Review

Long-Range Wireless Radio Technologies: A Survey

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Abstract: Wireless networks are now a part of the everyday life of many people and are used for many applications. Recently, new technologies that enable low-power and long-range communications have emerged. These technologies, in opposition to more traditional communication technologies rather defined as "short range", allow kilometer-wide wireless communications. Long-range technologies are used to form Low-Power Wide-Area Networks (LPWAN). Many LPWAN technologies are available, and they offer different performances, business models etc., answering different applications' needs. This makes it hard to find the right tool for a specific use case. In this article, we present a survey about the long-range technologies available presently as well as the technical characteristics they offer. Then we propose a discussion about the energy consumption of each alternative and which one may be most adapted depending on the use case requirements and expectations, as well as guidelines to choose the best suited technology.

Keywords: long-range; wireless; IoT; LPWAN; mobile; cellular; LoRa; Sigfox; LTE-M; NB-IoT

1. Introduction

Wireless radio technologies, such as Wi-Fi, are used daily to enable inter-device communications. In the last few years, new kinds of wireless technologies have emerged. In opposition to standard wireless technologies referred to as "short-range", long-range radio technologies allow devices to communicate over kilometers-wide distances at a low energy cost, but at the expense of a low data rate. This allows the creation of what is known as Low-Power Wide-Area Networks (LPWAN), spanning tens of kilometers. This kind of technology has received and still benefits from a lot of academic and industrial attention. In this survey, we focus on long-range wireless technologies that provide kilometers-wide range only (in opposition to short-range technologies such as Wi-Fi or ZigBee).

While Sigfox and LoRa are pioneers of LPWAN technologies, presently, a lot of technologies are available. Those are generally based on similar principles but may heavily differ in terms of behavior. Some of those technologies are implementations of standards and offer small changes between the different implementations. Some are based on proprietary hardware or software, some are open. Some take advantage of the unlicensed Industrial, Scientific and Medical (ISM) radio bands, some use the GSM frequency bands. There are not only differences in terms of technical details, but also in commercial models. Some technologies offer the users to deploy their own base stations while other offer services like an operator.

Because of those differences, the actual performance provided by these technologies greatly differ on several metrics. Each one offers different range, data rate, energy consumption, delay etc., Even those may vary depending on actual deployments, since depending on frequencies, modulation etc., in the same environment setting, different signals will not behave similarly. The most important metrics that are usually put into light are the following: (i) range, which is the maximal distance of communication, (ii) data rate which is the speed of the communication and (iii) energy consumption which is directly dependent on the other metrics.

Many different technologies are available, and it may be rather hard to get information about the different characteristics and performances offered. Thus, in this paper, we present a comprehensive study of the different current LPWAN radio technologies and their characteristics. We propose a guide to choose the most appropriated LPWAN technology based on application requirements and expectations. We have gathered and classified information from the literature but also from commercial sources. After the raw information about the different technologies, we propose a discussion about the different strengths and weaknesses that are associated with each technology. This is done in terms of coverage, range, energy consumption, and other important factors. Then depending on the planned use case, we propose a subjective recommendation on which technology may be more adapted to it.

While the literature already contains several surveys about long-range wireless technologies [1–7], to the best of our knowledge, no work gives an overview of all the available possibilities including commercial and mobile technologies. We provide useful technical detail about those technologies. Moreover, we propose a discussion about the energy consumption of each long-range wireless technology and general guidelines on how to easily choose which one is the most suitable relative to the targeted use case.

Please note that the choice between long-range or short-range technologies is dictated by the applications requirements and environments. In some cases, both kinds of technology can fit. Nevertheless, this survey aims to provide a clear overview of long-range technologies only and a guide for choosing the most appropriated one. Thus, we will not discuss about choosing between long-range and short-range technologies.

The rest of this article is structured as follows. First, Section 2 introduces the long-range wireless technologies that are available for use as of today with technical information. Section 3 proposes a discussion about the previously introduced technologies, relative to the different aspects of performance such as the energy consumption of each alternative, as well as guidelines to choose the best suited technology. Finally, Section 4 summarizes and concludes this article.

2. Long-Range Wireless Technologies

In this section, we give an overview of the long-range wireless technologies that are available presently. Classifying those based on their proprietary or open aspects is not appropriate as some may be part of both worlds, as LoRa [8]. Instead, we propose to gather them based on which frequency band they use: (i) either the licensed mobile frequencies (a.k.a. cellular frequencies) (ii) or the unlicensed ISM bands.

On the one hand, using the licensed mobile frequencies ensures that the band is used by authorized devices in a sane manner. However, on the other hand, the use of these frequencies requires subscription costs and they may already be very busy because of the wide spread of cellular devices, especially in crowded urban areas.

On the contrary, using the unlicensed ISM bands [9] does not ensure a sane use of the frequencies, as anybody is allowed to emit and a lot of devices may interfere. Still, the duty cycle restrictions must be respected depending on the used frequency band, the power and the geographical location of the device. However, at the same time, using unlicensed bands also implies that we can freely expand the network with new base stations, create private networks and use those technologies to possibly communicate in a peer-to-peer fashion between devices. One can wish to deploy their own infrastructure for two main reasons : (i) either because the area to monitor is not covered by any other technology (ii) or to keep control over the infrastructure management.

Managing the energy consumption of LPWAN devices is a key factor, because those devices are usually expected to run autonomously for long periods of time, commonly several years. Replacing or recharging batteries is often unpractical, especially when numerous devices are deployed in different places, hostile or unreachable environments. Additionally, those devices may have to receive firmware updates, e.g., for optimization or security reasons. As with battery replacement, mandatory physical access to the devices for firmware updates is highly unpractical. Thus, supporting remote firmware

updates, known as Firmware over the Air (FotA) updates, may turn out to be a key factor for choosing a long-range technology.

