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# Effects of Traffic Characteristics on Energy Consumption of IoT End Devices in Smart City

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***Abstract*—The rapid urbanisation in many parts of the world in the last few decades has intensified the challenges of urban living. Internet of Things (IoT) can be leveraged as a tool for transformation to provide technology-assisted city development and management. However, given that many of the nodes in smart cities are constrained devices, part of the medium-long term challenges is how to sustain the real-time monitoring capabilities of the city without disrupting services. This paper investigates the effects of data traffic characteristics on the active life of constrained devices in smart cities. The access network model employs two leading low-power wide area network (LP-WAN) technologies; long range wide area network (LoRaWAN) and Sigfox specifications in a star topology. The results show that in Europe, for light-weight applications such as smart street lighting that sends small payloads once a day, Sigfox and LoRaWAN can provide device lives of about 5.82 years and 13.25 years respectively. On the other hand, for intense applications such as smart bus stops, using payload of 12 bytes, if the number of messages sent per day is increased from 1 to 140, Sigfox device life reduces from 4.43 years to 0.8 years while that of that of LoRaWAN reduces from 13.1 years to 10.48 years.**

***Index Terms*—Smart city, low-power wide area network (LP-WAN), Internet of things (IoT), LoRaWAN, Sigfox.**

## I. Introduction

Municipalities face the complex challenges of meeting the diverse developmental needs of their citizens in terms of physical and social infrastructure. According to a report from United Nations (UN) [1], the world population is expected to reach 9.7 billion by 2050. A 2008 habitat survey also predicted that about 70% of the world's population will live in urban centres by 2050 [2]. Such a high influx will not only exert pressure on the social infrastructure but also aggravate the many challenges associated with urban living in vital areas including energy, environment, transportation, waste management, security, pollution, traffic management and the rising awareness to improve quality of life (QoL) of the citizens [3]. These challenges have motivated city councils, policy makers, the research community and other stakeholders to consider new ways of managing cities to make them compliant with 21st century citizen's needs. One key approach is to increase digital presence through deployment of various smart technologies such as Internet of things (IoT) [3], [4].

In a smart city context, the role of IoT is to integrate information and communication technologies (ICT) into the city fabrics and enable the acquisition of multi-level data sets about physical assets and other infrastructural elements related to citizens' welfare and service delivery. IoT enables the generation of real-time data which can be analysed to create new knowledge that will guide city planning, development and management as well as facilitate data-driven decision making. The smart city domain is dominated by battery-powered devices which are constrained in terms of energy, communication and computational capabilities. Thus the energy requirements and battery life of each device in smart city varies with data traffic pattern and use-case.

Although the IoT design paradigm does not restrict the type of communication technology to be used for connecting the objects, there are many smart city use-cases in which wireless is the only feasible option. In many applications, long range transmissions are required in addition to low energy consumption and the battery-powered nodes are expected to function for at least 10 years without battery recharge or replacement. However, many of the conventional long-range wireless technologies consume too much energy (e.g. WiMAX, 2G, 3G and 4G technologies) and are not optimised for smart city scenarios. Low-power wide area network (LP-WAN) technologies provide features that can be explored to achieve the delicate balance between these seemingly conflicting requirements through some trade-offs between performance, complexity and cost, e.g. data rate, data size vs energy consumption. The aim of this paper is therefore to investigate the effects of the traffic characteristics of smart city applications on the battery life of the end devices and explore the trade-offs using the features available in each LP-WAN technology.

The energy consumed during message transmission is affected by the message length. In Sigfox transcievers, the current required ranges from 10 mA to 50 mA, with maximum of 30mA in Europe and about 49mA in US [5], [6]. Despite the higher current requirement of the US specification, its higher data rate of 600bps means it can send messages 6 times as fast as the European specification which positively impacts its energy consumption. In LoRa, the spreading factor (SF) provides additional flexibility to trade between coverage, throughput and energy consumption. To illustrate these, we consider the battery life in two extreme cases of 1 message per day and up to 140 messages per day using 1-byte and 12-byte payloads. We adopt a 1200 mAh AA battery as a reference point and assume an ideal battery with a linear characteristics.

The contribution of this paper is two-fold. First, we evaluate the impact of different application traffic on energy consumption of the devices. Secondly, we show that the SF in LoRa can be leveraged to optimise the trade-off between data rate or message size and energy consumption. These outcomes provide indicators to consider when developing IoT solutions for smart city.

