SINTEF A27942 - Unrestricted

Report

Comparison of wireless techniques applied to environmental sensor monitoring

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Acoustics and Communication
2017-03-27

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KEYWORDS:
[Keywords]

REPORT NO.	VERSION	DATE
SINTEF A27942	1.0	2017-03-27

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CLIENT(S)
Norges forskningsråd

CLIENT'S REF.	NUMBER OF PAGES/APPENDICES:
EEA SIM-SCP, 66236/17.11.2014	19

CLASSIFICATION	CLASSIFICATION THIS PAGE	ISBN
Unrestricted	Unrestricted	978-82-14-06148-2

ABSTRACT

This report investigates the technological basis for low power, low bitrate, medium range, wireless transmission of environmental sensor data. This is a typical 'Internet of Things' (IoT) application, and most of our findings are therefore generally applicable to the wider IoT field. The report starts with an overview of the relevant regulatory framework, in particular the differences between Europe and the USA. It then discusses the various key performance indicators of the wireless IoT communication channel and presents an overview of some of the wireless standards available today. While performances are often discussed, ecosystems appear as important for the sustainability of different systems. Future work includes a more in-depth analysis of selected standards in order to assess the scalability potential.

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This document has been approved according to SINTEF's approval procedure, and is digitally secured

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Document history

VERSION	DATE	VERSION DESCRIPTION

SINTEF

Table of contents

1 Background

The SIM-SCP (http://www.sim-scp.ro) project entitled "IMPLEMENTATION OF AN INTEGRATED SYSTEM FOR ACQUISITION AND TRANSMISSION OF MONITORING DATA FROM HAZARDOUS SUBSTANCES IN THE CLUJ COUNTY" is a European Economic Area collaboration between Norway and Romania. It is led by the Environmental Agency in Cluj-Napoca, Romania, and other partners include The University of Cluj-Napoca, Control Data System, and SINTEF. The goal is the implementation and testing of a wireless sensor network for the monitoring of BTEX (benzene, toluene, ethylbenzene and xylene) and small particles in five Romanian municipalities.

SINTEF's roles in the project have been to advice and test portable detection methods and sensors, and review affordable wireless solutions for transmission of data between measurement and analysis locations. This report is related to the latter of these topics, and gives an overview of relevant regulatory framework for low-cost wireless transmission (with focus on Europe and the USA), before examining key performance indicators and ecosystems of key wireless technologies.

The report is structured as follows:

- Chapter 2 introduces wireless solutions for collecting sensor data.
- Chapter 3 presents the regulations that apply to the use of sensor-related wireless communication, with a focus on European and US regulations.
- Chapter 4 briefly describes the main figures of merit for these wireless systems
- Chapter 5 presents a twofold comparison on performances and ecosystems of major wireless solutions

2 Introduction

Current mobile networks are suited for data hungry services, on the move. However, those networks are poorly suited to low data rate, low power, inexpensive, battery-operated devices. The vision of the *Internet of Things* (IoT) has sparked a number of new protocols to serve low data rates, IoT applications with likely more uplink (from the thing/edge to the gateway) than downlink (from the gateway to the thing/edge) traffic, the opposite asymmetry of mobile broadband systems that have more downlink than uplink. Note that some downlink capacity allows for regular and automated updates of edge nodes. Typical wireless sensor network traffic is described as 'bursty, not thirsty'.

The characteristics of the needed wireless networks encompass

- ✓ Long battery life, with a minimum of 10 years of battery duration for simple daily connectivity with small packets,
- ✓ Low device cost, with a module cost below 5 US dollars,
- ✓ Low deployment cost through limited new hardware installations and site visits, and
- ✓ Full coverage both indoor and outdoor

GPRS [1] was one of the first networks used for low data rate services. Being part of a mobile network, the nodes send frequent requests to find the adequate base station and therefore use a non-negligible part of its transmission capability on signalling. It is worth doing so in case of the amount of signalling bits do not exceed that of data. Since then, 3GPP has started study groups and defined a machine (or "thing") alternative of its otherwise high data rate LTE protocol. This is the LTE-M [1]. It has two versions, a narrow-band (NB-IoT or LTE Release 13 Cat-NB1) and wider band. The edge nodes can be classified according to usage; range, data rate, mobility. 3GPP [1] suggests several types, the latest including also IoT applications [2].

In parallel, Low Power Wide Area Networks (LPWAN) have been developed for connecting sensors and machines. They have been conceived for low power devices sending a few bytes of information occasionally, mostly as an uplink transmission to a gateway and the core system.

Wireless sensor networks can therefore be divided in two categories; the ones using licenced spectrum (e.g., NB-IoT) and the ones using unlicensed spectrum (e.g., SIGFOX, Long Range LoRa, Wireless M-Bus, DASH7 and many others initiatives).

The regulatory constraints and some metrics are detailed hereafter in an attempt to compare the different systems and markets.

3 Regulatory framework

NB-IoT [1] is set to operate in the cellular, **licensed bands**. NB-IoT has 200 KHz channels that can be arranged in LTE bands, between two LTE channels. This means that the NB-IoT deployment will not interfere with that of LTE, in order to avoid any coordination issues with other operators.

Conversely, most of the LPWAN protocols operate in the **unlicensed** spectrum, in various frequency bands such as unlicensed spectrum under 1 GHz left by the shift from analogue to digital television. In unlicensed bands, interferences are more likely to occur, resulting in unreliable, unstable services. In addition, the 868 MHz band will be threatened by adjacent cellular operations, causing additional interference. Inside these internationally regulated frequency bands, each technology uses channels of different capacities, opening up for variations about data rates and vulnerability to interference. Narrower channels will mitigate the effect of noise while wider channels may need adaptive coding gain to compensate for link quality variations.