Figure 1 summarizes this section by positioning each main technology with regards to its maximum data rate and theoretical urban range (based on data available in datasheets referenced further). Tables A1 and A2 summarize the technologies' technical information.
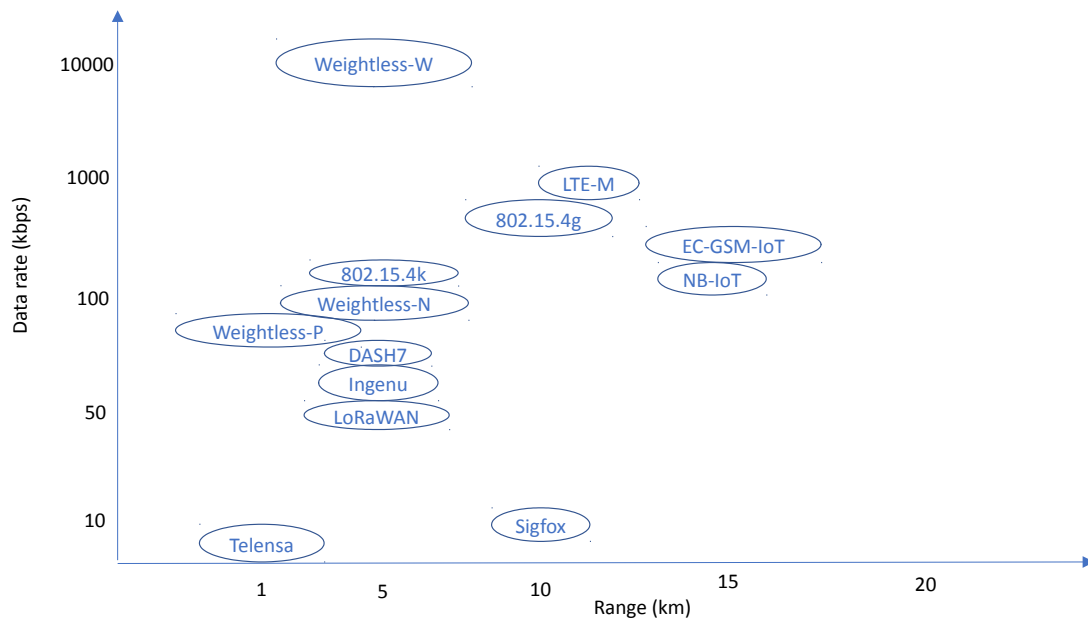

Figure 1. Technologies' maximum data rate over urban range.

2.1. Mobile Band-Based Technologies

Mobile technologies are widely deployed and used worldwide, as we can see in Figure 2. Although white zones remain, mobile networks may well be the widest wireless networks deployed to provide Internet access. The 3rd Generation Partnership Project (3GPP) consortium, which defines and proposes standards for mobile technologies, recently proposed an amendment to existing mobile standards. These amendments aim to make mobile communications usable for Internet of Things (IoT) applications, in respect to IoT special constraints, mainly in terms of computation power and energy restriction.
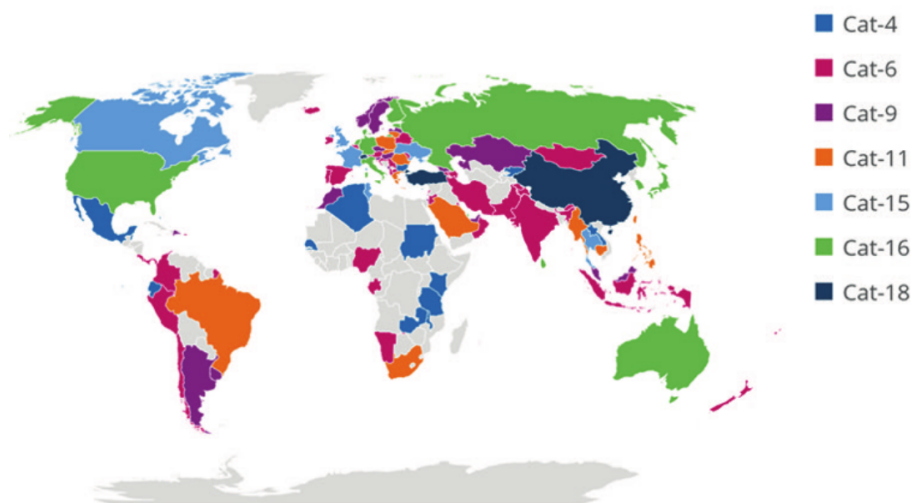

Figure 2. LTE-Advanced (LTE-A) coverage map [10].

There are two main mobile IoT technologies that are deployed and widely used right now: enhanced Machine-Type Communication (eMTC), and Narrow-Band IoT (NB-IoT). Both are derived from the LTE 3GPP standard. Two other technologies could be potential candidates: Extended Coverage GSM IoT (EC-GSM-IoT), and 5G. These technologies are going to be presented in more depth further in this section.

