoRaWAN connections reaches 471 million, while Sigfox has 43 million connections, and NB-IoT connections are roughly 491 million [19]. These technologies have different properties, such as costs, security, and data rate. Thus, these technologies are going to be investigated and a specific technology that suits the product's requirements is going to be tested and evaluated in a real-life scenario to verify that it can fulfil the product's requirements.

1.2 Problem Statement

In this research, an investigation on which LPWAN technology would suit best for household appliances to replace the current system architecture is going to be carried out. The investigation will

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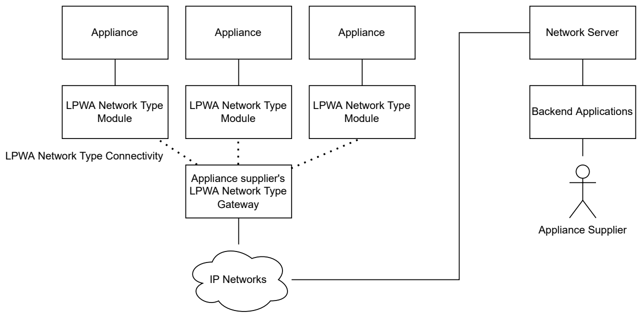


Fig. 2. Envisioned system architecture

determine which LPWAN technology matches best for the markets according to the customers' needs and the business use cases of the household appliances. These business use cases need to be retrieved from the customers such that a list of product requirements that could be constructed by the use of the LPWAN technology could be derived from these business use cases. These product's requirements are put into a selection criterion to determine which LPWAN technology suits best the product's requirements. In the end, a performance evaluation of the chosen LPWAN technology is going to be done to verify that it can fulfil the business use cases. The envisioned system architecture is shown in Figure 2.

1.3 Goals and Research Questions

The goal of this research project is to strategically choose the best suited LPWAN technology in accordance with the product's requirements and ultimately evaluate that the chosen LPWAN technology can fulfil the business use cases.

To achieve the goal of the research project, the following research questions (RQ) are defined:

- **Research Question 1:** Which business use cases can be constructed with the use of the LPWAN?
- **Research Question 2:** Which requirements can be derived from the business use cases?
- **Research Question 3:** What is the best fitting LPWAN technology (e.g. LoRaWAN, Sigfox, NB-IoT) to the specified requirements?
- **Research Question 4:** What is the performance of the chosen LPWAN technology?

1.4 Related Work

In order to gather related literature to the research domain, Scopus, Science Direct, and IEEE were used. Several documents could be retrieved using the search phrases "internet of things" and "lpwan".

The work by Raza et al. [22] explains the technical details and specifications between different LPWAN technologies and the standardization. The standard 3GPP along with its features and characteristics is also discussed in more detail in this article [21]. In a similar manner, there are also official articles and literature that discuss in more technical details and specifications about LoRaWAN [1] [16] [5], Sigfox [24] [23] [11], and NB-IoT [12] [13] [21].

Updating their work from 2018 [14], the work from Mekki et al. in 2019 [15] describes the different key elements and factors to consider when choosing an LPWAN technology with regards to IoT factors in a large-scale deployment. Other studies also managed to discuss the important properties that need to be looked at when choosing which LPWAN technology would suit best for a specific IoT application [6, 10, 25].

In 2016, Centenaro et al. [4] did a study on different LPWAN technologies and did a deployment test to find out the characteristics of the network in different applications scenario. More specific experiments have also been conducted in the past on using different LPWAN technologies in different applications scenarios, such as parking sensors [27], river monitoring use-case [9], and geo-location tracking [2].

2 METHODOLOGIES

The methodologies that are going to be used in conducting the research vary from interviewing the customer in retrieving business use cases, deriving a list of technical requirements from the business use cases, literature reviews of related works on LPWAN technologies, and experimental testing under a real-life scenario of the chosen LPWAN technology will be carried out. Refer to the subsections below for a more thorough explanation of the methodology.

2.1 On Answering Business Use Cases with LPWAN

Collecting information from customers about the product's requirements of what the end customers in the market wish from the product is necessary to construct business use cases with the use of the LPWAN. Therefore, interviews with customers are going to be conducted. The interviews are done with three different customers and consist of one-time 30 minutes online interviews. The interview questions are shown in Appendix A of this document. Finally, a list of business use cases that were retrieved is going to be made. The list of business use cases along with the detailed results is shown in subsection 3.1.