All use of radio frequencies are subject to regulatory restrictions, imposed by national authorities. Regulatory regimes impose restrictions, notably on power in order to allow for several operators and un-coordinated deployments. ITU (The International Telecommunication Union) has divided the world into three Regions, as shown in Figure 1, where each region has its own set of frequency allocations. For Europe the overall frequency allocation is coordinated by CEPT (European Conference on Postal and Telecommunications Administration), but it should be noted that CEPT does not have any formal authority when it comes to frequency allocation.

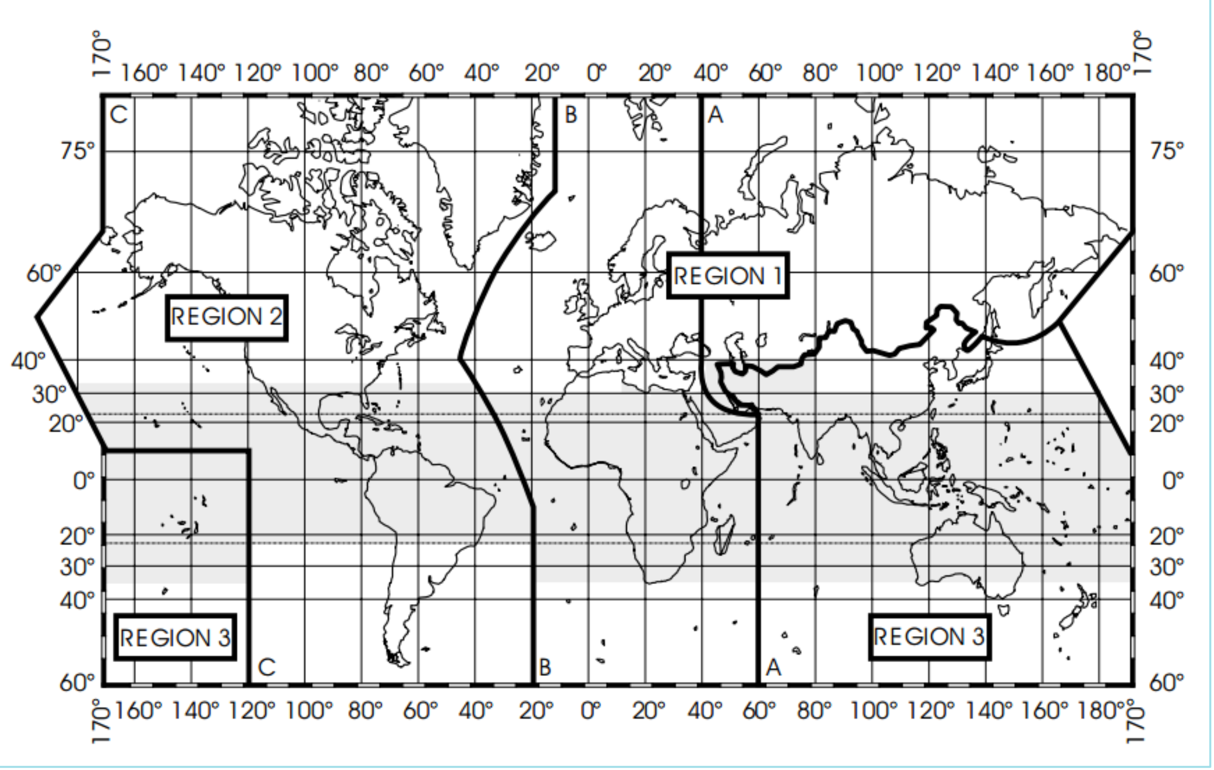

Figure 1 - The three ITU Regions (source [3]).

3.1 Relevant frequencies for IoT applications

For **licensed** frequency bands, the regulations are handled by service providers having purchased a license to use the specific frequency bands. This implicates that the end-user will normally not know which exact frequencies are used, and that the end-user will have no influence over how each device uses the radio spectrum.

For **unlicensed** frequency bands, any device may make use of the frequency as long as national regulations are followed. This means that an end-user may configure or specify any radio transmission scheme as long as it adheres to the local regulations. However, as making new radio schemes is cumbersome, radio manufacturers have focused on frequency ranges that are acceptable in as many countries as possible. Therefore, the following frequencies have become most relevant when it comes to IoT applications in Europe and North America:

- 433 MHz (Europe)
- 868 [865-870] MHz (Europe)
- 915 [902-928] MHz (USA and Canada)
- 2.45 GHz (Worldwide)

Below we present some excerpts from European and US regulations regarding "Short Range Devices". Note that US authorities operate with field strength limitations in millivolts/meter and output power limitations in EIRP[1], while European authorities present the output power limits in ERP[2].
The difference can be expressed as ERP = EIRP/1.64, or EIRP=ERP+2.15 dB, see [4] for details.

[1] Effective Isotropic Radiated Power
[2] Effective Radiated Power

Also, note that the text below only covers the main aspects of the regulations, and that the original documents should be consulted if more detail is needed.

3.2 Regulations in Europe

When it comes to the use of wireless short-range communication in Europe, CEPT presents a detailed description of the various national requirements in the ERC Recommendation 70-03 "Relating to the use of Short Range Devices (SRD)" (Edition of 27 May 2016) [5]. Below the most relevant information is extracted:

- Regarding 433.05-434.79 MHz, see Figure 2.
- Regarding 863-870 MHz, see Figure 3.
- Regarding 2400-2483.5 MHz, see Figure 4.

