An Analysis of the Energy Consumption of LPWA-based IoT Devices

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***Abstract*—The unique challenges posed by the breadth of Internet of Things applications have resulted in the development of a number of different Low Power Wide Area wireless solutions. These technologies enable scalable long range networks on cheap low power devices, facilitating the development of a ubiquitous Internet of Things. The energy efficiency of these wireless technologies have a significant impact on battery lifetime. In this paper we propose an approach to energy efficiency calculations suited to this new paradigm by focusing on daily throughput. We present a set of deployment cases, develop energy models to represent each of the technologies studied, and use these models to provide a thorough comparison in terms of predicted device lifetime for a range of daily throughputs. This quantitative analysis of network device efficiency vs. daily throughput enables identification of the changeover point between optimal solutions. Our contributions are the integration of different energy models that have not been previously compared into a common framework, and the identification of the energy-efficiency crossover points between these models. This enables the selection of the most efficient wireless solution for specific Internet of Things applications, which is a key factor in optimising device lifetime.**

I. Introduction

Wireless communications have become ubiquitous in everyday life. In the near future, a much wider range of devices is expected [1]. In particular, it is expected that we will see the development of data generating devices: collecting data, reacting to the environment, and automating tasks. This is the essence of the Internet of Things (IoT). IoT devices will be used in the smart home, smart city, in industrial applications, agricultural applications, and monitoring and sensing applications. Cisco predicts there will be 12.2 billion connected devices by 2020 [2], and the EU predicts 6 billion IoT connections within the EU by 2020 [3].

The increasing diversity of IoT use cases has motivated the development of a number of new wireless protocols designed specifically for long distance, low power devices, which have been designated Low Power-Wide Area (LPWA).

Previous LPWA comparative surveys have targeted a potential ten year lifetime for devices [4], [5]. The goal of this paper is to show the reality of the energy consumption rates of different wireless technologies. Throughput is not the sole factor in determining the device lifetime of a node, but it is a factor. We directly compare estimated device lifetimes of European deployments of LoRaWAN, Sigfox, NB-IoT, and EC-GSM-IoT nodes for a set of daily throughputs.

In this paper we present related work, energy models, the device lifetime results, and identify the crossover points between optimal solutions. We use energy equations for each device to define their energy needed to transmit the data for three different use cases at defined data rates. We find that there is no overall best solution - the most suitable technology depends on availability, range, noise, and required throughput. Our findings indicate that there is a strong differentiation between the technologies that operate in the unlicensed bands and the Cellular-IoT options. We provide a quantitative methodology for the mapping of requirements of an IoT application to a particular wireless technology. LoRaWAN and Sigfox can operate for much longer than the device lifetime target for cases requiring less than 1kB per day, whereas NB-IoT and EC-GSM-IoT are more suitable for devices which require more regular reporting to the base station. Once the required daily throughput exceeds approximately 10kB, LPWA technologies are not realistically suitable.

II. Related Work

The paradigm of LPWA has only emerged in recent years, and so while there exist studies on the performance of individual technologies, there is limited comparative work. In [6], a number of unlicensed LPWA technologies are introduced and a coverage analysis of LoRa is performed. In [7], several competing formats of IoT wireless technologies are reviewed, including long range Wi-Fi, unlicensed LPWA, and cellular M2M. In [8] the focus is a comparison of unlicensed and licensed technologies from the perspective of bandwidth usage. In [5], the researchers directly compare unlicensed LPWA technologies and outline future challenges in the area. In [9], the PHY and MAC layers of unlicensed LPWA technologies are compared. In [10], technologies are compared in terms of coverage and capacity, and in [11] in terms of localization. Open research challenges have been identified in [12].

Most similar to this work is the research in [13] and [14], which analyze wireless technologies in terms of device lifetime. [13] focuses primarily on short-range technologies: beacon-enabled 802.15.4, TSCH 802.15.4e, BLE, 802.11 PSM, and 802.11ah. LoRa and Sigfox are included but because

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of the set of traffic intensities chosen the LPWA technologies only feature in a subset of the results. In [14], a comparison of the device lifetime of 802.11b/g to 802.15.4 is performed. The new results presented in this paper focus solely on LPWA technologies, targets throughputs that are realistic for LPWA use cases, and includes C-IoT options.