2.1.1. Enhanced Machine-Type Communication (eMTC, a.k.a. LTE-M)

Long Term Evolution (LTE), a.k.a. 4G, is a standard from the 3GPP. LTE Cat M1, which is known as either LTE-M or eMTC, is derived from the LTE standard and specified in 3GPP release 13 [11]. It is designed for Machine to Machine (M2M) communications (e.g., IoT). eMTC is a simplified version of LTE that aims to draw less battery power and to extend its range. In contrast to classic LTE, eMTC reduces the data rate to a tenth of LTE (up to 1 Mbps) and strips down the bandwidth from 20 MHz to 1.4 MHz. eMTC supports full duplex communications, as well as optional half duplex operations to reduce consumed power. FotA updates are possible using eMTC. It may be worth noting that Voice over LTE (VoLTE) is also usable on LTE-M communications. Two new features are enabled in eMTC, namely extended Discontinuous Reception (eDRX), and Power Saving Mode (PSM). The former allows longer paging cycles, while the latter allows nodes to be inactive for an indefinite period of time. Both aim at reducing the power consumption. eMTC also supports handover, which makes it usable when considering mobile IoT applications.

eMTC is already deployed in numerous countries worldwide, as we can see in Figure 3. It is rather easy for Mobile Network Operators (MNO) to deploy eMTC, as the infrastructure only needs a software upgrade, without any physical hardware modifications. As an example, Orange, one of the main MNO in France, recently launched its own eMTC network. Its current coverage is available in [12].
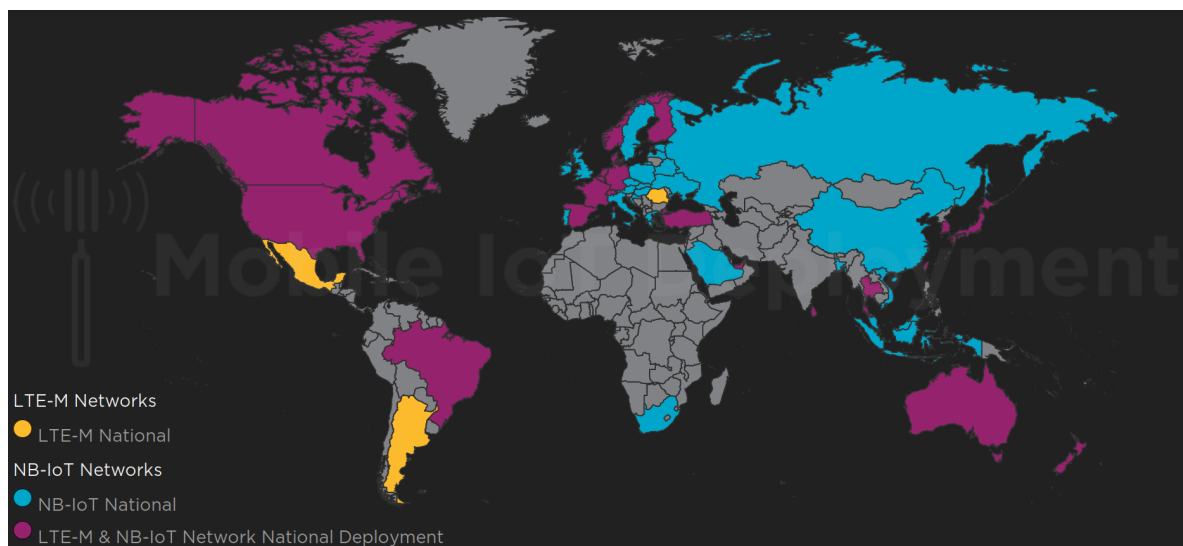
Figure 3. LTE-M and NB-IoT coverage map [13].

2.1.2. Narrow-Band IoT (NB-IoT)

Narrow-Band IoT (NB-IoT), a.k.a. LTE Cat NB1, is another derivation of the LTE standard which is also specified in 3GPP release 13. It is designed for IoT applications that are even more constrained than the ones using eMTC. It is based on narrow-band communications, and uses a bandwidth of 180 kHz. As a result, the data rate is greatly reduced (around 250 kbps down-link and 20 kbps up-link), which makes FotA updates hard to achieve using NB-IoT. On the bright side, NB-IoT consumes less energy power, and benefits from a greater range than eMTC. NB-IoT can be used with three different modes: in-band, guard-band LTE, and standalone. In-band mode uses the LTE band, guard-band uses

the unused part of the LTE band, and standalone uses a dedicated spectrum (e.g., GSM bands). NB-IoT does not support handover, so it is hardly worth consideration for mobile IoT applications.

NB-IoT is already available in some regions and is still being deployed in other countries, as visible in Figure 3. However, its deployment is not as easy as eMTC because NB-IoT requires a hardware upgrade of the existing LTE infrastructure.

2.1.3. Extended Coverage GSM IoT (EC-GSM-IoT)

Extended Coverage GSM IoT (EC-GSM-IoT) is also specified in 3GPP release 13. In contrast with eMTC and NB-IoT, EC-GSM-IoT is based on eGPRS technology (a.k.a. 2.75G) and not LTE (4G). EC-GSM-IoT could be considered to be the equivalent of LTE-M in the GSM spectrum, as it mainly brings range and power efficiency improvements. Bandwidth per channel is of 200 kHz, for a total bandwidth of 2.4 MHz. It offers a data rate of 70 or 240 kbps depending on the modulation used (GMSK or 8PSK).

While this technology could be extremely useful for already existing and deployed IoT applications that use the GSM network, it is getting much less attention than its two aforementioned counterparts. This is because some MNO are planning to decommission their GSM network soon [14]. On top of that, no operational EC-GSM-IoT network is available for use today.