	Frequency Band	Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation / maximum occupied bandwidth	ECC/ERC Deliverable	Notes
g1	433.05-434.79 MHz	10 mW e.r.p.	≤ 10 % duty cycle (note 1)	Not specified		
g2	433.05-434.79 MHz	1 mW e.r.p. -13 dBm/10 kHz	No requirement except for (note 11)	Not specified		Power density limited to -13 dBm/10 kHz for wideband modulation with a bandwidth greater than 250 kHz
g3	434.04-434.79 MHz	10 mW e.r.p.	No requirement except for (note 11)	≤ 25 kHz		

Note 1: When either duty cycle, Listen Before Talk (LBT) or equivalent technique applies then it shall not be user dependent/adjustable and shall be guaranteed by appropriate technical means. For LBT devices without Adaptive Frequency Agility (AFA), or equivalent techniques, the duty cycle limit applies. For any type of frequency agile device the duty cycle limit applies to the total transmission unless LBT or equivalent technique is used.

Note 11: Audio and video applications are excluded. Voice applications (analogue or digital) are allowed with a maximum bandwidth of ≤ 25 kHz, and with spectrum access technique such as LBT or equivalent and shall include a power output sensor controlling the transmitter to a maximum transmit period of 1 minute for each transmission.

Figure 2 - Information regarding the frequency band 433.05-434.79 MHz, including relevant notes, (source [5]).

	Frequency Band	Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation / maximum occupied bandwidth	ECC/ERC Deliverable	Notes
h1.1	863-870 MHz	25 mW e.r.p.	≤ 0.1% duty cycle or LBT (notes 1 and 5)	≤ 100 kHz for 47 or more channels (note 2)		FHSS
h1.2	863-870 MHz	25 mW e.r.p. Power density: -4.5 dBm/100 kHz (note 7)	≤ 0.1% duty cycle or LBT+AFA (notes 1, 5 and 6)	Not specified		DSSS and other wideband techniques other than FHSS
h1.3	863-870 MHz	25 mW e.r.p.	≤ 0.1% duty cycle or LBT + AFA (notes 1 and 5)	≤ 100 kHz, for 1 or more channels modulation bandwidth ≤ 300 kHz (note 2)		Narrow /wide-band modulation
h1.4	868-868.6 MHz	25 mW e.r.p.	≤ 1% duty cycle or LBT +AFA (note 1)	No spacing, for 1 or more channels (note 2)		Narrow / wide-band modulation. No channel spacing, however the whole stated frequency band may be used
h1.5	868.7-869.2 MHz	25 mW e.r.p.	≤ 0.1% duty cycle or LBT+AFA (note 1)	No spacing, for 1 or more channels (note 2)		Narrow / wide-band modulation. No channel spacing, however the whole stated frequency band may be used
h1.6	869.4-869.65 MHz	500 mW e.r.p.	≤ 10% duty cycle or LBT+AFA (note 1)	No spacing, for 1 or more channels		Narrow / wide-band modulation The whole stated frequency band may be used as 1 channel for high speed data transmission
h1.7	869.7-870 MHz	5 mW e.r.p.; 25 mW e.r.p.	No requirement for 5 mW e.r.p., ≤ 1% duty cycle or LBT+AFA (note 1) for 25 mW e.r.p.	No spacing for 1 or more channels		Narrow / wide-band modulation. No channel spacing, however the whole stated frequency band may be used

Note 1: When either duty cycle, Listen Before Talk (LBT) or equivalent technique applies then it shall not be user dependent/adjustable and shall be guaranteed by appropriate technical means. For LBT devices without Adaptive Frequency Agility (AFA), or equivalent techniques, the duty cycle limit applies. For any type of frequency agile device the duty cycle limit applies to the total transmission unless LBT or equivalent technique is used.

Note 2: The preferred channel spacing is 100 kHz allowing for a subdivision into 50 kHz or 25 kHz.

Note 5: Duty cycle may be increased to 1% if the band is limited to 865-868 MHz.

Note 6: For wide-band techniques, other than FHSS, operating with a bandwidth of 200 kHz to 3 MHz, the duty cycle can be increased to 1% if the band is limited to 865-868 MHz and power to =10 mW e.r.p.

Figure 3 - Information regarding the frequency band 863-870 MHz, including relevant notes (source [5]).

Frequency Band		Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation / maximum occupied bandwidth	ECC/ERC Deliverable	Notes
i	2400-2483.5 MHz	10 mW e.i.r.p.	No requirement	Not specified		The frequency band is also identified in Annexes 3 and 6

Note 1: When either duty cycle, Listen Before Talk (LBT) or equivalent technique applies then it shall not be user dependent/adjustable and shall be guaranteed by appropriate technical means. For LBT devices without Adaptive Frequency Agility (AFA), or equivalent techniques, the duty cycle limit applies. For any type of frequency agile device the duty cycle limit applies to the total transmission unless LBT or equivalent technique is used.

Figure 4 - Information regarding the frequency band 2400-2483.5 MHz, including relevant notes, (source [5]).

Annexes 3 and 6, mentioned in the notes above, cover Wideband Data Transmission Systems and Radio determination Applications respectively, and are therefore not relevant for IoT applications.

Figure 5 shows which parts/annexes of the recommendation that are implemented by each nation by May 2016.