2.2 On Answering LPWAN Technology Requirements

From the defined business use cases, a list of technical requirements that could be constructed by the use of the LPWAN was derived. The technical requirements are going to be derived manually from the product's requirements that the customers envisioned. These technical requirements are made to be able to compare with LPWAN technology requirements and choose the best suited LPWAN technology according to the technical requirements of the product. The list of the technical requirements along with the detailed results is shown in subsection 3.2.

2.3 On Answering Suitable LPWAN Technology

In order to research the currently available LPWAN technology, literature reviews of related works on LPWAN technologies, such as books, papers, and articles, focusing on the different properties of these technologies are going to be done. To select the suitable LPWAN technology, a list of selection criteria will be defined to prioritize the technical requirements that the LPWAN technology needs to have. This list of selection criteria is derived from the product's requirements. Afterwards, the best-suited LPWAN technology will be chosen. Therefore, the technical specifications of each LPWAN technology are going to be discussed and a list of selection criteria is made to choose the suitable LPWAN technology in accordance with the customers. These are going to be discussed in more detail in subsection 3.3.

2.4 On Answering Performance of Chosen LPWAN Technology

Finally, experimental testing under a real-life scenario will be carried out to evaluate the performance of chosen LPWAN technology. The experimental testing uses hardware that consists of a gateway and an end node. The LPWAN technology performance will be evaluated according to the metrics of transmission time and transmission range. The evaluation of the metrics will be done by transferring a variety of data packets from the end node to a public server via the gateway. This evaluation will ultimately verify the assumption that the chosen LPWAN technology fulfils the product's requirements and business use cases. The evaluation setup and its results are shown in subsection 3.4.

3 RESULTS

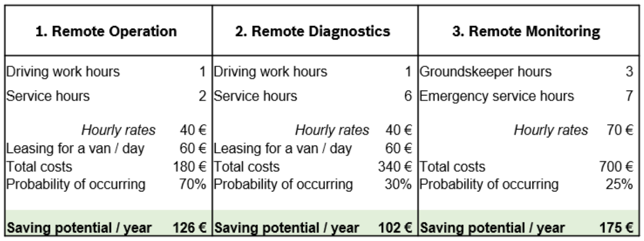
3.1 Answering Business Use Cases with LPWAN

As specified in the methodology, interviews with the customers are going to be carried out to get a better understanding of the product's requirements and what business use cases could be fulfilled with the envisioned architecture. From these interviews, the product's requirements are retrieved as follows:

1. Cheap and easy
   The first Installation should be cheap and easy.
2. Minimize maintenance cost
   Minimize current maintenance costs by preventing breakdown and eliminating visits for the appliances.
3. Remote diagnostics with error messages
   Remote appliance diagnosis before appliances breakdown.
4. Remote control
   Limited Remote control of appliances to avoid simple service visits to the end customer's house.
5. Satisfied end customers
   Able to know earlier about problems with the appliance.

Thus, several business use cases are constructed according to what the customers wish for the product. The business use cases are as follows:

1. Remote operation
   The business use case refers to simple remote control that the appliance technician can do remotely instead of coming to the site. This eliminates the hassle of the end customer for simple visits and reduces the maintenance cost by 31.26% of the current maintenance cost as shown in Figure 3. Some of the remote operation use cases are turning on and off the appliances and changing the settings of the appliance.
2. Remote diagnostics
   This business use case refers to the remote data retrieval for the appliance diagnosis. This prevents the appliance technician to do a second visit for appliance maintenance because required parts for maintenance are known beforehand. This reduces the maintenance cost by 25.31% of the current maintenance cost as shown in Figure 3. Some of the remote diagnostics use cases are diagnosing the appliance operating status info and error information.



1. Remote Operation		**2. Remote Diagnostics**		**3. Remote Monitoring**	
Driving work hours	1	Driving work hours	1	Groundskeeper hours	3
Service hours	2	Service hours	6	Emergency service hours	7
Hourly rates	40 €	*Hourly rates*	40 €	*Hourly rates*	70 €
Leasing for a van / day	60 €	Leasing for a van / day	60 €		
Total costs	180 €	Total costs	340 €	Total costs	700 €
Probability of occurring	70%	Probability of occurring	30%	Probability of occurring	25%
Saving potential / year	**126 €**	**Saving potential / year**	**102 €**	**Saving potential / year**	**175 €**

Fig. 3. Current household appliances maintenance cost for each business use cases in The Netherlands according to the customers

3. Remote monitoring
   This business use case refers to remote data retrieval for appliance monitoring. This limits and prevents the breakdown of the appliance by predicting when the maintenance should be done before it is broken. This would satisfy the end customers and reduce the maintenance cost by 43.42% of the current maintenance cost as shown in Figure 3. Some of the remote monitoring use cases are monitoring the appliances' power consumption and temperature.