III. Overview of technologies

In this section, we provide a brief overview of the examined LPWA technologies. We focus on LoRaWAN as it is an open standard, Sigfox because it is the proprietary technology with the greatest current coverage of Europe, and NB-IoT and EC-GSM-IoT as they operate in licensed spectrum. We do not consider LTE-M, which as of yet has not been deployed anywhere in Europe. We leave analysis of recent proposals from research such as SNOW [15] as future work. A number of other, proprietary technologies are also not included.

A. LoRaWAN

LoRa is a physical layer technology developed by Semtech which is a form of Chirp Spread Spectrum with integrated Forward Error Correction. The most well supported upper layer protocol for LoRa is LoRaWAN. LoRaWAN range depends on the data rate, coding scheme, and transmission power. The possible data rates for the $EU863-870$ band are shown in Table I.

TABLE I
LoRaWAN Data Rates for EU863-870

DR	SF	Bandwidth	Bit rate	Max payload
0	12	125kHz	250	51
1	11	125kHz	440	51
2	10	125kHz	980	51
3	9	125kHz	1760	115
4	8	125kHz	3125	222
5	7	125kHz	5470	222
6	7	250kHz	11000	222
7	FSK	—	50000	222

As LoRa communicates on the license-free sub-1GHz ISM bands, it must adhere to duty cycle regulations, defined for Europe in [16]. LoRaWAN defines 3 types of devices: Class A (device-initiated communication), Class B (Class A, with scheduled receive windows), and Class C (Class A, but always listening). Communication with the gateway is through an ALOHA-based protocol. As a higher spreading factor corresponds to an increase in number of chips used per symbol, the use of higher spreading factors leads to a higher energy usage and transmission time per packet, meaning that the maximum daily throughput and energy consumption of a device are directly dependent on its distance from the nearest gateway.

B. Sigfox

Sigfox's technology is a proprietary, ultra-narrowband approach. Sigfox functions on an operator model - users purchase end devices and subscriptions to regional Sigfox-supported networks operated by network providers, and access data through a web portal or callback functions. The available engagement models are outlined in Table II. The platinum level is the most amount of messages that can be sent to still hold to the regulations for the $EU863-870$ band.

The channel access method of Sigfox is R-FDMA with no channel pre-transmission sensing; the end device randomly transmits on three of 360 available 100Hz channels. The base station scans the spectrum listening at every channel and uses signal processing algorithms to retrieve the message.

TABLE II
Sigfox Throughput

Scheme	Number of packets	Max. bytes per day
Platinum	101-140 + 4 downlink	1680
Gold	51-100 + 2 downlink	1200
Silver	3-50 + 1 downlink	600
One	1-2 + no downlink	24

Downlink messages are limited, and may only immediately follow uplink messages. Uplink uses a BPSK scheme operating at a fixed 100bps. For downlink, a GFSK scheme operating at 500bps on a 600Hz spectrum segment is used. A maximum of 12 byte payloads are supported for uplink, with 8 bytes for downlink. The protocol overhead is 14 bytes, and the time to send a 12 byte packet is 6 seconds. The time to send a packet with a one byte payload is 1.8 seconds.

C. NB-IoT

Narrowband Internet of Things (NB-IoT) is one of three solutions, along with EC-GSM-IoT and LTE-M, forming 3GPP's Cellular-IoT (C-IoT), in anticipation of the development of the IoT [17]. NB-IoT has good co-existence performance but not fully backward compatibility with existing 3GPP technologies. Essentially, NB-IoT modifies LTE to achieve enhanced coverage and reduced power consumption in exchange for relaxed latency, a lower data rate, and lower spectrum efficiency.

NB-IoT supports three different deployment scenarios: within an LTE wideband system (comprising 1 or more of the LTE Physical Resource Blocks), co-located with an LTE cell (placed in the guard band of an LTE carrier), and in a standalone 200kHz of spectrum (e.g. as replacement of GSM carriers). The downlink of NB-IoT is based on OFDMA, with 15kHz subcarrier spacing, and reuses the same OFDM numerology as LTE. Both single-tone and multi-tone are supported in the uplink. Multi-tone is based on SC-FDMA with 15kHz subcarrier spacing. With single-tone, sub-carrier spacing can be 15kHz or 3.75kHz. NB-IoT achieves a 20 dB improvement over GPRS, giving an MCL of 164dB. NB-IoT targets covering 52k devices per channel per cell.