APPENDIX 1: NATIONAL IMPLEMENTATION

The CEPT country codes can be seen under http://www.cept.org/cept/cept-country-codes

Annexes to ERC/REC 70-03	ALB	AND	AUT	AZE	BEL	BIH	BLR	BUL	CYP	CZE	D	DNK	E	EST	F	FIN	G	GEO	GRC	HNG	HOL	HRV	I	IRL	ISL	LIE	LTU	LUX	LVA	MDA	MKD	MLT	MNE	NOR	POL	POR	ROU	RUS	S	SRB	SUI	SVK	SVN	TUR	UKR
ANNEX 1: NON-SPECIFIC SHORT RANGE DEVICES																																													
Annex a: 6765-6795 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L
Annex b: 13553-13567 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Annex c: 26957-27283 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Annex c1.1: 26990-27000 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N
Annex c1.2: 27040-27050 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N
Annex c1.3: 27090-27100 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N
Annex c1.4: 27140-27150 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N
Annex c1.5: 27190-27200 kHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N
Annex d: 40.66-40.7 MHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Annex e: 138.2-138.45 MHz **ECC/DEC/(05)02**	Y	N	Y		N	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	Y	N	Y	N	N	Y	N	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y	N	N	Y	N	N	N	Y	N
Annex f1: 169.4-169.475 MHz **ECC/DEC/(05)02**	Y	Y	Y		Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	U
Annex f2: 169.4-169.4875 MHz **ECC/DEC/(05)02**	Y	Y	Y		Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Annex f3: 169.4875-169.5875 MHz **ECC/DEC/(05)02**	Y	Y	Y		Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Annex f4: 169.5875-169.8125 MHz **ECC/DEC/(05)02**	Y	Y	Y		Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Annex g1: 433.05-434.79 MHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	Y	Y	Y	L
Annex g2: 433.05-434.79 MHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	Y	Y	Y	L
Annex g3: 434.04-434.79 MHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	Y	Y	Y	L
Annex h1.1: 863-870 MHz	Y	Y	Y		Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	L	N	Y	Y	Y	Y	Y	L
Annex h1.2: 863-870 MHz	Y	Y	Y		Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	L	N	Y	Y	Y	Y	Y	L
Annex h1.3: 863-870 MHz	Y	Y	Y		Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	L	N	Y	Y	Y	Y	Y	L
Annex h1.4: 868-868.6 MHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Annex h1.5: 868.7-869.2 MHz	Y	Y	Y		Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Annex h1.6: 869.4-869.65 MHz	Y	Y	Y		Y	Y	L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Annex h1.7: 869.7-870 MHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Annex h2: 870-876 MHz	Y	N	U	N			N	N			N	Y	*	Y	N	P	Y				N	N		P		L	N	Y		Y				N		N		P	Y	N	L	Y	Y	N	N
Annex h2.1: 870-875.8 MHz	Y	N	U	N			N	N			N	Y	*	Y	N	P	Y				N	N		P		L	N	Y		Y				N		N		P	Y	N	L	Y	Y	N	N
Annex h3: 915-921 MHz	Y	N	U	N			N	N			N	Y	*	Y	N	N	Y				N	N		P		L	N	Y		Y				N		N		P	Y	N	L	Y	Y	N	N
Annex h3.1: 915.2-920.8 MHz	Y	N	U	N			N	N			N	Y	*	Y	N	N	Y				N	N		P		L	N	Y		Y				N		N		P	Y	N	L	Y	Y	N	N
Annex i: 2400-2483.5 MHz	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L
Annex j: 5725-5875 MHz	Y	Y	Y		Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	Y	Y	Y	Y	Y	Y
Annex k1: 3100-4800 MHz **ECC/DEC/(06)04**	Y	Y	Y		Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	N	Y	Y	Y	Y	U
Annex k2: 6000-9000 MHz **ECC/DEC/(06)04**	Y	Y	Y		Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	L	Y	N	Y	Y	Y	Y	U
Annex l: 6000-8500 MHz **ECC/DEC/(12)03**	Y	N	P	*	P	N	N	P	P	P	U	Y	P	L	P	Y	L	N	P	L	Y	Y	P	P	P	Y	L	Y	P	Y	N	P	N	L	P	P	P	N	P	N	Y	P	Y	U	N

Highlighted yellow = not implemented   Y = implemented   L = limited implementation   P = planned   U = under study

Figure 5 – National implementations of [5] (as of May 2016).

3.3 Regulations in USA

In USA, the use of radio frequency devices is regulated by FCC as described in Part 15 of Title 47 in the Code of Federal Regulations [6]. Title 47 covers the field of "Telecommunication", while Part 15 covers "Radio Frequency Devices". Paragraph 15.247 in Title 47 of CFR regulates *spread spectrum transmitters*, and states that they can have a maximum of 1 Watt output power (EIRP) in the following relevant frequency ranges:

- 902-928 MHz
- 2400-2483.5 MHz

Furthermore, paragraph 15.249 states that any mobile transmitter (independent of modulation technique) within the same frequency ranges shall operate with a field strength limit of 50 millivolts/meter measured at a distance of 3 meters. This is equivalent to 750 mW, and is thus a tougher constraint than what is required by paragraph 15.247.

The highest EIRP allowed in sub 2.5 GHz in ITU regions 1 and 2 are compared and shown in Table 1.

Table 1. Maximal EIRP in USA and Europe.