2.1.4. 5G

5G is the latest innovation in mobile network technologies that is currently being developed. It is expected to be a "revolutionizing technology" for the mobile world as well as for IoT communications [15]. However, for now, few to no explanations exist on how to integrate the high-speed technology of 5G with the low power consumption that is needed for IoT applications. Indeed, 5G is meant to enable ultra-high-speed communications, using high frequency (e.g., 60 GHz) and wide bandwidth [16]. It aims to offer a very high data rate (1–10 Gbps). This does not seem applicable out-of-the-box when you consider energy constrained IoT objects. Moreover, this technology is not available right now for use outside of test labs. 5G should begin to be commercially deployed and available around 2020.

As for now, 5G aims at two things: massive Machine-Type Communications (mMTC), and critical Machine-Type Communications (cMTC) leveraging Ultra Reliable and Low Latency Communications (URLLC). The requirements for cMTC are too strict for IoT, while mMTC was developed for IoT. LTE-M and NB-IoT already fulfill mMTC 5G requirements, so there is no dedicated solution other than eMTC and NB-IoT that is planned to be specified for 5G IoT [17].

2.2. ISM Band-Based Technologies

In contrast to mobile IoT technologies, ISM-based LPWAN technologies are using unlicensed parts of the spectrum to carry communications. Unlicensed bands are usable by everyone without any specific authorization. In return, legal restrictions must be respected, e.g., a given duty cycle that must not be overrun.

2.2.1. Sigfox

Sigfox [18] is a proprietary end-to-end solution for IoT connectivity. Sigfox positions itself as an alternative network operator, and deploys base stations around the world, as we can see in Figure 4. This technology uses Binary Phase Shift Keying (BPSK) modulation over an Ultra-Narrow-Band (UNB) carrier of the sub-GHz ISM bands. UNB greatly reduces noise levels, which extends the communication range. The counterpart is a very slow data rate of 100 bps. To respect the duty cycle regulation imposed on the sub-GHz bands, Sigfox limits up-link communications to 140 transmissions of 12 bytes payload, and down-link to 4 transmissions of 8 bytes payload, per day and per device. The Sigfox network is available in several countries of the world, as we can see in Figure 4. Because it

is the same network, which is managed by a single operator, there is no roaming involved when using Sigfox in different countries.
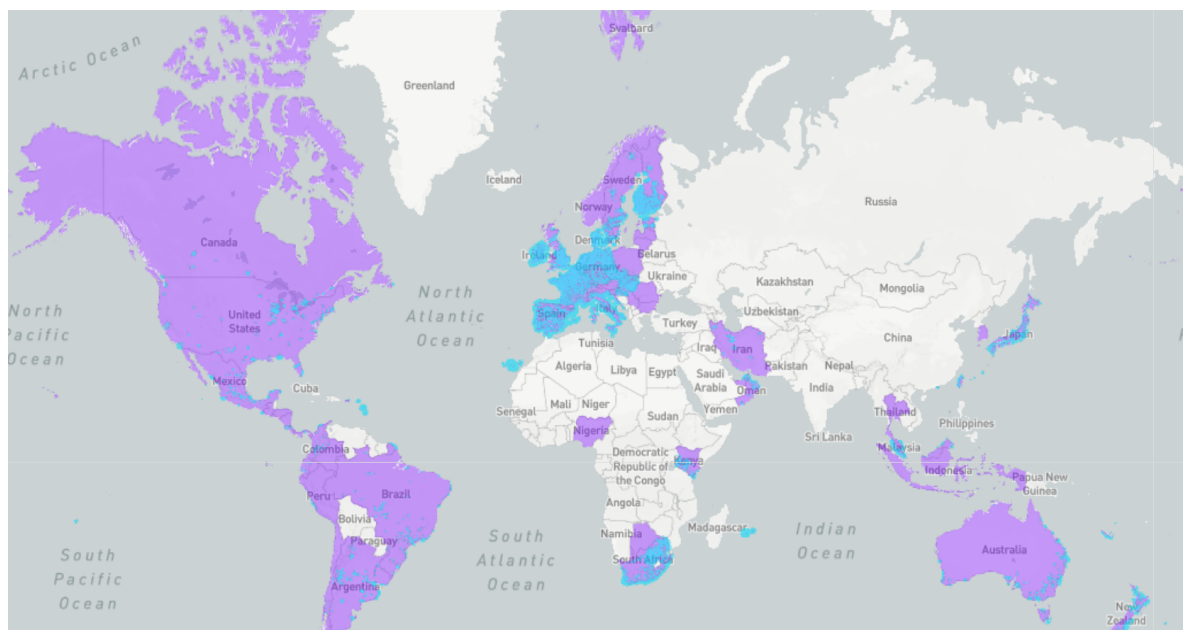

Figure 4. Sigfox coverage map [19]—blue is current coverage/purple is future coverage.

2.2.2. LoRa

Long Range (LoRa) is a proprietary technology from Semtech [8]. Based on Chirp Spread Spectrum (CSS) modulation, it can use several bands of the ISM sub-GHz spectrum depending on the geographical location. LoRa communications are reasonably resilient to detection and jamming, and are immune to Doppler deviation. LoRa offers several parameters that can be modified to adjust the trade-off between range and data rate (from 0.3 to 50 kbps), e.g., the spreading factor. While LoRa is the technology of the physical layer, LoRaWAN [20] which is supported by the LoRa Alliance, is an open protocol for the MAC and network layers. LoRaWAN describes 3 classes of devices. Roughly, class-A is for heavily energy constrained devices, class-B for moderately energy constrained devices and class-C for always-on devices. FotA updates over LoRa may be conceivable, but hard to achieve. They may need to use multicast class-C devices only, which uses a lot of power [21]. Several scientific studies (e.g., [22,23] show that LoRa performs well in terms of range when a line of sight is available for communications, but the range is greatly reduced when it is not available, like in an urban environment.