## II. Smart City and Triangulum

A number of projects [7]–[10] have demonstrated the possibility of city-wide monitoring through the use of sensors and other smart technologies. For instance in Europe, municipalities such as Antwerp [8], Barcelona [11] and Helsinki [12] have introduced smart city as means of improving the QoL and living experience of both citizens and visitors. In reality, building a large-scale smart city is tasking and sustaining it is even more challenging. One of the medium-long term challenges is how to sustain the monitoring capabilities of the city by ensuring that the constrained devices such as wireless sensors last for many years without battery replacement or recharge. Triangulum is an ongoing project that aims to demonstrate, disseminate and replicate systems innovation approach to smart city development, with the citizens as the focus. The main work streams of the project are Energy, mobility and ICT.

Due to the scale and wide diversity of applications, smart city will be supported by a mix of wired and wireless communication technologies including LP-WANs and conventional short-range technologies such as Wi-Fi, ZigBee, etc. Within Triangulum, different types of sensors (e.g. air quality sensors) are deployed at different parts of the Manchester city to monitor and send half-hourly reports on the observed phenomena to the central data platform using different access technologies including Wi-Fi, 3G, etc. The idea of this study is to consider alternative communication technologies for the long-range low-power requirements in such scenarios.

A lot of work has been carried out to define the requirements and uses-cases within the smart city construct. Many recent works in IoT have also proposed architectural reference models and protocols as well as security architecture for IoT-based smart city. In many ways, the emergence of IoT is foundational to the development of smart city [13]. LP-WAN technologies are increasingly being deployed to provide connectivity in many applications that require long-range communication [14] and is therefore suitable for interconnecting the nodes in Triangulum smart city project to the processing centre.

Though a range of LP-WAN exists, each is characterised by range, data rate and energy consumption. In many nodes such as wireless sensors and other simple devices where it is impractical to recharge or replace their batteries, a device is expected to use a single battery throughout its lifetime and operate until the battery runs out of energy. While data rate and coverage affect the application performance on one hand, the data traffic characteristics in each application affect the energy consumption of the device on the other.

Many aspects of LP-WAN technologies have been investigated for different applications including smart cities. In that regard, various analytical as well as simulation models have been reported in the literature including pathloss, scalability, coverage and capacity [15], [16] [17]–[19] of LP-WANs. However, a considerable amount of follow-on work is required on energy consumption and network life, taking into account the the characteristics of each application. That is the focus of this paper.

## III. LP-WANs and System Model

### A. LoRaWAN

LoRa is a chirp spread spectrum (CSS)-based low-power modulation scheme developed by Semtech Corporation while LoRaWAN the long range communication protocol which adopts LoRa at the physical layer. LoRaWAN defines the MAC layer and some network layer functionalities. Thus, it is possible to deploy LoRa without using LoRaWAN. There are 3 classes of LoRaWAN devices. Communication with Class A devices is asynchronous using ALOHA-type technique [20], [21] . This means the end devices transmit whenever they have data and go to sleep afterwards which makes them the most energy-efficient device class. Example include battery-powered sensors. Class B support slotted communication which is synchronised with a beacon from the gateway. This device class also supports an extra receive window in addition to that in class A. Examples include battery-powered actuators. Class C devices continuously listen to download and can receive message from the getaway at any time. This device class provides the lowest latency, however they consume the most energy and are more suitable for mains-power [20], [21]. Bandwidth of 125KHz, 250 KHz and 500 KHz can be employed, depending on the SF.

### B. Sigfox

Sigfox end points do not execute or exchange any form of signalling with the gateway before they transmit data. However, to improve the chances of detection by the surrounding base stations, each message is transmitted 3 times. As it is a narrowband technology, Sigfox the network provides low data rate and supports small data size, typically 12 bytes payload in uplink and 8 bytes payload in downlink (excluding header information and other transmission overheads). Hence, it is suitable for sensors measurements and other applications that require small message lengths. Sigfox employs differential binary phase shift keying (DBPSK) and Gaussian frequency shift eying (GFSK) modulation and coding techniques [22]. Each message occupies 100Hz-600KHz with a data rate between 100-600bps, depending on the region (600bps in US and 100bps in Europe) [5].

### C. System Model

In smart city end devices, energy consumption is affected by transmission duration, throughput and payload size. Although multi-year battery life is a major performance target, the battery capacity usually depends on the requirements of the specific use-case. The field condition can be worsened by obstruction losses which will further reduce the link budget. Fig. 1 illustrates the IoT-based data acquisition model employed in this work.