Frequency band (MHz)	*Europe*	*USA*
433-434,75	Maximal in [433,05-434,79 MHz] 10 mW ERP and < 10% duty cycle 12.15 mW	-
863-870	Maximal in [869,4-869,65 MHz] 500 mW ERP and < 10% duty cycle 502.15 mW	-
902-928	-	Field strength 50 mW at 3m or 1W EIRP 750 mW
2400-2483,5	10 mW	Field strength 50 mW at 3m or 1W EIRP * 750 mW

* $(50\ mW/mx3m)^2/30=750\ mW$

4 Relevant parameters for wireless communication systems

The following section gives a description of the relevant system parameters that are used to characterise the performance of the various wireless solutions.

4.1 Range and topology

The achieved range in any radio system is subject to several factors including the propagation environment, the transmitted power, frequency, modulation type, and access method. Therefore, there is usually a bracket of possible ranges, with the "up to" achieved only on rare occasions and under very favourable conditions. In addition, extending the topology can help to compensate for lack of single-hop range through, either a tree or mesh architecture, whereby the signal is relayed from node to node. Some technologies exist only in a star topology with edge nodes around a single gateway, others have tree structures, while others also have mesh capability and possible combinations thereof.

4.2 Transmitted power

Higher transmission power will lead to higher data rates or longer range. Europe and USA have different regulatory regimes and values for allowed transmitted power [3], [4], [5], [12]. Sometimes, only the maximum Effective Isotropic Radiated Power (EIRP) is specified. In [5], the frequency band 433.05-434.79 MHz imposes a maximum EIRP of 10 mW for links with 10 % or less duty cycle in Europe[3] .
The theoretical single-hop range will be a result of the combination of transmitted power, modulation type and access method. Yet an additional important factor in wireless systems is interference from neighbouring radio transmitters that can substantially limit range (see next paragraph for details on this topic).

4.3 Effect of interference on the physical channel and access scheme

Interference will happen at the physical level where (rather inexpensive) receivers will try to sort relevant signals from the surrounding noise. Consequently, the ideal range will be reduced in a noisy environment. Noise is usually caused by other transmitters in the vicinity. Blockage by walls, vehicles, even people also alters range by attenuating or distorting the received signal.

Additionally, different transmitters may try to access the system and get a channel concurrently. In order to avoid collisions, one can use collision avoidance techniques following the principle: “Listen before talk (LBT).” This means that the receiver must be capable of listening before the device gets to transmit if it found the bandwidth unused. This significantly reduces the probability of collisions when more transmitters wish to transmit in the same space.

Another strategy consists in transmitting and waiting for an acknowledgement. If this acknowledgement is not received, one assumes collision and resends according to a back-off algorithm like a collision detection mechanism (e.g., Aloha protocol). Protocols that do not infer collision avoidance nor detection run the risk of saturating the network.

4.4 Duty cycle

The duty cycle of a device is defined as the fraction of time a radio is actively transmitting, i.e. that it is in 'active duty'. A radio with 50% duty cycle transmits on average 50% of the time. The higher the duty cycle, the more data it will be able to transmit but the more it will also prevent others from transmitting. It is therefore in everybody's interest that a shared radio spectrum is governed to allow all users a fair share of the available bandwidth. Limiting the duty cycle can be complemented by LBT.

4.5 Mobility

GPRS and LTE-M are natural preferences for network operators as these systems are compatible with legacy infrastructure. These are also mobile technologies; in contrast with the rest of the technologies considered here that do not consider handover. Mobility is ensured through handovers, where the edge devices' signal is tracked and relationship to the base station (gateway) is established, while having constantly a list of neighbouring base stations the device can be connected to in case of a more preferable location. The downside of mobility is that this process consumes network-signalling resources, both on the uplink and downlink radio link. Although it is at an early stage for LTE-M and roaming agreements for LTE-M SIM

[3] *When either duty cycle, LBT or equivalent technique applies, then it shall not be user dependent/adjustable and shall be guaranteed by appropriate technical means. For LBT devices without Adaptive Frequency Agility (AFA), or equivalent techniques, the duty cycle limit applies. For any type of frequency agile device the duty cycle limit applies to the total transmission unless LBT or equivalent technique is used.*

cards have not yet been addressed, the LTE-M group of technologies raises interest in the mobile and international IoT service community.

4.6 Energy consumption

An important metric for LPWAN is the energy consumption as the end device may be battery operated. The energy consumption is of primary importance at the edge of the network, as a service turns profitable only if the battery remains unchanged for a long time, typically years. Several factors will impinge on the energy consumption, including but not limited to, modulation technique, media access protocol, acknowledgement with the gateway, possible adaptive techniques, mobility and tracking, and duty cycle.

Low duty cycles allow the devices to be in sleep mode for a long period and awake only for transmitting data. Power used to transmit data is also an important factor that will vary according to technology and range, whether power is used for a short period or not. A high power for a short time can lead to longer sleep mode periods and extended battery life.

4.7 Internet Protocol version 6 (IPv6) support

The Internet Protocol (IP) simplifies connectivity and allows the use of a wide range of low-level communication technologies without having to deal with implementation details below the network or transport layers. Not all technologies however will likely allow for the IPv6 evolution (with 128 bits addressing), which casts doubts about the longevity of these technologies.

4.8 Cost - CAPEX/OPEX

The more complex the edge node, the higher cost for the service provider. However, in order to compare costs of different systems, one has to take into account the cost of the edge nodes, the gateway, and operational costs. For technologies relying on public service like those of 3GPP (GPRS, NB-IoT) or deployed in partnership with telecommunication operators (SIGFOX and to some extent LoRa), the end customer pays for the edge node and service operation, while the operator pays for the backhaul infrastructure. Conversely, other networks can be run on a private ownership model where the service provider pays for the whole chain.