Several MNO are deploying LoRa (e.g., Orange in France [12]), as well as public community initiative such as The Things Network [24]. A map of the current LoRaWAN worldwide deployment is visible in Figure 5. An additional benefit of using LoRa is the possibility to deploy personal LoRa base stations to extend the network.
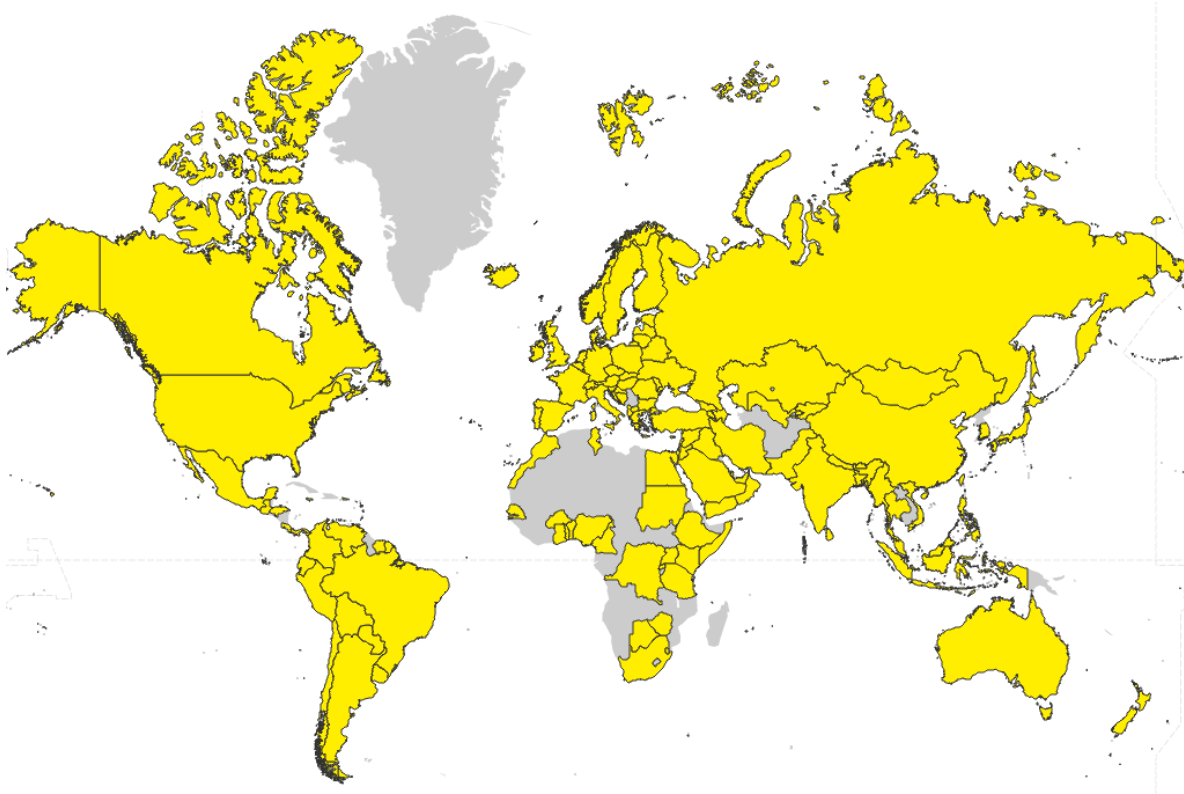
Figure 5. Countries with a LoRaWAN deployment [20].

2.2.3. Ingenu

Ingenu is another proprietary LPWAN technology. In contrast to other LPWAN, Ingenu proposes to use the 2.4 GHz ISM band, which is already used by other technologies (e.g., Wi-Fi), instead of the sub-GHz ISM bands. The advantage is that this band does not fall under heavy restrictions regarding duty cycle as the sub-GHz does. Ingenu is based on a proprietary physical technology known as Random Phase Multiple Access (RPMA), which is a variation of Code Division Multiple Access (CDMA). Ingenu is reported to have better performance than most of the other LPWAN technologies [25], especially in terms of range and data rate (78 kbps up-link and 19.5 kbps down-link). However, no scientific study is available to verify these claims.

2.2.4. Weightless

Weightless [26] is a set of standards developed by the Weightless Special Interest Group (Weightless-SIG). Three different standards exist: W, P, and N. Weightless-W uses TV white space frequencies, and offers a data rate between 1 kbps and 10 Mbps using a narrow-band signal, based on QAM and several other modulations. This is interesting because it takes advantage of a part of the unused ultra-high frequency spectrum. However, access to TV white space is not permitted worldwide as the regulation differs for different countries, which makes it impossible to build a small antenna that could access all the usable frequencies [27]. Weightless-N is based on UNB for upward only communications, using the ISM sub-GHz bands, and a DBPSK modulation. It is similar to Sigfox technology-wise, which means that it shares the same advantages and limitations, but has a higher data rate (30 to 100 kbps). Nwave [28] is the main company supporting Weightless-N technology. Weightless-P [29] is the latest Weightless standard. It offers bidirectional connectivity based on the ISM sub-GHz bands as well, using channels 12.5 kHz wide which results in a data rate between 0.2 kbps and 100 kbps. GMSK and QPSK modulations are used. It also officially supports acknowledgments and FotA updates [30]. Ubiik [31] is the main provider of Weightless-P technology today.