In Triangulum project, the data infrastructure is built on OSI-soft platform [3] with API connection to data sources. Manchester Metropolitan University (MMU) and University of Manchester (UoM) within the consortium push data (energy and mobility) to the OSI-soft platform through VPN connection over the Internet. These devices send their reports through the communication networks to central data repository. The energy consumed during the

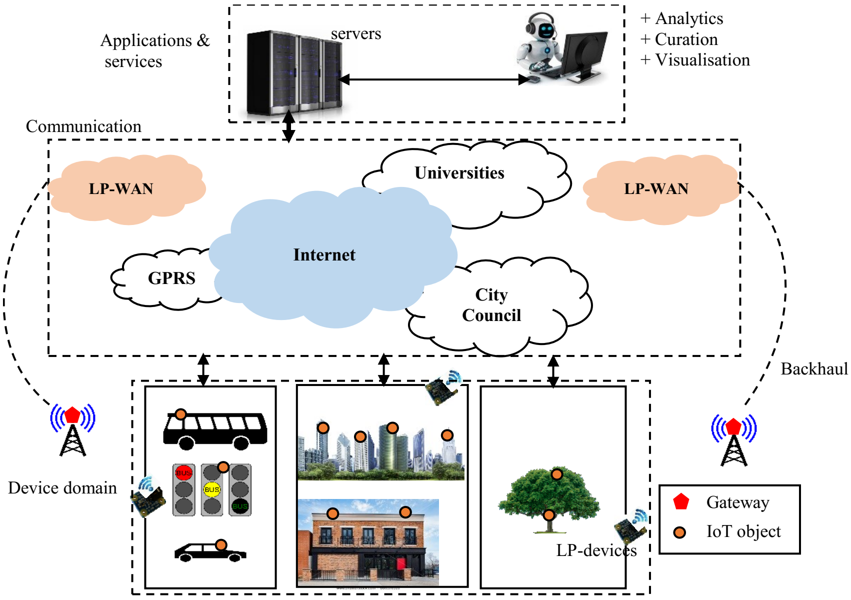



Figure 1: A high-level representation of IoT-based data acquisition model for smart city in Triangulum project

Table I: Additional Simulation Parameters

| Parameter | Value |
|---|---|
| Number of gateways | 1 |
| Number of end devices | 1 |
| Power amplifier current | 300mA |
| Transmit current, mA | US 49mA , Europe 30mA @3.3V |
| On-Air time | Sigfox-US 1.04s (US), Sigfox -EU 6.24s LoRa (varies with SF) |
| Fade margin | 0 dB |
| Battery reference | 1200 mAh AAA |
| Sleep current | Sigfox 6$\mu A$, LoRa 10$\mu A$ @3.3V |

data transmission directly affects the life time of the battery and by extension the device itself. For example, a wireless sensor will cease to function once the battery runs out of energy.

Parameters in Table I are used to simulate the transmission from sensors to the gateway. The battery life discussed here is with respect to 1 uplink of the radio transmitter (with power amplifier) only, downlink, micro-controller unit (MCU), wait windows, and other consumptions in the system are not included. Generally, the average power $\bar{P}_{Tx}$ required by the transmitter is related to the energy used to send a message and the transmission interval between messages $T_M^{(j)}$. The average power during transmission can be expressed as [23]

$$\bar{P}_{Tx} = \sum_{j=1}^{N} \frac{E_M^{(j)}}{T_M^{(j)}} \tag{1}$$

where $E_M$ is the energy dissipated per message, $N$ is the number of messages within the observsation period, and $j$ is the index of the summation. Thus the value of $E_M$ depends on the chips used and duration of each transmission. For IoT applications that require periodic reporting e.g. smart metering or air quality sensing, $T_M^{(j)}$ is a constant parameter. Therefore, (1) can be rewritten as

$$\bar{P}_{Tx} = \frac{1}{T_M^0} \sum_{j=1}^{N} E_M^{(j)} \tag{2}$$

where $T_M^0$ is the constant interval between reporting instances. The energy consumed for each report transmitted by the IoT network is given by