5 Current market ecosystems

5.1 Technology overview

In **licensed** bands, NB-IoT [1]is a system entering the prototyping phase [15]. It is not based on conventional LTE. It uses direct-sequence spread spectrum (DSSS) modulation, which reduces the hardware complexity. The bandwidth is 180 kHz bandwidth with 20 kHz guard band, and uplink and downlink data rates around 200 kbps with half-duplex operation. NB-IoT offers similar data rates than LPWA technologies, but more guarantee to achieve them in a stable way as the frequency band is licensed. Although in a band that allows for up to 23 dBm transmission, NB-IoT is likely to be deployed at a maximum 14 dBm in order to limit power consumption. As low power consumption is vital for most LPWAN use cases, NB-IoT proves more than capable of fulfilling such a requirement, as it enables a battery life of approximately 10 years. eDRX (extended discontinuous reception) and PSM (power save mode) are two innovative features that extend NB-IoT battery life to beyond 15 years. The initial NB-IoT module cost is expected to be less than 5 dollars. Additionally, NB-IoT enables a vast array of connections per cell (50k) to send small amounts of data in parallel.

SIGFOX [8], LoRa [7], Wireless M-Bus [9] and DASH7 [10] are the most known **unlicensed** band LPWAN technologies. These are described in more detail in the subsections below.

5.1.1 SIGFOX

SIGFOX is both the name of a company and a narrowband (or ultra-narrowband) technology. The technology uses a standard radio transmission method called binary phase-shift keying (BPSK), and it takes very narrow chunks of spectrum and changes the phase of the carrier radio wave to encode the data. This allows the receiver to listen only in a tiny slice of spectrum, which mitigates the effect of noise. It requires an inexpensive endpoint radio, but a more sophisticated base station to manage the network. The base station sensitivity can be as low as -142 dBm for 100 b/s uplinks, and -134 dBm for 600 b/s links. The demodulation is close to the noise floor and no error coding added. SIGFOX has implemented transmission diversity with respect to both time (payload in three consecutive frames), frequency (in three pseudo random sub carriers and space (a node can see several base stations) in order to minimize the risks of interference. It offers bidirectional communication, but its capacity to downlink direction (i.e., from the base station to the end-point) is more limited. The SIGFOX company owns all of its technology from the backend data and cloud server to the endpoints software. The company has opened its endpoint technology to silicon manufacturers or vendors as long as certain business terms are agreed. The business idea is to allow the applications to be very inexpensive and offer already-installed nation-wide networks, and the company seems to have an ambition of making mobile network operators to adopt their technology for IoT deployments over both city and nationwide LPWANs [17],[18]. A drawback is that only one SIGFOX network can be deployed in an area due to exclusive arrangements with the selected network operator. Moreover, the technology is not applicable for continuous communication due to the relatively high latency with low predictability.

5.1.2 LoRa

LoRa uses the same radio for a receiver on the base station and at the endpoints. The cost of a LoRa terminal is higher than a SIGFOX terminal while the complexity of the endpoint and gateway are more balanced in a LoRa system. The LoRa ecosystem is in principle open (by joining the LoRa Alliance), so anyone can build and manage their own network. Both large network operators, private companies and startups can exploit LoRa networks. However, there is an issue related to the roaming from public network to public network and vice versa. Roaming requires simultaneous connection to several networks. The specifications can be downloaded, and any hardware or gateway manufacturer can build a module or gateway that conforms to the LoRa specifications. Even if the ecosystem itself is open, it contains a proprietary element, as LoRa is based on a spread spectrum wireless technology developed by Semtech Corporation. The LoRa Alliance seems to share SIGFOX's goal of being the preferred LPWAN technology for mobile network operators, although their business models and technologies are quite different [17],[18].

5.1.3 Wireless M-Bus

Wireless M-Bus has specifically been standardized for the smart grid market where the interface is M-Bus, and the wireless part merely an extension. The standard [9] allows for several data rate channels (labelled N in the 196 MHz band and S, T or R modes in the 868 MHz band) with simple FSK modulations.

5.1.4 DASH7

DASH7 was designed according to the concept of B.L.A.S.T. = bursty, light (packet size is limited to 256 bytes), asynchronous (no periodic, energy-consuming handshake), stealth (no beacon), transitive (focus on uplink). In the default tree configuration, the end devices are first connected to duty-cycling sub-controllers, which then connect to the always-on base stations. In addition, the end device periodically listens for a possible downlink signal. This mechanism can cut latency, at the expense of battery time and some complexity.

5.2 Ecosystem considerations

3GPP technologies [1] can claim international coverage and well established ecosystems. These are a natural preference for network operators as 3GPP technologies are either already installed or can be installed in existing infrastructure, saving the burden of finding new sites. In addition, this infrastructure is deployed on a worldwide basis, making a powerful argument for IoT services with international market ambitions. The downside of the highest frequency bands is that at lower range is expected. NB-IoT, as the underlying network technology for the low power wide area (LPWA) market has several useful characteristics for IoT solutions. NB-IoT is in its infancy, while GPRS will soon be retired. Chip manufacturers that back NB-IoT include Altair, Sequans and Qualcomm. 3GPP release 13 [15] includes definitions of NB-IoT, but is set to evolve with the next release.