2.2.5. Telensa

Telensa [32] is a company providing end-to-end LPWAN connectivity. It has mainly deployed smart lighting networks in cities. It uses a proprietary UNB technology operating in the sub-GHz ISM bands [33], offering a low data rate of 62.5 bps up-link and 500 bps down-link. Telensa does not seem to propose its network for an external use other than their own applications for now, but they aim to standardize their technology.

2.2.6. DASH7

The DASH7 Alliance [34] is an industry consortium. They propose a full stack protocol known as DASH7 Alliance Protocol (D7AP) based on narrow-band modulation in the ISM sub-GHz bands. D7AP defines a complex network stack and has features such as inevitable periodic wake up of the nodes. This results in a much lower latency for the communications, but it also results in an increase in power consumption. It offers a data rate of 9.6 to 166.7 kbps.

2.2.7. IEEE Standards

The Institute of Electrical and Electronics Engineers (IEEE) defined three standards for IoT communications. These are based on 802.15.4 and 802.11 specifications. IEEE 802.15.4k [35] is a standard operating in the ISM bands (sub-GHz and 2.4 GHz). The 802.15.4 modulation schemes are switched to DSSS and FSK, and MAC layer to CSMA/CA without Priority Channel Access (PCA), CSMA, and ALOHA with PCA. This allows a data rate between 1.5 bps and 128 kbps. It is worth noting that Ingenu's technology is compliant with this standard. IEEE 802.15.4g [36] is a different specification based on the same standard as 802.15.4k. Here, we have three different modulation schemes usable at the physical layer: FSK, OFDMA and QPSK. Data rate is between 4.8 and 800 kbps. The sub-GHz bands are also used. One of the differences with traditional 802.15.4 is that frames can be up to 1500 bytes instead of only 127 bytes to avoid IP fragmentation. MAC layer is the same as in 802.15.4e. IEEE 802.11ah [37] a.k.a. Wi-Fi HaLow is based on OFDM and aims to increase the transmission range and decrease energy consumption of Wi-Fi, at the expense of a lower data rate (0.6 to 8 Mbps). It achieves better performance than e.g., ZigBee or Bluetooth but far from previous LPWAN technologies presented in this report.

2.2.8. Others

In this section, we focused on the main LPWAN technologies but there exist plenty of others. For instance, Qowisio [38] proposes a dual LPWAN technology based on its own UNB technology and LoRa as a service for the end users. No technical specifications of the technology are available. Previously mentioned, Nwave [28] propose a protocol based on UNB (like Sigfox) in the sub-GHz ISM bands. The company mainly offers Smart Parking devices. Little technical information is available but they are claimed to achieve 10 km range [39]. WAVIoT [40] proposes a full stack protocol known as Narrow-Band Fidelity (NB-Fi). Based on a DBPSK modulation scheme, it uses the sub-GHz ISM bands.

3. Discussion

3.1. On the Energy Consumption

As the energy consumption of each technology entirely depends on the hardware and the transmitting power, it is not very relevant to present an energy consumption rate alongside each technology. Rather, here we propose a ranking of which technology should consume more or less energy compared to the others, based on the modulation and the frequency used, as well as the data rate offered by each protocol. We also present informative energy rate reported from the data-sheet of popular wireless chipsets. Also note that some low-energy technologies feature low data rates and thus, require more time to send the same amount of data, leading to equivalent energy consumption than

more energy greedy but faster technologies. UNB technologies should be the ones that use less energy, thanks to the modulation used and the very narrow bandwidth (which in return also means a very low data rate). Among all the aforementioned technologies, Sigfox and Telensa are UNB technologies. As an example, this Sigfox chipset [41] consumes 37 mA in transmission mode. Nwave, which is based on Weightless-N, is also a UNB technology, and thus should have a similarly low energy consumption. Qowisio should offer a similar consumption although the specification is not yet known. Then, the LoRa technology have a similar or higher consumption than UNB technologies, depending on the parameters used (e.g., [42] consumes between 18 and 125 mA in transmission mode). Weightless-P consume an amount of energy that is close to LoRa's (e.g., [43] 49 mA at 15 dBm in transmission). Mobile technologies come after as they consume much more power (e.g., [44] 235 mA LTE-M and 190 mA NB-IoT in transmission mode). This is mainly due to the modulation, the data rate and the synchronization to the base stations which is required for mobile communications. We can note that due to a high data rate and a fast frequency, Ingenu RPMA should consume more energy than the previously cited technologies, although they claim the opposite.

While the absolute energy rates are important, another aspect that must be taken into account is the on-air duration of the communications [45]. Indeed, if a technology provides a better data rate, the transmission time will be shorter. Thus, a technology consuming a higher amount of energy could, in the end, consume less energy than a more restrained technology. This is because, for the same amount of information, the duration of the transmission would be shorter.

3.2. On Which Technology to Use

Considering all the above, mobile IoT technologies have numerous advantages to be used as a one-hop technology to access the Internet. First, considering coverage, mobile technology is more likely to be available worldwide than ISM-based LPWAN. Using ISM-based LPWAN, there is a need to deploy base stations in isolated areas which is costly. Furthermore, deploying a network connected to the Internet may not be part of a company's purpose. In reverse, using mobile would also mean that there is no way to extend the base mobile network in an isolated area if needed, as the spectrum is under licensed use.

As for the spectrum, many long-range technologies make use of the sub-GHz ISM unlicensed bands. This means that everyone can use it, and it is likely that a high level of interference will become common as the number of connected devices using those technologies increases, especially considering technologies such as LoRa that spread the signal across a wide bandwidth. Mobile may bypass noise produced in the sub-GHz, but on the other side, mobile IoT technologies are partly based on the existing and already widely used LTE bands, which are also used for cellphone communications (i.e., more interference).