D. EC-GSM-IoT

EC-GSM-IoT is designed to enhance GSM in terms of capacity, range, and energy efficiency [17]. Network upgrades can be provided with a software upgrade, and traffic from legacy GSM devices and EC-GSM-IoT devices can be multiplexed on the same channels. EC-GSM-IoT uses 200kHz of bandwidth per channel, for a total system bandwidth of 2.4MHz.

On the downlink, the primary modification is that a new packet control channel format limits the amount of control signaling required. On the uplink, this is also used, along with an overlaid CDMA technique (on EC-PDTCH/U, EC-PACCH/U, and on the EC-RACH) to increase capacity, enabling multiple devices to transmit on the same physical channel simultaneously. Beyond this, the design follows GSM principles.

Extending coverage is achieved through blind repetitions, defined through coverage classes which throughput rates varying from 350bps to 70kbps. 50,000 devices can be supported per cell. All GSM power classes are supported, as well as an additional power class of 23 dBm. Power Saving Mode, eDRX and a relaxed idle mode behaviour are supported on EC-GSM-IoT devices.

IV. Approach / Methodology

Our approach is to calculate the effect an increasing daily throughput has on energy consumption at defined data rates. The particular case we consider is a static, wireless, battery-powered device that regularly reports data gathered from its environment to a gateway a number of kilometers away. This fits the requirements of many LPWA use cases, such as smart water meters, agricultural data gathering, or environmental monitoring. In particular, for each technology the conditions we set are that the device has minimal downlink traffic, adheres to European regulations, and that transmissions are periodic. Immediate transition between states is assumed, and battery discharge unrelated to wireless transmission is neglected. To allow direct comparison, each device is modelling as having a 5Wh battery operating at 3.3V, and each device has the same sensor and CPU load, which is not included in the model as this is a common factor. For each technology, we model a packet error rate of 10%.

A. Cases Considered

For each technology, we calculate the node lifetime against increasing daily data throughputs for the *(a)* best case, *(b)* worst case, and *(c)* a defined comparative case.

The best case is the configuration of each technology which results in the longest possible battery life while still delivering the necessary throughput. Similarly, the worst case is the configuration which results in the shortest possible battery lifetime. Because of the fundamental differences in each of the technologies, the coverage achieved in the best and worst cases will differ for each technology; the estimated Maximum Coupling Loss (MCL) [17] for each is shown in each technology's case table. MCL can be essentially regarded as a proxy for distance or noise levels, and is the limit of the coupling loss at which the service can still be delivered. The comparative case is defined as the necessary configuration of each technology to obtain the closest MCL to 154dB.

V. Energy Models

LoRaWAN and Sigfox use simple ALOHA-based access schemes, enabling the use of a simplified energy model based on Equation 1.

$$E_{day} = E_{report} * Reports_{day} + E_{sleep} \tag{1}$$

Daily energy usage for NB-IoT and EC-GSM-IoT has been calculated based on the battery lifetime estimates performed in [17], and described below.

A. LoRaWAN

Equation 2 defines the energy consumed per report for LoRaWAN. The current usage in each state and supply voltage are taken from the datasheet of the SX1272 [18], a standard LoRa chip, and described in Table III.

$$E_{report} = t_{tx} * I_{tx} * V + t_{rx} * I_{rx} * V \tag{2}$$

TABLE III
SX1272 Current Consumption

Mode	Current
Sleep	1nA
Idle	15nA
Standby	0.0014A
Receive	0.0105A
Transmit (+13dBm)	0.028A
Transmit (+7dBm)	0.018A

Uplink airtime: For the uplink, airtime calculations were generated based on the formulas given in the Semtech LoRa modem designer's guide [19]:

$$t_{tx} = t_{pre} + t_{payload} \tag{3}$$
$$t_{pre} = (N_{pre} + 4.25) * (2^{SF})/BW \tag{4}$$
$$t_{payload} = p_{sym} * (2^{SF})/BW \tag{5}$$
$$p_{sym} = 8 + max(ceil(\frac{8PL - 4SF + 44 - 20H}{4 * (SF - 2DE)}) * (CR + 4), 0) \tag{6}$$

where N_{pre} is the number of symbols in the preamble, SF is the spreading factor, BW is the bandwidth, PL is the size of the payload in bytes, H indicates the existence of a header, DE indicates the use of low data rate optimization, and CR is the coding rate.