LoRa has open network specifications (LoRaWAN), but the chip producers rely on IP licenses of LoRa (Semtech). The alliance procedures may cause a slow deployment, but cooperation with telecommunication operators is sought and discussion on roaming started. Roll-out also has started. Both LoRa and IEEE802.11ah have had a 2016 release [7] [16].

SIGFOX has been deployed since 2009. It is well adapted to low bitrates applications. It has opened the end node to silicon manufacturers and allows almost free applications. SIGFOX gives practically away hardware but sells Network as a Service (NaaS) or Software as a Service (SaaS) when associated with a network operator [8][16]. The costs reside essentially in the manpower needed to install the networks.

Although Wireless M-Bus has been deployed for advanced metering infrastructures (AMI) for some years, application are not limited to this. However, the limitation may lie in the current IPv4 restriction that will limit deployments, particularly in Asia where most available IP addresses are based on version 6.

The DASH7 standard defines all ISO layers, as opposed to other standards that address the physical and MAC layers only [10]. Other physical layers technologies, such as SIGFOX, LoRa or NB-IoT can be coupled to the rest of DASH7 protocol stack, as illustrated in Figure 6. However, while flexibility might be an advantage in some situations, it could also be regarded as a drawback as it hinders standardisation.

Note that both LoRa and DASH7 might gain an advantage of achieving longer range by using the 433 MHz band, which is a lower frequency than most competitors use. For this band, ETSI (in Europe) states 10 mW Effective Radiated Power (ERP) when the duty cycle is less than 10% or when then channel spacing is smaller than 25 kHz or with 1 mW ERP without duty cycle limitations. In the USA, the FCC limits the ERP to −14.4 dBm for periodic control applications and −22.36 dBm otherwise. Texas Instruments, ST Microelectronics, Silicon Labs, Semtech and Analog Devices offer DASH7 enabled hardware development kits or system-on-a-chip products. Additionally, the open source stack on all ISO layers allows common understanding on a reference implementation.

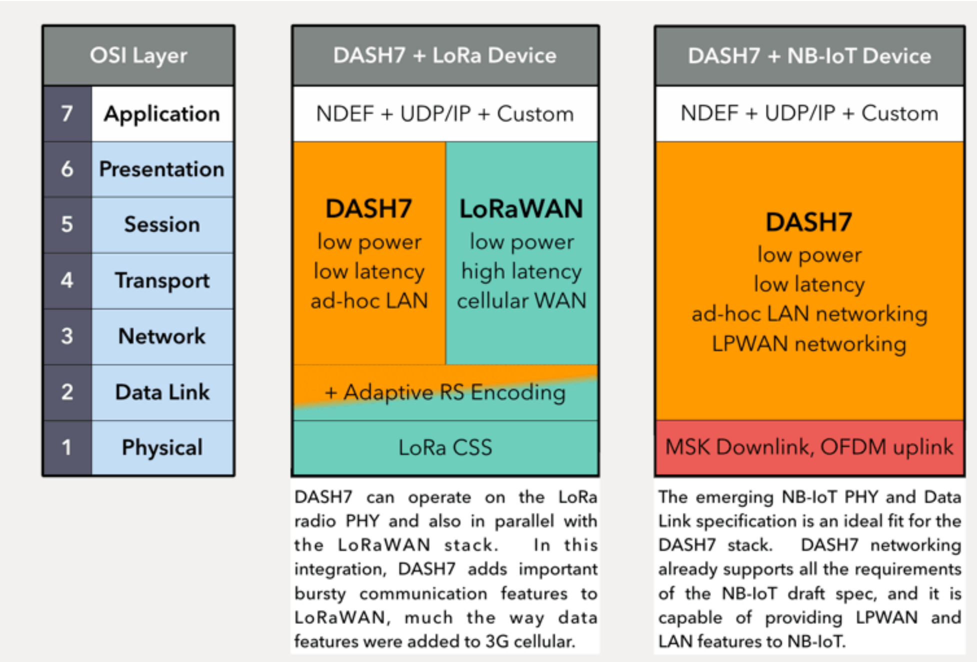

Figure 6. DASH7 interconnection to other LPWAN standards (source [11]).

5.3 Comparison of some LPWANs

Although a fair comparison is a difficult exercise because many of the key performance indicators are both situation-dependent and dependent on each other (i.e., data rate, range, power and cost cannot be optimized simultaneously), some trends emerge for the LPWAN systems mentioned above. Different parameters are compared [11], [13], [16], [17], [18] and summarized in Table 2. The governing body, as well as some parameters affecting CAPEX/OPEX (e.g. the number of nodes per gateway) are also included in Table 2. For the sake of comparison, the current WiFi solution based on IEEE 802.11ah standard [13],[18] was also added.

Table 2. Comparison of the some current LPWAN systems.