Regarding the financial cost of using mobile networks, several things need to be taken into account. A summary of the module and connectivity costs depending on the technology is shown in Table 1. The prices are given on an indicative basis, as they depend on the countries, the operators and different other factors. Alternative solutions exist, e.g., Hologram [46], which proposes worldwide mobile connectivity and provides a universal SIM card for 1$ per month plus 40 cents (prices vary depending on the number of devices). As it gives an access to every mobile network available on our planet, hologram benefits from an excellent coverage, as depicted in Figure 6.

Table 1. Cost to connect [47].

	Module	Connectivity	Infrastructure
LTE-M	$10–15	$3–5 / mo for 1 Mb	
NB-IoT	$7–12	<$1 / mo for 100 kb	
Sigfox	$5–10	<$1 / mo	
Ingenu	$10–15	Unknown	
LoRaWAN Public	$9–12	$1–2 / mo	
LoRaWAN Private	$9–12	$0.25 / mo	$500

Figure 6. Hologram coverage [46].

If we consider using mobile IoT, we need to choose which technology. EC-GSM-IoT and 5G can be put aside right away. The former is not going to be deployed anymore and the network may even be decommissioned soon [14], while the latter is not deployed at all by the time of writing and will not be usable before several years.

eMTC and NB-IoT both propose interesting features and are likely to be deployed and used increasingly in the upcoming years, while being already available in several countries. Choosing between one or the other is difficult: eMTC supports FotA updates, while NB-IoT does not. On the other side, eMTC have a high energy cost, while NB-IoT consumes less power. Considering world coverage, restricting to only one of the two would also restrict the possible deployments to the countries where that technology is available (cf. Figure 3).

Regarding these issues, the best answer may be to keep both technologies. Several radio chips supporting both eMTC and NB-IoT are already available (e.g., [44]). A simple idea could be to use NB-IoT for regular monitoring communications, and eMTC for FotA updates. However, this can create new issues too, as areas where coverage for both technologies may be scarce. So, we would need to provide viable solutions also for scenarios where only one of these two technologies are available.

This is where LPWAN technologies presented in Section 2.2 may be useful. Devices could form a network in a multi-hop fashion where only one node would need to relay the communications to the Internet, whereas the other nodes would use an ISM-based LPWAN technology to share their data. This would extend the range for nodes out of direct mobile coverage. As mobile technologies cannot

be used (licensed spectrum) for this kind of "local LPWAN", another LPWAN technology based on the sub-GHz unlicensed bands such as the ones previously introduced could be used instead.

To address this, we need an LPWAN technology which could enable FotA redistribution by the gateway once it has acquired the firmware via mobile communications and which costs less in terms of energy at the same time. Among the ones presented before, LoRa and Weightless-P are the best candidates for this. As mentioned previously, Weightless-P already support FotA updates. However, because of the modulation it uses, it offers a shorter range than LoRa. A combination of multiple LPWAN technologies (e.g., Weightless-P and Weightless-N or LoRa) could be used depending on the type of traffic to share data on a local scale, which may allow further energy savings.

Considering all the above, we can see a simplified decision diagram in Figure 7. It can be followed to find which technology to use depending on the application requirements. We will introduce it with simple use case examples. First, let us consider an agriculture use case, where static devices remotely monitor weather metrics in fields. For this use case, we assume that the monitored fields are covered by an already deployed technology and that we do not want to operate our own infrastructure. Static monitoring of the weather does not generate an important volume of data (data rate < 50 kbps), but may need long-range communications as fields may be isolated (range > 10 km). Thus, the Sigfox technology is a choice worth considering. As a second example, let us consider a tracking system for patients in hospitals. Here, we may need to deploy our own base stations to cover special areas, e.g., basements, and be independent from any operator. We do not need a high data rate (data rate < 70 kbps), thus Ingenu and LoRa are interesting choices. As LoRa communications are known to be resilient against low speed mobility, LoRa may be the best choice for this use case.
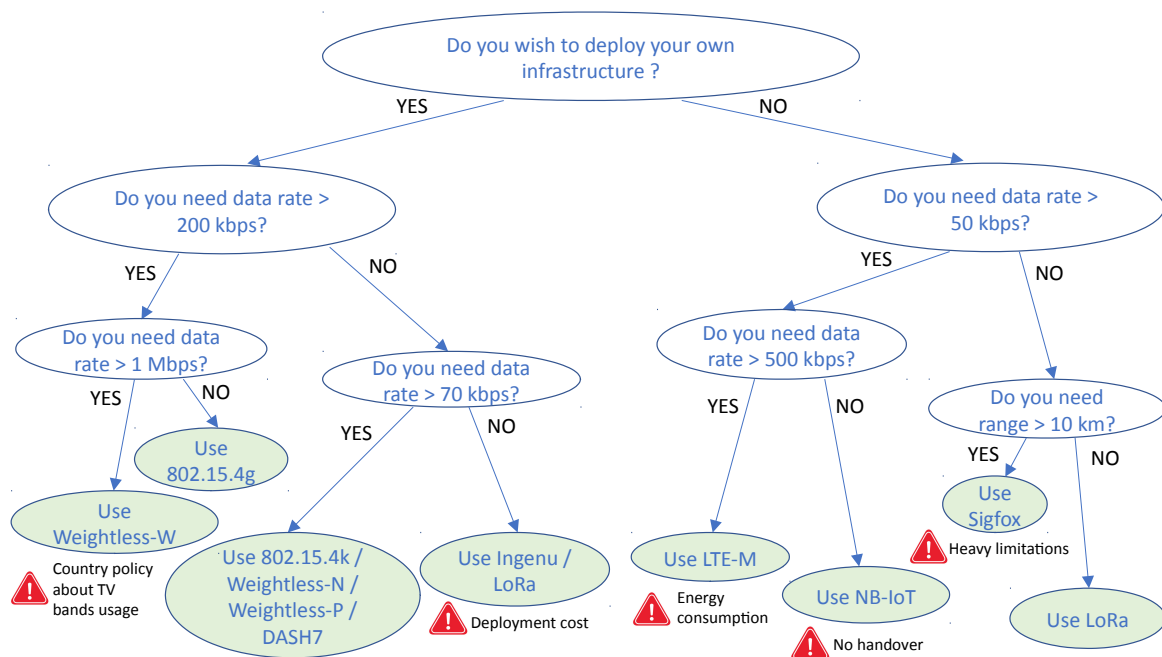