Downlink airtime: For Class A devices after each transmission the device has two short receive windows: $RX1$ and $RX2$. $RX1$ uses a channel and data rate based on the previous uplink, and the $RX2$ configuration is predefined, using $DR0$ by default. In our calculations we include minimal possible downlink, the most scalable option. To factor in the lack of acknowledgements, in our calculations we assume the LoRaWAN device sends 10% more packets than what would be required to achieve the throughput without any packet loss. We also set downlink parameters to the LoRaWAN recommendations for the $EU863 - 870$ band. For minimal possible downlink the device will have to stay in receive mode long enough to receive the potential preambles in $RX1$ (with a data rate based on the uplink data rate) and $RX2$ (with $DR0$), plus the in-between airtime when the device is in standby mode.

In our calculations for LoRaWAN we consider the case that the Adaptive Data Rate mechanism is not in use, that the device is Class A, and that channels are available for use in one subband with a duty cycle limit of 1%, corresponding to a total allowable daily transmission time of 864 seconds. The largest payload size available to the chosen data rate is used. For daily throughputs that are lower than the size of the max payload of the data rate, one single packet with a payload the size of the daily throughput is sent. We also dis-count the use of FSK mode. The defined cases for LoRaWAN are described in Table IV. Note that a Tx power of +20dBm is supported but not mandatory for LoRaWAN devices; devices must support a Tx power of +14dBm to be LoRaWAN compliant.

TABLE IV
LoRaWAN DEFINED CASES

Case	DR	Code Rate	Tx power	MCL
Best	6	4/5	+7dBm	127dB
Worst	0	4/8	+20dBm	157dB
Comp.	0	4/5	+20dBm	157dB

B. Sigfox

Sigfox's simple MAC layer enables the definition of an energy model in a similar method to LoRaWAN, with the energy per day being calculated using Equation 1 defined above, and energy per report being calculated using Equation 3. The current usage in each state and supply voltage are taken from the datasheet of the AX-Sigfox [20], and are detailed in Table V. The current consumption to transmit a packet takes into account the redundant simultaneous transmissions Sigfox performs for each sent packet. The defined cases are outlined in Table VI.

$$E_{report} = Q_{packet} * V \tag{7}$$

TABLE V
AX-SIGFOX CURRENT CONSUMPTION

Mode	Typical
Sleep	$1.3\mu A$
Standby	0.5mA
Current to send 1 bit @ 0dBm	0.08C
Current to send 12 bytes @ 0dBm	0.27C
Current to send 1 bit @ 12dBm	0.20C
Current to send 12 bytes @ 12dBm	0.39C

TABLE VI
SIGFOX DEFINED CASES

Case	Power Level	MCL
Best	0dBm	156dB
Worst	12dBm	168db
Comp.	0dBm	156dB

C. NB-IoT

The energy model for NB-IoT is based on the battery lifetime calculations defined in [21] and [17]. We recalculated the cases defined in the documents based on the protocol definition and arrived at battery lifetimes comparable to those found by the authors (within 5%). We then modified the calculations to model increasing daily throughputs for the worst, best, and a defined comparative case. The formulas which form the basis of our calculations are shown in equations 8 through 12 . The values for each t variable are dependent on the packet size and coverage class, and can be found in [17]. The W values are power consumption estimates for a typical device in different modes, and are outlined in Table VII. Retransmissions have been factored into the calculations to model a Block Error Ratio of 10%. In addition to the constraints outlined above we assume that the NB-IoT network is deployed standalone. The defined cases are given in Table VIII.

$$E_{report} = E_{tx} + E_{rx} + E_{idle} \tag{8}$$

where:

$$E_{tx} = t_{tx} * W_{tx} \tag{9}$$

$$t_{tx} = t_{RACH} + t_{uplink} + t_{CoAPACK} \tag{10}$$

$$E_{rx} = t_{rxsync} * W_{rxsync} + t_{rxnorm} * W_{rxnorm} \tag{11}$$

$$t_{rxnormal} = t_{PSI} + t_{uplinkACK} + t_{CoAPACK} \tag{12}$$

TABLE VII
NB-IoT POWER CONSUMPTION IN DIFFERENT MODES

Mode	Power (mW)
Sleep	3
Standby	0.015
Transmit (+23 dBm)	
- Integrated PA	500
- External PA	460
Receive	
- Synchronization (PSCH)	80
- Normal (PBCH, PDCCH, PDSCH)	70