3.2 Answering LPWAN Technology Requirements

From the defined list of product requirements, a list of technical requirements of the LPWAN technology can also be obtained to fulfil the customer needs. The following are technical requirements that the LPWAN technology should have:

1. The product end device pricing must cost less than 3€ per year.
2. The product must be able to be installed within an hour.
3. The product must be able to retrieve the data every 10 minutes and upload it to the server database.
4. The product must fetch the appliance data with a throughput of 4500 bits (0.45 kb) per second.
5. The product must not have a lot of maintenance with either no maintenance or once in the appliance lifetime.
6. The product must have a secured connection to the server database in transmitting the data.

3.3 Answering Suitable LPWAN Technology

In the previous subsections, the business use cases and technical requirements for the LPWAN have been defined. In this subsection, the technical specifications from the three mentioned LPWAN technologies - namely LoRaWAN, Sigfox, and NB-IoT - will be explained. The summary of their technical specifications is shown in Table 1 and the details of each LPWAN technology technical specifications could be seen in the following subsections.

3.3.1 LoRaWAN. LoRaWAN is a communication protocol which is based on LoRa, a physical layer technology which transmits signals

Features	**LoRaWAN**	**Sigfox**	**NB-IoT**
Technology	Proprietary Wide area wireless [1]	Proprietary Ultra Narrow-Band [24]	Open Standard Narrow-Band [12]
Standardization	LoRa Alliance [1]	Sigfox company [24]	3GPP Release 13 [21]
Spectrum	Unlicensed spectrum ISM band [1]	Unlicensed spectrum ISM band [11]	Licensed spectrum ISM band [12]
Modulation	Chirp Spread Spectrum radio modulation [1]	DBPSK modulation [24]	SC-FDMA modulation (UL) and OFDM modulation (DL) [12]
Bidirectional	Half-duplex [1]	Half-duplex [24]	Half-duplex [12]
Data rate	0.3 - 50 kbps [1]	0.1 - 0.4 kbps [11]	5-27 kbps [13]
Messages per day	Unlimited [1]	140 (UL) [23] | 4 (DL) [24]	Unlimited [13]
Payload length	243 bytes [1]	12 bytes (UL) [23] | 8 bytes (DL) [24]	1600 bytes [13]
Latency	Medium (depending SF numbers) [16]	High (a few seconds) [23]	Low (< 1 second) [13]
Range	5 (urban) - 10 (rural) km [5]	10 (urban) - 40 (rural) km [23]	1 (urban) - 10 (rural) km [13]
Security	AES-128 encryption [1]	AES-128 encryption (applicable) [24]	AES and end-to-end encryption [12]
Price (end device)	2-10€	<2€	>10€

Table 1. LPWAN technical comparison

in the unlicensed spectrum of the sub-GHz Industrial, Scientific and Medical (ISM) band using a proprietary spread spectrum technique [1]. It was introduced in 2015 by the LoRa Alliance^{TM}, an open association of companies from different sectors, several of them including the telecommunications and network operators company.

LoRaWAN transmits each message from the end device (modules), that have collected the data from various sources, to all of the base stations (gateways) that are in the range of the end device. These base stations will then transmit the received messages from the end device to the cloud network and eventually to the back-end application servers through IP connectivity [5]. In addition, LoRaWAN transmits each message with a specific spreading factor (SF) feature. It offers a way to adjust the trade-off between data rate and communication range using different SF in its transmission. There are six SF from SF7 to SF12 with the lowest (SF7) offering the highest data rate and lowest communication range. When the SF number increases, the data rate decreases and the communication range increases [16]. The maximum payload for each message is 243 bytes and the protocol could adjust for the data rate of 300 bps (SF12) up to 50 kbps (SF7) with the tradeoff of communication range.

Several communication classes are defined by LoRaWAN for the end devices operation, namely class A, class B, and class C. Each of these classes has different usage and also requirements [1].