$$E_{Tx} = \bar{P}_{Tx}(mW) \cdot T_M^0(ms). \tag{3}$$

The energy consumed during data reception is given by

$$E_{Rx} = T_{RX}(ms) \cdot \bar{P}_{Rx}(mW), \tag{4}$$

where $T_{Rx}$ is the period during which data is received and $P_{Rx}$ is the battery power consumed in the process. In an active network, each node must be silent for a minimum period of $T_{SM}$. Assume the device goes into sleep mode (SM) after each transmission, the SM duration is given by

$$T_{SM} = T_a\left(\frac{1}{dc} - 1\right) \tag{5}$$

where $T_a$ is the time-on-air and $dc$ is the duty cycle. In the SM state, all processes and instruction execution are shut down, except the watchdog or realtime clock which is used to trigger periodic measurements in sensors. For an uplink-centric technology such as Sigfox, the daily energy consumption due to message transmission is described as

$$E_2(Joule) = E_{Tx} \cdot N + B_{SM}(mW) \cdot \frac{T_{SM}}{3600} \cdot \frac{3}{125} \tag{6}$$

where $T_{SM}$ is the time spent in SM (in seconds) and $B_{SM}(mW)$ is the battery power in mW.

## IV. Results

In this section, we adopt the SX1272 LoRa model [24] and present the variation of battery life with data traffic for different applications in smart city. In addition to the parameters in Table 1, Semtech's LoRaWAN 868 MHz battery life calculator v2.0 is also employed in the simulations.

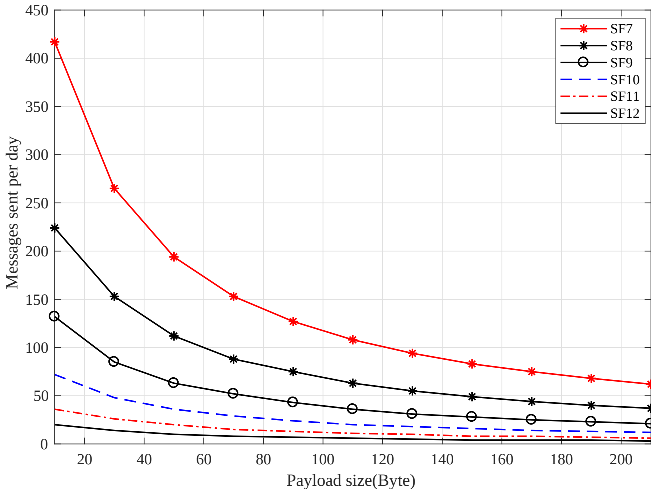



Figure 2: Message sent per day for LoRaWAN devices with various payload sizes and explicit header enabled. Other parameters are coding rate 4/5, preamble symbols 8, bandwidth 125kHz, DC 0.1%

### A. *Message Per Day*

For a given smart city application, the number of messages transmitted per day plays an important role in the annual energy budget and battery life. In Europe, the maximum duty cycle (DC) of 1% [5] means that the Sigfox network in principle can support a maximum 140 fully loaded frames of 12-byte payload per day while 4 message slots are reserved for the Sigfox protocol to exchange control information. However, LoRa supports up to 242 bytes payloads and employs a spread spectrum technique which allows multiple messages transmitted on different SF to be received as orthogonal (independent) signals. This feature allows the nodes to send more messages per day which invariably affect energy consumption.

Fig. 2 presents the number of messages per day for different SF values in LoRaWAN. In explicit header (EH) mode, LoRa frame header carries 3 values-coding rate (CR), size of the forthcoming payload and CRC flag. These values affect the data payload carried in each packet transmitted over the network. The figure indicates that the number of sent messages per day generally decreases with the payload size for all SF values. The figure further shows that SF 7 not only support the highest number of messages but also the most suitable for applications that involve large payloads.

Fig.3 compares the effects of payload size on battery life for EU and US specifications of Sigfox technology. Similarly, the battery life of LoRaWAN transceiver is illustrated in Fig. 4. Figs. 3 and 4 respectively illustrate the estimated battery life of Sigfox and LoRaWAN by taking into account different payload sizes and number of daily messages. Both figures reveal the following