TABLE VIII
NB-IoT DEFINED CASES

Case	Coverage Class (MCL)	PA
Best	144dB	External
Worst	164dB	Integrated
Comparison	154dB	Integrated

D. EC-GSM-IoT

The energy model used in our calculations is based on the battery lifetime calculations defined in [17]. The daily usage is calculated using Equation 1, and the energy consumed per report is defined using Equation 13 shown below. There is not sufficient space in this paper to show the full calculations; interested readers are recommended to refer to [17]. We recalculated the cases defined in the document based on the protocol definition and arrived at comparable battery lifetimes. We then modified the calculations to model increasing daily throughputs for the worst, best, and comparative cases. Defined cases are outlined in Table X.

$$E_{report} = E_{sync} + E_{access} + E_{ass} + E_{datatx} + E_{ready} + E_{ls} \tag{13}$$

TABLE IX
EC-GSM-IoT Average Current Consumption

Mode	Current (A)
Deep Sleep	0.0000045
Light Sleep	0.001
PLL	0.03
Transmit	
- 33dBm	1.227431
- 23dBm	0.152543
Receive	0.03

TABLE X
EC-GSM-IoT defined cases

Case	Tx Power	Coverage Class	MCL
Best	23dBm	+0dB	144dB
Worst	33dBm	+20dB	164dB
Comparison	33dBm	+10dB	154dB

VI. Results

The results were generated from Equations 1-13 and the use cases *(a)*, *(b)*, and *(c)*. As there is no ideal set baseline, for comparison, we show an estimated lifetime for an 802.15.4 device for the same daily throughputs, using the same power source. The results for the 802.15.4 device have been derived from the mean battery lifetime calculations performed in [22]. Note 802.15.4 packets will only travel in the tens of meters whereas LPWA technologies transmit packets in the range of kilometers. In our calculations the very low throughput requirements cases give estimated lifetimes in the decades; this represents an opportunity to reduce battery size.

Figure 1 shows the device lifetime results for the *(a)* best case (devices close to gateway), showing LoRaWAN outperforms the other options up to its regulatory limits, when NB-IoT becomes the most efficient technology. Figure 2 shows the *(b)* worst case (more distant devices), when initially Sigfox, then finally NB-IoT perform best. Figure 3 shows the *(c)* comparative case (equivalent MCL), when initially Sigfox, and finally NB-IoT and EC-GSM-IoT are most efficient.

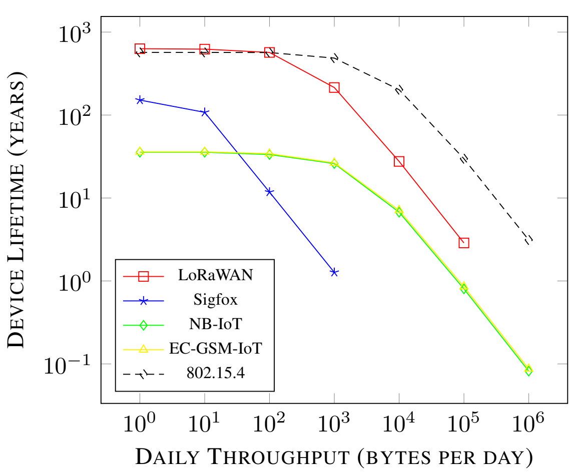

Fig. 1. Device Lifetime for the *(a)* Best Case

TABLE XI
Seconds transmitting per day - LoRaWAN

Bytes per day	Best Case	Worst Case	Comp. Case
1	0.0463	2.8999	2.3101
10	0.0617	3.9485	2.9655
100	0.1897	12.2143	8.3804
1,000	1.0145	89.5713	61.4564
10,000	9.4068	**883.4990**	606.1834
100,000	91.6707	**8786.1330**	**6028.3126**
1,000,000	**914.1243**	**87816.5442**	**60252.3976**