- Class A features must be implemented by all end devices. These devices accept bidirectional communication. It first delivers uplink messages from the end device to the application and gets replies to two short downlink messages. The server must only respond in one of two windows, such that it allows for downlink transmission at predetermined intervals following the uplink transmission. Compared to the other classes, Class A could be considered the most energy-efficient device.
- Class B features are not required to be implemented, but this feature is optimized for end devices that have source energy of battery and that are either mobile or mounted at a fixed location. These devices accept extra receive windows for downlink messages, which are based on time-synchronized beacons received by the base station. Class B devices are energy-efficient and latency-controlled devices.
- Class C features are not required to be implemented, but this is mostly used for applications that have sufficient power and could tolerate reception time devices. These devices have a feature to open the receive windows continuously, given the condition that the devices are not transmitting. Class C devices operate with high power consumption and low latency downlink.

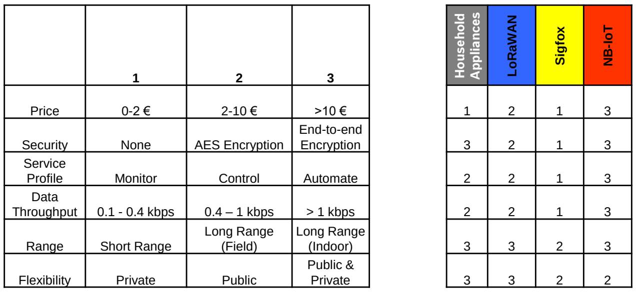
3.3.2 *Sigfox.*

Sigfox was developed by a French global network operator in 2010. The LPWAN technology uses a patented radio technology based on "Ultra Narrow-Band" (UNB), which uses differential binary phase-shift keying (DBPSK) and the Gaussian frequency-shift keying (GFSK) that transmits signals using the unlicensed spectrum of ISM band [24] [11]. With the UNB technology, Sigfox manages to use the frequency band efficiently and reduces noise levels, which leads to very low power consumption, high receiver sensitivity, and low-cost antenna design. However, this technology trades off the specified characteristics with very limited data transmission.

Sigfox can have bidirectional communication, which happens as follows. The uplink transmission needs to take place first for the downlink transmission to happen. The tradeoff of the UNB between low power consumption and low cost is the data transmission. The number of messages over the uplink transmission is limited to only 140 messages per day with the maximum payload length for each uplink transmission message being 12 bytes [23]. Furthermore, the number of messages over the downlink transmission is limited to only 4 messages per day and the maximum payload length for each downlink message is 8 bytes [24]. The number of downlink transmission messages being less than uplink transmission messages means that only some of the uplink transmission messages could be acknowledged. Consequently, transmission reliability could not be achieved.

3.3.3 *NB-IoT.*

Narrow Band IoT (NB-IoT) is a new radio access network (RAN) technology that was standardized by the Third Generation Partnership Project (3GPP) in 2016 for the Long Term Evolution (LTE) Release 13. The technology operates in a narrow band using the licensed spectrum of the ISM band and inherits the main functions of the LTE system as the communication protocol is based on LTE protocol. A software upgrade can enable the core



	1	2	3
Price	0-2 €	2-10 €	>10 €
Security	None	AES Encryption	End-to-end Encryption
Service Profile	Monitor	Control	Automate
Data Throughput	0.1 - 0.4 kbps	0.4 – 1 kbps	> 1 kbps
Range	Short Range	Long Range (Field)	Long Range (Indoor)
Flexibility	Private	Public	Public & Private

Household Appliances	LoRaWAN	Sigfox	NB-IoT
1	2	1	3
3	2	1	3
2	2	1	3
2	2	1	3
3	3	2	3
3	3	2	2

Fig. 4. Network criterion overview of household appliances and LPWAN technologies with regards to their classes marked as numbers from 1 until 3

network of an operator's existing LTE network to support the NB-IoT technology [12].

Because NB-IoT communication protocol is based on LTE protocol, it is able to use the licensed spectrum from the existing LTE network and could be divided into 3 modes according to the frequency bands [12].

- Stand-alone operation: it deploys on its own or uses already existing GSM frequency bands (e.g., 700MHz, 800MHz, and 900MHz).
- Guard band operation: it uses the existing LTE spectrum's guard-band unused resources.
- In-band operation: it uses the existing LTE spectrum's resources.

NB-IoT supports bidirectional communication. It uses Single Carrier Frequency Division Multiple Access (SC-FDMA) modulation for uplink transmission and Orthogonal Frequency Division Multiplexing (OFDM) for downlink transmission [12]. The maximum data rate for the uplink transmission is 20 kbps, while for the downlink transmission, the maximum data rate is 200 kbps. Additionally, the maximum payload size is 1600 bytes in each message both for uplink and downlink transmission [13].