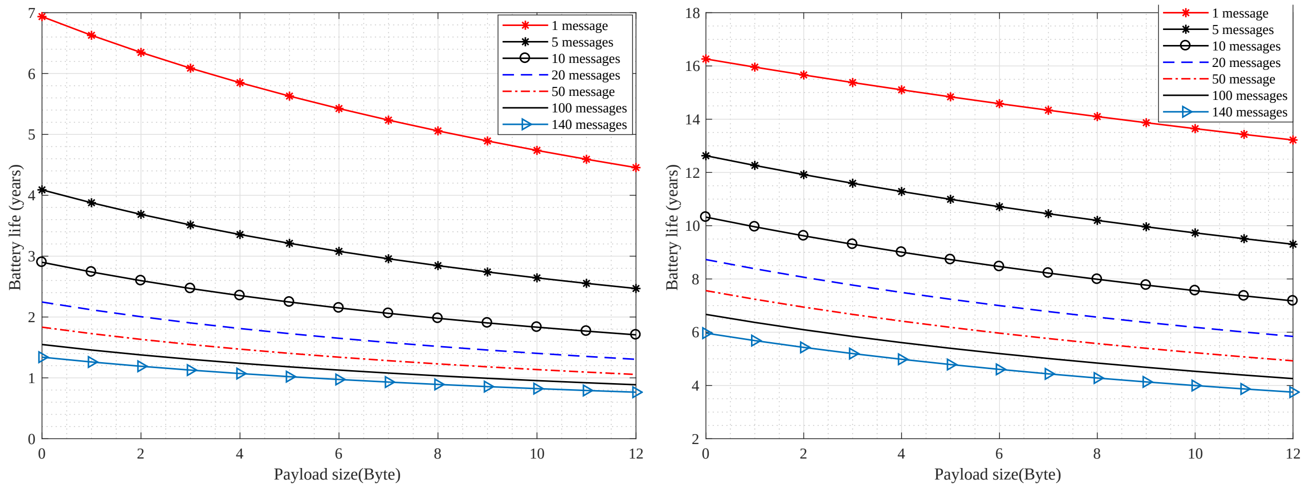
- Battery life is affected by the size of application data and number of messages per day.
- In comparative terms, the US specification of Sigfox transceiver battery will significantly outlast its EU counterpart given the same capacity.
- As the payload size increases, the rate of battery depletion is more pronounced in Sigfox than LoRaWAN. (0 byte is equivalent to control messages).
- For applications that require very few number ($< 5$) of messages per day, Sigfox-US can potentially offer longer battery life than LoRaWAN with a moderate data rate (SF 10). However, it is seen that LoRaWAN is more promising for all other applications requiring 5 of more messages per day. This is in addition to the fact that LoRaWAN also supports larger payloads.

LoRaWAN is also subject to 1% maximum DC in Europe and other regulations as Sigfox. However, the availability of SF in LoRaWAN provides a way to further trade-off between system variables and performance (range, data rate, energy consumption, etc), thereby offering additional degree of flexibility in connectivity deployment for smart city applications. Fig. 4 shows the impact of payload size and SF on LoRaWAN annual energy budget. These results are based on Semtech's LoRaWAN design guide. In this study, the low data rate (DR) optimisation flag is enabled in the LoRa frame for SF 11 and 12. The effect of this flag is smaller throughput occasioned by the reduction in the number of bit/symbol.

Fig. 5 shows that energy requirement of LoRAWAN network is affected by SF in addition to transmission interval and payload size observed in Sigfox. The results are based on link budget 150.5dB, symbol length 4.1ms, preamble duration 50.2 ms. The annual budget in Fig. 5 includes all energy consumption except sensor circuit, sensor processing and MCU. Here it is assumed that each device has enough data to transmit as much as the DC allows. Whereas Sigfox supports maximum payload size of 12 bytes, LoRaWAN can support up to 242 bytes. Generally, heavy payload increases the power requirements, nevertheless it may be suitable in private LoRaWAN networks for applications that involve monitoring of different aspects of a system once a day (e.g. monitoring of wildlife). In Fig. 5, it appears the LoRaWAN end devices transmitting 10-bytes payload require the higher annual energy budget than 50-bytes and 200-bytes. This can be explained as follows. The relatively smaller payload size means each message will spend less time in the air thereby, allowing more message to be transmitted within the regulatory DC in private LoRaWAN network. This will naturally result in higher energy consumption. The apparent smaller energy requirement of 200-byte payload is a consequence of reduced number of messages transmitted. Heavier packets occupy the channel for longer period thereby limiting the number of messages that can be transmitted within the DC. Secondly, a protocol overhead of 13 bytes is applied to each message, regardless of the payload size. In other words, for every 10-byte payload, a 13-byte overhead information is incurred, this duplication of overhead further increases the energy consumption when many messages are transmitted within the DC.