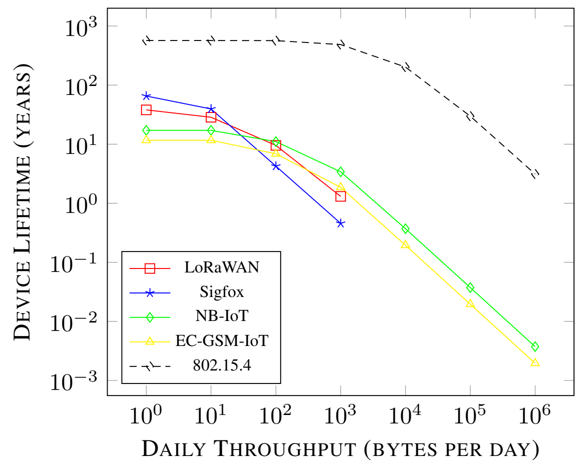

Fig. 2. Device Lifetime for the *(b)* Worst Case

VII. Discussion

Sigfox is limited by system regulations, which prevent the device from transmitting more than 1680 bytes per day. Even in the best case, the Sigfox device will only last just over one year sending the maximum of 140 packets. For an extended lifetime, the device should only transmit at most 100 bytes per day. Sigfox outperforms LoRaWAN in the long range case, but not in the short range - therefore, in cases where extremely long range is a requirement Sigfox is more suitable, and otherwise LoRaWAN is more appropriate.

LoRaWAN can theoretically reach a daily throughput of several hundred kBs per day, but this requires specific network configuration parameters. In every case, throughput becomes limited by ETSI regulations. Table XI highlights the time-on-air required for each case, with regulation-breaking cases bolded.

NB-IoT and EC-GSM-IoT can provide up to 1MB per day, but the lifetime for these devices would be only about 1 month. To provide a throughput of 100kB, the estimated lifetime is still less than 1 year even in the best conditions. For high throughput applications, these technologies are not feasible at this battery capacity. For a daily throughput of 10kB, the device lifetime of NB-IoT can last years and consistently outperforms LoRaWAN in all but the best case.

From this, we can conclude that, if network coverage is available, LoRaWAN and Sigfox outperform the C-IoT technologies in terms of device lifetime for small required daily throughputs, and the C-IoT technologies outperform the

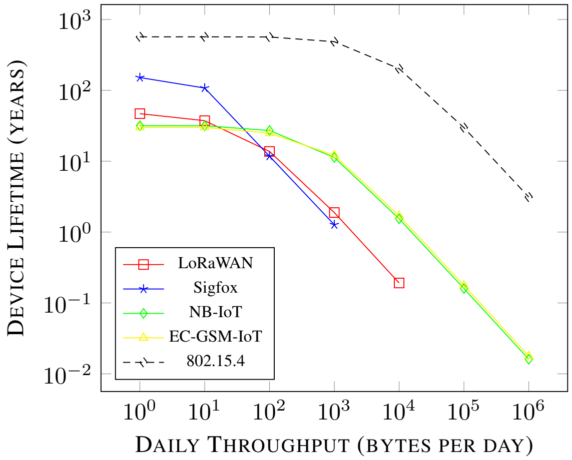

Fig. 3. Device Lifetime for the *(c)* Comparative Case

unlicensed options for higher required throughputs. For a daily throughput over 10kB use of the C-IoT technologies may be feasible but a larger battery would be required.

VIII. Conclusion

In this paper, we directly compare a number of LPWA technologies in terms of energy efficiency and their impact on battery life. Our results identify the complexity in selecting the optimum solution for maximum device lifetime. Our contribution is a methodology, which enables the quantification of the changeover points between optimal solutions. We provide 3 different cases, but it should be noted that devices will often exist in intermediate cases, and external factors may cause a device to essentially move between these cases. NB-IoT and EC-GSM-IoT can realistically send between 1000 and 10,000 bytes per day while maintaining an extended device lifetime. LoRaWAN and Sigfox are more suitable when the amount of data that must be sent daily is beneath 1000 bytes. In addition, LPWA technologies are not suitable when the required daily throughput exceeds 10,000 bytes.

In the future, we intend to expand our study to a wider range of technologies, including 802.11ax, SNOW, and the long range 802.11ah. In certain situations, such as in mobile use cases or deployments in dense urban areas, the most suitable technology may change over time. We plan to apply these results to develop adaptive multi-stack systems that react to their environment and context, choosing the most suitable wireless technology for optimal node lifetime. In addition, it would be valuable to extend our results to factor in downlink throughput, for those use cases that require some bi-directional communication.

From the results provided we can conclude that there is no overall best solution - the most suitable technology depends on availability, range, noise, and required throughput. The results we provide enable the identification of the optimal technology for any particular use case.