In this subsection, the fundamentals along with technical specifications of LoRaWAN, Sigfox, and NB-IoT technologies have been covered. These fundamentals are necessary in order to compare each LPWAN technology with the technical requirements and ultimately to choose the best-suited one for the product.

3.3.4 Comparison between each technology in accordance with the business use cases technical requirements. In order to choose the suitable LPWAN technology for the product, various network criteria are listed with regard to their priority as the selection criteria. These criteria are the price of the end device, security of the network's transmission, the service profile representative use case, data rate, network range, and network flexibility. The aforementioned network criterion details are going to be discussed more along with the comparison of each LPWAN technology, such as LoRaWAN, Sigfox, and NB-IoT, to the product's requirements regarding the criterion. The summary of the criterion of household appliances and LPWAN technologies is depicted in Figure 4 and the details could be seen below.

The appliance system price needs to be as low as possible since it is the customers' priority. It needs to be able to upload securely to the server, which could be extended to end-to-end encryption. The main use case is for monitoring, extended to controlling. For the realisation of the specified use case, the appliance needs to send 4500 bits (0.45 kb) per second. The product needs to have a long transmission range as it is located indoors. Lastly, the architecture could be configured to either use a public or private network architecture.

LoRaWAN offers a relatively cheap price for the end devices to operate. It has the AES encryption implemented enabling secured connectivity. The main use cases are for monitoring and control, as it has a low data rate of 300 bits (0.3 kb) per second in the worst case. The network has a long transmission range reaching the indoor area. The network can be configured to either be a public or private network with a privately owned gateway.

Sigfox offers a very cheap price for end devices and is the cheapest compared to the others. It does not have default security and encryption needs to be implemented. The main use case is only for monitoring due to its very low data volume with 100 bits (0.1 kb) per second in the worst case. The network has a long transmission range inside and outside the city area. The network could only be operated using a public network owned by Sigfox.

NB-IoT has the highest price compared to the other two technologies. It has the default security of AES encryption and could be extended to end-to-end encryption. The main use cases are for monitoring, controlling, and also automation since it has a high data volume reaching up to 27000 bits (27 kb) per second. The network has a very long transmission range that could reach the basement. The network could only be operated using a public network owned by telecommunication vendor companies.

In conclusion, each LPWAN technology has its advantages and disadvantages with the different criterion that has been defined for the product's requirements. For a more detailed comparison between the product's requirements and each LPWAN technology, please refer to Figure 5.

3.3.5 The best fitting LPWAN technology to the specified requirements. From Figure 5, it could be analyzed that LoRaWAN offers a relatively cheap price for end devices while still sufficiently fulfilling the technical requirements for the business use cases. On the other hand, while Sigfox offers a very cheap price for the end devices, it does not fulfil the technical requirements sufficiently for the business use cases. Lastly, NB-IoT fulfils the technical requirements perfectly, but the problem is the end device's price is too expensive. In selecting the best suitable LPWAN technology, meetings were held with the customers to get their opinions on which LPWAN technology will suit best. After these meetings, it was decided that LoRaWAN was chosen because it offers a cheap price while still also sufficiently fulfilling the technical requirements. This makes it possible for customers to increase the scalability of the end devices without spending too much money as the price criteria are the main priority.

3.4 Answering Performance of Chosen LPWAN Technology

In this subsection, LoRaWAN performance is going to be investigated to verify the assumption that LoRaWAN fulfils the technical requirements. Thus, performance evaluation is conducted in