Figure 7. Technology decision diagram.

4. Conclusions

Long-range radio technologies are attracting a lot of attention. In opposition to short-range technologies, LPWAN technologies enable kilometers-wide communications. Those technologies provide an interesting connectivity solution for IoT networks in terms of range and energy consumption, and enable the use of networks known as LPWAN. As a result, an increasing amount of standards and technologies are conceived and become available on the market. In this article, we introduced the technologies available along with technical detail. Those are based either on licensed or

unlicensed frequency bands and offer different performances. They feature so different performances in terms of data rate, range, payload size etc. that there is a wide range of possibilities for each use case.

Based on those performances and other factors, we discussed which of these technologies may be the best suited depending on the use case. In particular, in terms of energy efficiency, which is the main point of focus for constrained devices, each technology offers different consumption rates. We have tried to provide a comprehensive state-of-the-art that includes commercial costs and coverage status besides technical characteristics. We have proposed an easy-to-use guide to assist one wishing to deploy such an application in choosing a given technology.

We can conclude that there is no perfect technology that fits all applications at once and that there is often a trade-off to consider between every performance criteria and cost.

Appendix A

Table A1. Technology table.

Technology	Sigfox	LoRaWAN	Ingenu	Telensa	LTE-M	NB-IoT	EC-GSM-IoT
Modulation	UNB DBPSK, GFSK	CSS	RPMA-DSSS, CDMA	UNB 2-FSK	16QAM	QPSK	GMSK
Band	Sub-GHz ISM: EU (868 MHz), US (902 MHz)	Sub-GHz ISM: EU (433 MHz, 868 MHz), US (915 MHz), Asia (430 MHz)	ISM 2.4 GHz	Sub-GHz bands including ISM: EU (868 MHz), US (915 MHz), Asia (430 MHz)	Licensed 700–900 MHz	Licensed 700–900 MHz	Licensed 800–900 MHz
Data rate	100 bps (UL), 600 bps (DL)	03–37.5 kbps (LoRa), 50 kbps (FSK)	78 kbps (UL), 19.5 kbps (DL)	62.5 bps (UL), 500 bps (DL)	1 Mbps	158.5 kbps (UL), 106 kbps (DL)	70–240 kbps
Range	10 km (urban), 50 km (rural)	5 km (urban), 15 km (rural)	15 km (urban), 500 km line LOS	1 km (urban)	11 km	15 km	15 km
MAC	pure ALOHA	pure ALOHA	CDMA-like	Unknown	FDMA/OFDMA	FDMA/OFDMA	CDMA
Topology	star	star of stars	star, tree	star	star	star	star
Payload size	12 B (UL), 8 B (DL)	up to 250 B	10 KB	64 KB	Unknown	125 B (UL), 85 B (DL) [48]	Unknown
Proprietary aspects	PHY and MAC layers	PHY layer	Full stack	Full stack	Full stack	Full stack	Full stack
Deployment model	Operator-based	Private and operator-based	Private	Private	Operator-based	Operator-based	Operator-based

Table A2. Standard table.

Standard	DASH7	IEEE 802.15.4k	IEEE 802.15.4g	Weightless-W	Weightless-N	Weightless-P
Modulation	GFSK	DSSS, FSK	MR-(FSK, OFDMA, OQPSK)	16-QAM, BPSK, QPSK, DBPSK	UNB DBPSK	GMSK, offset-QPSK
Band	Sub-GHz 433 MHz, 868 MHz, 915 MHz	ISM Sub-GHz & 2.4 GHz	ISM Sub-GHz & 2.4 GHz	TV white spaces 470-790 MHz	ISM Sub-GHz EU (868 MHz), US (915 MHz)	ISM Sub-GHz (169/433/470/780/ 868/915/923 MHz)
Data rate	9.6, 55.6, 166.7 kbps	1.5 bps–128 kbps	4.8 kbps–800 kbps	1 kbps–10 Mbps	30 kbps–100 kbps	200 bps–100 kbps
Range	0–5 km (urban)	5 km (urban)	10 km [49]	5 km (urban)	3 km (urban)	2 km (urban)
MAC	CSMA/CA	CSMA/CA or ALOHA with PCA	CSMA/CA	TDMA/FDMA	slotted ALOHA	TDMA/FDMA
Topology	tree, star	star	star, mesh, peer-to-peer	star	star	star
Payload size	256 B	2047 B	2047 B	>10 B	20 B	>10 B
Proprietary aspects	Open standard	Open standard	Open standard	Open standard	Open standard	Open standard
Deployment model	Private	Private	Private	Private	Private	Private

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