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References

[1] G. Margelis, R. Piechocki, D. Kaleshi, and P. Thomas. Low throughput networks for the iot: Lessons learned from industrial implementations. In *Proceedings of the 2015 IEEE 2Nd World Forum on Internet of Things (WF-IoT)*, WF-IOT '15, pages 181–186, 2015.
[2] Cisco. Vni mobile forecast (2015–2020). *White Paper*, 5 2015.
[3] European Commission. Advancing the internet of things in europe. *White Paper*, 4 2016.
[4] K. E. Nolan, W. Guibene, and M. Y. Kelly. An evaluation of low power wide area network technologies for the internet of things. In *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*, pages 439–444, 9 2016.
[5] U. Raza, P. Kulkarni, and M. Sooriyabandara. Low power wide area networks: An overview. *IEEE Communications Surveys Tutorials*, PP(99):1–1, 2017.
[6] 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 Communications*, 23(5):60–67, 10 2016.
[7] S. Andreev, O. Galinina, A. Pyattaev, M. Gerasimenko, T. Tirronen, J. Torsner, J. Sachs, M. Dohler, and Y. Koucheryavy. Understanding the iot connectivity landscape: a contemporary m2m radio technology roadmap. *IEEE Communications Magazine*, 53(9):32–40, 9 2015.
[8] W. Yang, M. Wang, J. Zhang, J. Zou, M. Hua, T. Xia, and X. You. Narrowband wireless access for low-power massive internet of things: A bandwidth perspective. *IEEE Wireless Communications*, 24(3):138–145, 2017.
[9] C. Goursaud and J-M. Gorce. Dedicated networks for IoT : PHY / MAC state of the art and challenges. *EAI endorsed transactions on Internet of Things*, October 2015.
[10] Benny Vejlgaard, Mads Lauridsen, Huan Cong Nguyen, Istvan Kovacs, Preben Elgaard Mogensen, and Mads Sorensen. *Coverage and Capacity Analysis of Sigfox, LoRa, GPRS, and NB-IoT*. IEEE, United States, 6 2017.
[11] L. Chen, S. Thombre, K. Jarvinen, E. S. Lohan, A. Alen-Savikko, H. Leppakoski, M. Z. H. Bhuiyan, S. Bu-Pasha, G. N. Ferrara, S. Honkala, J. Lindqvist, L. Ruotsalainen, P. Korpisaari, and H. Kuusniemi. Robustness, security and privacy in location-based services for future iot: A survey. *IEEE Access*, 5:8956–8977, 2017.
[12] Eli De Poorter, Jeroen Hoebeke, Matthias Strobbe, Ingrid Moerman, Steven Latre, Maarten Weyn, Bart Lannoo, and Jeroen Famaey. Sub-ghz lpwan network coexistence, management and virtualization: An overview and open research challenges. *Wireless Personal Communications*, 95(1):187–213, 7 2017.
[13] E. Morin, M. Maman, R. Guizzetti, and A. Duda. Comparison of the device lifetime in wireless networks for the internet of things. *IEEE Access*, 5:7097–7114, 2017.
[14] A. Varghese, D. Tandur, and A. Ray. Suitability of wifi based communication devices in low power industrial applications. In *2017 IEEE International Conference on Industrial Technology (ICIT)*, pages 1307–1312, 3 2017.
[15] A Saifullah, M Rahman, D Ismail, C Lu, R Chandra, and J Liu. Enabling reliable, asynchronous, and bidirectional communication in sensor networks over white spaces. *SysSys*, 2017.
[16] ETSI. Electromagnetic compatibility and radio spectrum matters: Short range devices; part 1. 1 2012.
[17] 3GPP. Tr 45.820: Cellular system support for ultra-low complexity and low throughput internet of things (ciot). 2015.
[18] Semtech. Sx1272/73 - 860 mhz to 1020 mhz low power long range transceiver rev. 3.1, 3 2017.
[19] Semtech. Sx1272/3/6/7/8: Lora modem designer's guide, 7 2013.
[20] On-Semiconductor. Ax-sigfox datasheet, 3 2016.
[21] 3GPP. R1-157647: Summary of evaluation results. 2015.
[22] Eduardo Casilari, Jose Cano-Garcia, and Gonzalo Campos-Garrido. Modeling of current consumption in 802.15.4/zigbee sensor motes. *Sensors*, 10(1):5443–5468, 5 2010.