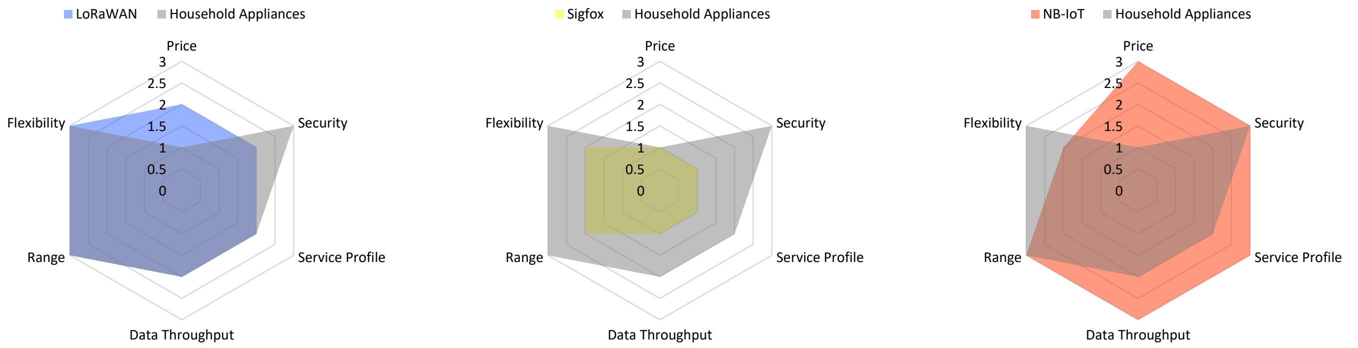


Fig. 5. Chart comparison of network criterion between household appliances to each LPWAN technology

experimental testing under a real-life scenario. The performance evaluation will use the specific metrics of transmission time and transmission range. The evaluation of the metrics will be done by transferring data packets from the end device to a public server via the gateway.

The performance evaluation will be under the scenario of an indoor to indoor evaluation in different buildings. The evaluation uses the hardware of one end device, one gateway, and a public network server. The evaluated hardware is shown in Appendix B of this paper. The scenario is done only indoors as household appliances are often indoors which means that the end device will only be tested indoors and the gateway is limited to be tested only indoors due to hardware limitations.

The end device is composed of a board from “STM32” that is connected to the Semtech SX126X LoRa module which periodically sends a command to LoRa module [28]. On the other hand, the gateway consists of an SX1301 chip and 2 LoRa Transceiver that supports packet forward mode to a public network server using IPv4/TCP stack via WiFi [3]. The public network server involves using “The Things Network (TTN)” server, which is a cooperative global Internet of Things ecosystem, to create networks, end devices, and solutions via LoRaWAN [18]. To evaluate LoRaWAN, a gateway and an end device must be connected first to The Things Network. All communication from the end devices will be received by The Things Network server via the registered gateway and stored on the server.

The performance evaluation will be first tested on the transmission time metric and followed up with the transmission range metric. As specified in subsection 3.3.1 about LoRaWAN specification, each packet needs to be transmitted with a specific spreading factor (SF). Thus, there is a trade-off between transmission range and data rate. The higher SF number gives a lower data rate and increases the transmission range. This is important in performance evaluation testing to measure how the tradeoffs are between the two in a real-life scenario testing. Moreover, there is a feature of Adaptive Data Rate (ADR), which optimizes data rate, transmission time, and energy consumption [1]. Different SF is going to be evaluated according to its metrics in the following subsections.

3.4.1 Transmission time. The evaluation setup is by sending a variety of data packets from the end device over a bandwidth channel of 125 kHz and coding rate 4/5 to the TTN server via the gateway. Afterwards, the transmission time of each specific payload will be analyzed. Since LoRaWAN needs to use a specific SF for the data transmission, the evaluation will specifically evaluate SF numbers 7 and 12. The two SF numbers are used specifically to evaluate the worst and best case scenarios of the network. The results of this metric evaluation are shown in Figure 6 and the details of the evaluation results could be seen below.

The evaluation started with the transmission time of SF number 7. The evaluation is done by sending a variation payload of 160 until 1920 bits (0.16 - 1.92 kb). These payloads are specifically chosen to see how transmission time increase as data payload periodically increases and because 1936 bits (0.1936 kb) is the maximum payload to be sent in one transmission as it is a restriction from the TTN server. The results for transmission time of SF number 7 are depicted in Figure 6. For SF number 7, the maximum transmission time for transmitting 1920 bits (1.92 kb) is under 400 milliseconds (ms), which could be considered fast as this translates to 4800 bits (4.8 kb) per second. Moreover, the transmission time for each data payload goes down as the data payload size increases. At the start, it needs 71 ms in transmitting 160 bits (0.16 kb), which means that each bit needs 0.44 ms to be transmitted. But for transmitting 1920 bits (1.92 kb) payload, it only needs 394 ms to be transmitted, which translates to each bit only needing 0.21 ms to be sent.

Following the previous evaluation, the transmission time of SF number 12 is evaluated. Similarly, the evaluation is done by sending a variation payload of 80 to 400 bits (0.08 - 0.4 kb). These payloads are specifically chosen to see how transmission time increase as data payload periodically increases and because 408 bits (0.408 kb) is the maximum payload to be sent in one transmission as it is a restriction from the TTN server. The results for transmission time of SF number 12 are presented in Figure 6. It is seen that to transmit 400 bits (0.4 kb) with SF number 12, the maximum transmission time is 2800 ms. This is considered rather slow with 143.2 bits (0.14 kb) per second. Again, the transmission time for each data payload goes down as the data payload size increases. At the start, it needs 1482 ms in transmitting 80 bits (0.08 kb) and translates to 18.52 ms for each bit to be transmitted. However, it only needs 2793 ms to transmit 400 bits (0.4 kb), meaning each bit only needs 6.99 ms to be transmitted.