### B. *Use-Cases*

*1) Daily Reporting: One Message per day (e.g public lighting):* In smart cities, some applications require one message transmission per day. For example in smart street lighting, the turning ON and OFF are triggered by the diurnal conditions such as sunset and dawn respectively. Figs. 4 and 5 show that given a payload size of 4 bytes and using the equivalent of 1200 mAh AAA battery, the European specification can deliver an active battery life of about 5.82 years compared with 15.1 years of its American counterpart and 13.25 years for LoRaWAN at SF 10. At




(a) Sigfox (Europe) at 100bps Tx current= $30mA$, PA current=$300mA$, sleep current=$6\mu A$ at $3.3V$

(b) Sigfox (US) at 600bps, Tx current= $49mA$, PA current=$300mA$, sleep current=$6\mu A$ at $3.3V$

Figure 3: Payload size vs battery life for various number of daily messages in Sigfox access network

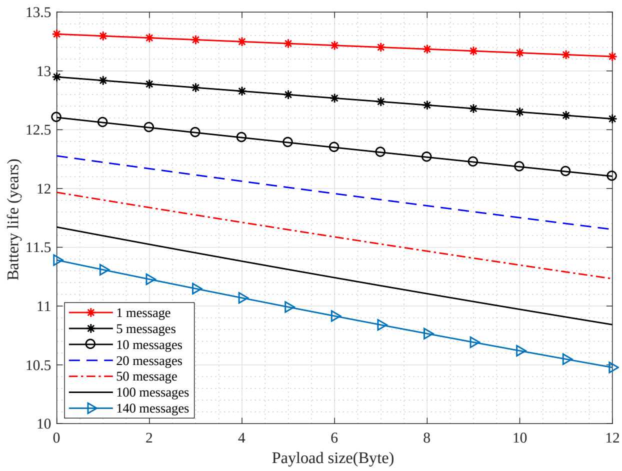



Figure 4: Battery life in LoRaWAN transceiver with various payload sizes, SF=10, coding rate $\frac{4}{6}$ and CRC enabled. Other parameters are 8 symbols preamble and bandwidth 125kHz. Tx current= $41mA$, sleep current=$10\mu A$ at $3.3V$

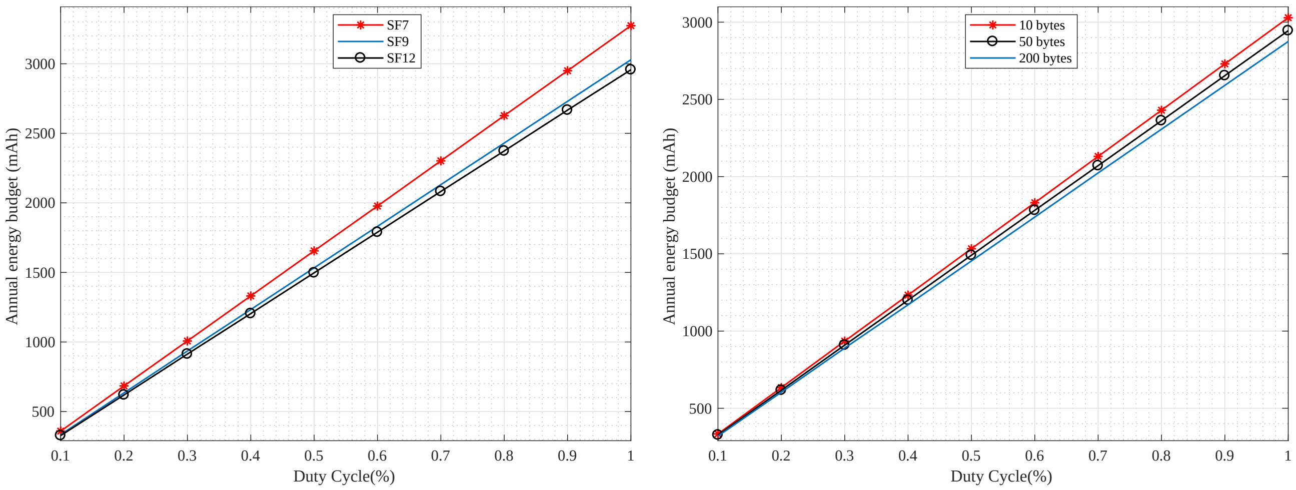
the other extreme, with Sigfox frames containing 12-byte payloads, the European and American transceiver can offer about 4.43 and 13.27 years, respectively while LoRaWAN yields 13.1 years.