The evaluation of the transmission time metric has shown that the transmission time for packets sent with SF numbers 7 and 12

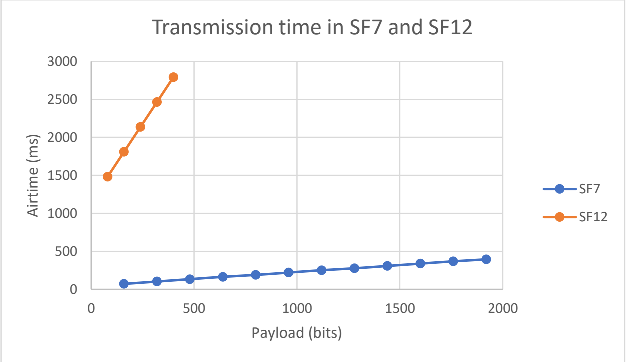


Fig. 6. Transmission time graph in spreading factor number 7 and 12

differed by 33 times faster for SF 7. In the following subsection, the transmission range of both SF numbers 7 and 12 will be evaluated to analyze the tradeoff between the two metrics.

3.4.2 Transmission range. The evaluation setup here is by sending fixed data packets over a bandwidth channel of 125 kHz and coding rate 4/5 to the TTN server via the gateway evaluation hardware. Afterwards, the end nodes will be put at some distance from the gateway to observe the transmission range. With the help of the ADR feature, the end device will automatically shift to the most efficient SF number. This SF number will then be observed to see how far the transmission could go from the end device to the gateway. The results of this metric evaluation are shown in Figure 7 and the details of the evaluation results could be seen below.

The evaluation with the scenario of indoor testing in a housing neighbourhood in The Netherlands is shown in Figure 7. The gateway is marked as the green point in the figure and is located 7 meters above the ground. For the end device, it is measured in several different locations marked as yellow, blue, purple, red, and orange colour points. These colour points indicate different SF numbers that are used in the transmission, as could be seen in Figure 7. The yellow points are located 60-80 meters from the gateway. On the other hand, the orange points are located 200-250 meters from the gateway. From these locations and their estimated boundaries, the end device uses SF numbers 7 and 12 respectively to transmit the data via the gateway. For the other colour points, it could not be indicated how far it could reach and what the estimated boundaries are as the evaluation tests on the same location show a variation of SF numbers due to the ADR feature.

The evaluation of the transmission range metric has shown that the transmission range for packets sent with SF numbers 7 and 12 differed by 4 times further for SF 12. However, for the other SF numbers, it is not possible to determine what are its estimated boundaries due to the ADR feature.

In this subsection, LoRaWAN performance has been evaluated in terms of transmission time and transmission range as the performance metrics. Along with the evaluation, the tradeoff between the two metrics has also been analyzed. From the results of the evaluation, the performance of LoRaWAN in a real-life scenario testing differed from its technical specifications. The technical specification explained that the data rate could achieve 50 kbps and the transmission range could be as far as 5 km in the urban area. However, these differ from the findings in the evaluation in which it only has a 0.5 kbps and 250 meters transmission range. With that said, several reasons why the findings differ will be discussed in section 4.

Fig. 7. Transmission range of different spreading factor numbers referenced as different colour points

4 DISCUSSION

In this section, the possible reasons why the technical specification and evaluation of LoRaWAN differs will be explained. It will also discuss what limitations of this research and why further research is needed to investigate the usage of LoRaWAN for the suitable LPWAN technology in the business use cases. Finally, it will be discussed if LoRaWAN is still the best suitable LPWAN technology compared to the other technologies for the business use cases.

4.1 Limitations

As stated in subsection 3.4, the performance of LoRaWAN in a real-life scenario testing differed from its technical specifications. The transmission time metric, which translates to the data rate, could be analyzed a hundred times slower and the transmission range metric is twenty times worse in the evaluation test compared to the specification. One possible reason for this is because of the hardware evaluation setup. To maximize signal strength between the transmitter and receiver, the gateway needs to be high above the ground, at least ten meters outdoors, for a direct transmission path without any obstacles as it weakens signal strength [7]. Hence, the reason why the evaluation differs a lot from the technical specifications.

The data rate, which in the worst case could only transmit 0.14 kbps, is a problem as the appliances need to send data up to 0.45 kbps on average according to the technical requirements specified in subsection 3.2. Moreover, a short transmission range would mean that the customers needing more gateways installed for its usage, which translates to a higher upfront cost investment.

4.2 Further Research

From the specified limitations in subsection 4.1, further research is needed to realise LoRaWAN usage for the business use cases. The problem with high transmission time and low data rate could be resolved in further research by implementing data compression for the appliances' data on the end device before sending it to the server. One idea of the implementation is using Huffman Coding [17], an algorithm that optimizes prefix code to achieve data compression without any data loss. The implementation of data compression could omit the dependency of using lower SF numbers from LoRaWAN for the realization.

On the other hand, the problem with short transmission range is greatly influenced by several parameters, such as antenna gains and height above the ground. In the evaluation, the gateway was located only 7 meters above the ground, which suffers interference from obstacles and other sources. Moreover, the antenna used was an omni-directional antenna, which radiates smaller power and gains compared to the directional antenna [8]. In the future, the directional antenna could be used to improve performance and minimize interference from obstacles and other sources.

In this section, the limitations and further research of LoRaWAN have been discussed. LoRaWAN showed to be usable in a real-life scenario where data needs to be transmitted from household appliances to the server via the gateway. It can fulfil most of the product's requirements that were retrieved in section 3.2, such as the end device price, security, reliability, installability, and usability. In terms of technical requirements, it has a sufficient performance based on the evaluation results, though it differs from its technical specifications. However, it still has the caveat that the SF needs to be in the lower numbers for sufficient performance. With that said, LoRaWAN still has some limitations and further research is needed to investigate the possibility of using LoRaWAN for the business use cases.

5 CONCLUSION

Household appliances are evolving technologically becoming "smarter" with the help of the Internet. Most household appliances sold in the market currently have a feature that enables connection between appliances and the server with WiFi. Even so, customers demand to have an independent connection without end customers' WiFi to minimize the ongoing maintenance cost, enable a reliable connection, and enable a secured connection. Hence, new technology needs to be explored since none of the current state-of-the-art technologies satisfies the product's requirements. Thus, LPWAN emerged as a viable solution to the specified problem by providing long-range, secured, and energy-efficient transmission due to its new technology.

Interviews with customers are carried out such that business use cases and product requirements could be retrieved. From the product's requirements, technical requirements are derived to choose a suitable LPWAN technology that matches the technical requirements. In doing so, literature reviews on different LPWAN technologies have been done to investigate which LPWAN technology suits the product's requirements and business use cases best. After the comparison, LoRaWAN proves as the most suitable LPWAN technology that is currently available in the market that fulfils the product's requirements for the business use cases. To verify the assumption that LoRaWAN is the most suitable LPWAN technology, the performance was evaluated under real-life scenario testing. In the evaluation testing, although LoRaWAN technical specification in subsection 3.3.1 differs from the evaluation testing in 3.4, it is still deemed to be usable in a real-life scenario for the business use cases under specific conditions. With that said, LoRaWAN also still has some limitations, such as high transmission time, low data rate, and short transmission range compared to the expected performance. Thus, further research is needed to investigate the practical usage possibility of LoRaWAN for the business use cases.

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A INTERVIEW QUESTIONS

(1) How is the current process of customers and end customers interaction with household appliances?
(2) What are the main objectives/goals that want to be achieved from this new architecture of household appliances?
(3) Why is a new architecture of household appliances needed?
(4) What are the end customers perspectives on the current architecture of household appliances?
(5) What are the end customers gripes/negatives with the current architecture of household appliances?
(6) What functionalities are expected in the new architecture of household appliances from the customers and/or end customers?
(7) What requirements are expected in the new architecture of household appliances from the customers and/or end customers?
(8) Are there anything specific that the customers and/or end customers want to be shown in the new architecture of household appliances?
(9) What has to be improved from the current architecture of household appliances?
(10) What are parts of the current architecture that the customers and/or end customers desire for the new architecture of household appliances?
(11) Is there anything else that you want to talk about for the new architecture of household appliances?
(12) What are the costs of the current process of appliance maintenance and repairs?
(13) How much data rate for the household appliances are needed in the current process?

B EVALUATED HARDWARE

Fig. 8. The end device and gateway used in the evaluation