*2) Intense Reporting: Multiple messages (e.g. smart parking, talkative bus stops):* In intense applications requiring multiple messages or measurement per day such as smart parking, temperature sensing, air quality sensing, talkative bus stops, smart dust bins, etc. In many of such applications, reporting is event-driven for example smart park application monitors and reports availability of space. Parking events are slow, hence the communication in smart parking application typically involves a few tens of messages per day, the frequency of transmission directly impacts the energy consumed by the end device. In other applications such as air quality monitoring, the sensor transmits half-hourly. With a fully loaded frame of 12 byte payload, the Sigfox transceiver will remain in communication state for 6.24 s in Europe and 1.04 s in US in each transmission. Fig. 3 shows that using 1200 mAh AAA battery or its equivalent, the active life of the Sigfox endpoint battery is about 1.06 years and 4.93 years in Europe and US respectively and about 11.2 years for LoRaWAN. However, if messages per day is increased to 140 (using Sigfox as benchmark), the Sigfox battery life reduces to 0.8 years in Europe and 3.75 years in US while LoRaWAN reduces to about 10.48 years.

These outcomes can be explained in two parts. First, Sigfox frames carry maximum payload of 12 byte and 14 byte overhead. To minimise energy consumption, Sigfox end points do not exchange synchronisation messages with the base station before transmitting the their data. While this is advantageous on one hand as it reduces overheads, it increases the possibility of frame loss on the other. The counter-measure is that each Sigfox message is transmitted three times. This has a multiplicative effect on Sigfox devices and further accelerates the battery depletion. Secondly, the relatively higher data rate of LoRaWAN means data frames will spend less time on the air than Sigfox, thereby saving even more energy. In particular, the 600 bps of Sigfox-US compared to 100 bps of the EU specification implies an effective data rate 33.3 bps for the latter. Furthermore, the absence repeated transmission of each frame and the signal pre-processing using SF for data rate adaptation all contribute to the overall energy conservation seen in LoRaWAN. Thus, the smart city solution developers must align energy performance with application requirements and make the necessary trade-offs, for example in the choice of data resolution.

## V. Conclusion

In smart cities, battery-operated devices and long-range communication are two key enablers. IoT offers a system-level approach to integrate heterogeneous devices with various capabilities into a unified network to drive monitoring and data-driven decision making. In this paper, we investigated the effects of smart city applications on energy consumption in the smart city objects. The results showed that Sigfox is ideal for smart city applications with very low payload size and few (<5) messages per day. The battery life is affected by payload and transmission interval, however, the SF in LoRa offers additional degree of flexibility to




(a) Energy budget vs DC for various SF

(b) Energy budget of various paylod sizes and DC using SF9

Figure 5: Annual energy budget of LoRaWAN using different payload sizes, SF 9, sleep current $4\mu A$, low DR flag enabled for SF12, 125KHz Tx current 32mA, Rx current , Gateway antenna +6dBi antenna in vertical polarisation

trade-off energy consumption, data rate and range. These results provide additional insights to be considered when designining IoT solutions for smart cities.

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## REFERENCES

[1] D. of Economic and S. Affairs, "World population projected to reach 9.7 billion by 2050," 2015, accessed on 05 Jul. 2018. [Online]. Available: Available:http://www.un.org/en/development/desa/news/population/2015-report.html

[2] A. N. Alvi, S. H. Bouk, S. H. Ahmed, M. A. Yaqub, M. Sarkar, and H. Song, "Best-mac: Bitmap-assisted efficient and scalable tdma-based wsn mac protocol for smart cities." *IEEE Access*, vol. 4, no. 1, pp. 312–322, 2016.

[3] A. Ikpehai, B. Adebisi, and R. Kharel, "Smart street lighting over narrowband PLC in a smart city: The Triangulum case study," in *Proc. IEEE Int. Workshop Comp. Aided Modelling and Design of Commun. Links and Networks*, 2016, pp. 242–247.

[4] Y. A. Shaâban, A. Ikpehai, B. Adebisi, and K. M. Rabie, "Bi-directional coordination of plug-in electric vehicles with economic model predictive control," *Energies*, vol. 10, no. 10, 2017.

[5] Sigfox, "Sigfox technical overview," 2017, accessed on 7 Mar. 2018. [Online]. Available: https://www.element14.com/community/docs/DOC-87914/l/sigfox-technical-overview

[6] F. Oudot, "Power consumption vs payload size," 2017. [Online]. Available: https://ask.sigfox.com/questions/1132/power-consumption-vs-payload-size.html7Mar.2018)

[7] E. Z. Tragos, V. Angelakis, A. Fragkiadakis, D. Gundlegard, C.-S. Nechifor, G. Oikonomou, H. C. Pohls, and A. Gavras, "Enabling reliable and secure IoT-based smart city applications," in *Proc. IEEE Int. Conf. Pervasive Comput. and Commun. Workshops (PERCOM Workshops)*. IEEE, 2014, pp. 111–116.

[8] S. Latre, P. Leroux, T. Coenen, B. Braem, P. Ballon, and P. Demeester, "City of things: An integrated and multi-technology testbed for IoT smart city experiments," in *Proc. IEEE Int. Smart Cities Conf. (ISC2), 2016*. IEEE, 2016, pp. 1–8.

[9] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, and S. Guizani, "Internet-of-things-based smart cities: Recent advances and challenges," *IEEE Communications Magazine*, vol. 55, no. 9, pp. 16–24, 2017.

[10] L. Sanchez, L. Muñoz, J. A. Galache, P. Sotres, J. R. Santana, V. Gutierrez, R. Ramdhany, A. Gluhak, S. Krco, E. Theodoridis *et al.*, "Smartsantander: IoT experimentation over a smart city testbed," *Computer Networks*, vol. 61, pp. 217–238, 2014.

[11] T. Bakıcı, E. Almirall, and J. Wareham, "A smart city initiative: the case of barcelona," *Journal of the Knowledge Economy*, vol. 4, no. 2, pp. 135–148, 2013.

[12] H. Hielkema and P. Hongisto, "Developing the helsinki smart city: The role of competitions for open data applications," *Journal of the Knowledge Economy*, vol. 4, no. 2, pp. 190–204, 2013.

[13] R. R. Harmon, E. G. Castro-Leon, and S. Bhide, "Smart cities and the Internet of things," in *Management of Engineering and Technology (PICMET), 2015 Portland International Conference on*. IEEE, 2015, pp. 485–494.

[14] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 60–67, 2016.

[15] O. Georgiou and U. Raza, "Low power wide area network analysis: Can LoRa scale?" *IEEE Wireless Commun. Lett.*, vol. 6, no. 2, pp. 162–165, 2017.

[16] Y. Mo, C. Goursaud, and J.-M. Gorce, "Theoretical analysis of UNB-based IoT networks with path loss and random spectrum access," in *Proc. IEEE Int. Symp. Personal, Indoor, and Mobile Radio Commun.*, 2016, pp. 1–6.

[17] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, "Understanding the limits of LoRaWAN," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 34–40, 2017.

[18] J. Petäjäjärvi, K. Mikhaylov, M. Hämäläinen, and J. Iinatti, "Evaluation of lora lpwan technology for remote health and wellbeing monitoring," in *Proc. IEEE Intl Symp. Medical Inform. and Commun. Tech*, 2016, pp. 1–5.

[19] F. Yu, Z. Zhu, and Z. Fan, "Study on the feasibility of LoRaWAN for smart city applications," in *Proc. IEEE Intl. Conf. Wireless and Mobile Comp, Network. and Commun.*, 2017, pp. 334–340.

[20] T. M. WG, "A technical overview of LoRa and LoRaWAN," 2015. [Online]. Available: https://docs.wixstatic.com/ugd/eccc1a_ed71ea1cd969417493c74e4a13c55685.pdf(accessedon29Jan.2018)

[21] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A study of lora: Long range & low power networks for the Internet of things," *Sensors*, vol. 16, no. 9, p. 1466, 2016.

[22] D. Ismail, M. Rahman, and A. Saifullah, "Low-power wide-area networks: opportunities, challenges, and directions," in *Proc. Intl. Conf. Distributed Computing and Networking*. ACM, 2018, p. 8.

[23] B. Martinez, M. Monton, I. Vilajosana, and J. D. Prades, "The power of models: Modeling power consumption for IoT devices," *IEEE Sensors Journal*, vol. 15, no. 10, pp. 5777–5789, 2015.

[24] Semtech, "Semtech SX1272," 2017, accessed on 14 Apr. 2018. [Online]. Available: https://www.semtech.com/uploads/documents/sx1272.pdf