	GPRS	NB-IoT	SIGFOX	LoRa	WiFi 802.11ah	Wireless M-Bus	DASH7
Frequency + Band	8-900 MHz licensed	7-900 MHz licensed or shared	ISM; 865-868 / 902-928 MHz	ISM; 433/868 (EU)/ 780/915 (USA) 902 MHz	Unlicensed under 1GHz, except TV	868 MHz, 169 MHz	ISM; 433/868(EU)/ 915 (USA) MHz
Channel width	200 kHz	200 kHz	100 Hz	≥125 kHz	1/2/4/8/16 MHz	10 kHz to 100 kHz	25 or 200 kHz
Modulation and Access technique	Time division multiple access	Frequency division multiple access (UL), Orthogonal frequency division multiplex(DL)	Binary phase-shift keying	Frequency shift keying + Chirp spread spectrum	Time division multiplexing / Orthogonal frequency division multiplexing	Frequency shift keying	Frequency shift keying + Carrier Sense Multiple Access

	GPRS	NB-IoT	SIGFOX	LoRa	WiFi 802.11ah	Wireless M-Bus	DASH7
Transmitted power (edge)	Up to 43 dBm	20 dBm	Up to 20 dBm	EU: 14 dBm, US: 27 dBm	0 dBm to 30 dBm, depending on region	10 dBm	433 MHz: +10dBm(ETSI)868/915 MHz: +27dBm
GW sensitivity (implementation specific)	-114 dBm	-123.4 dBm	-142 dBm	-137 dBm	-92 dBm (2 MHz)	-105 dBm (at 32kc)	-
Range (under ideal conditions)	5 km	2-5 km (rural)	5-10 km (urban), 100 km (rural)	5 km (urban), 15 km (rural)	1 km (rural)	500m	5-10 km
Topology	Star	Star	Star	Star	Star, tree (2-hop)	Star	Tree by default, star or mesh
Data rate DL	10 kb/s	150 kb/s (NB) < 1Mb/s	4x8b/day	EU: 30 b/s-50 kb/s US: 100-900 kb/s	150 kb/s, up to 300 Mb/s	4.8-100 kb/s	9.6-167 kb/s
Data rate UL	10 kb/s	150 kb/s (NB) < 1 Mb/s	100 b/s	EU: 30 b/s-50 kb/s US: 100-900 kb/s	150 kb/s, up to 300 Mb/s	4.8-100 kb/s	9.6-167 kb/s
Mobility	Yes	Yes	No	No	No	No	No
# nodes per gateway	5000	50000	1000000	250000	8191	Not specified	N/A (connectionless)
Duplex mode at gateway	Full	Full	Half	Half	Full	Full	Half
Battery life (estimated given duty cycle)	1 week	5 years	10 years	10 years	1 week	Years	10 years
Support for IPv6	no	Yes	Unlikely	Likely	Likely	No	Likely
Governing body	3GPP	3GPP	SIGFOX	LoRa alliance	WiFi alliance and IEEE standards	M-Bus	DASH7 alliance
Deployment status	Deployed for several decades	Planned	Deployed since 2009	Planned	Planned	Available	Deployed since 2015
Costs (est., in $)	Node: 2	Node: 5	Node: 2	Node: 30	Node: 5	Node: 10	Node: 2

The following main observations can be made from Table 2:

- LoRa has to use a specific modulation method based on spread spectrum in order to claim long range. This method will however substantially reduce data rate, meaning that figures given for LoRa should be interpreted as maximum possible and probably not simultaneously. LoRa has created an alliance as governing body and several communities where open source programs can be exchanged to support a wide acceptance of the standard. However, there are issues concerning IP rights and licensing, casting doubts about the openness of such alliance.
- A simple SIGFOX or GPRS node is substantially cheaper than competitors are. However, the cost of the entire network is shared with operators. Two other features characterize SIGFOX: Early systems

were uplink-only in order to save costs on the receiver equipment and power consumed for listening and synchronizing with the gateway. Still the uplink is favoured and updates from the central location of a service may take substantial time. Furthermore, in order to mitigate collisions, policies like that of SIGFOX does limit *a priori* the data rate in order to regulate entry into the network. This might be acceptable as long as the length of the messages is modest.

- DASH7 may be one of the most open standard as it addresses the whole protocol stack and can be combined with competing physical layers. For instance a vendor can implement all layers following DASH7, while the physical layer can be complementary technologies; DASH7 for relative high datarates and LoRa for relative high range.
- Wireless M-Bus is a simple, well-proven technology. It has been deployed for smart meters in Germany and the Netherlands. It is an affordable technology that likely scales well up to a case simlar to that of metering, but may not scale well when many nodes are involved. This doubt is actually common to many LPWANs.
- NB-IoT is in the start phase and being tested by some telecommunication operators. In a well-tested ecosystem, it is believed to be the operators preferred choice. However, due to uncertainties linked to unlicensed operations, operators that deploy SIGFOX or LoRa today may gradually replace these systems with the licensed NB-IoT solution in the long run.

From a technological point of view, there is yet no clear winner of the solutions evaluated in this report. This is partly because there is no trivial way to evaluate how the various solutions will handle an increasingly high number of nodes with regard to important service parameters such as throughput, latency and battery lifetime. However, when looking at all the technologies from a market perspective, the NB-IoT is backed by a strong international consortium and established infrastructure owners. Therefore, one might expect that this 3GPP-supported ecosystem has a considerable advantage over the unlicensed technologies, unless these either prove significantly better or are provided with new and disruptive business models.

6 Conclusions

This report has investigated possible technologies for affordable wireless transmission of data between measurement and analysis locations. The regulatory framework in both Europe and the USA, and the figures of merit of current IoT wireless standards was described. Main take-aways have been presented in order to highlight the main pros and cons of major wireless systems such as SIGFOX, LoRa, DASH7, Wireless M-Bus and NB-IoT. From a market perspective, the latter might however seem to be at an advantage, as it is backed by 3GPP and major mobile network operators.

However, some technical issues need further investigation. There is some doubt on how these systems can simultaneously score high on range, number of nodes, collision free and interference free deployments. There is also a need to understand how these systems can scale with increasing number of nodes, in more urban or noisy environments and check actual limitations. At last, interference in unlicensed bands should be expected with a growing number of uncoordinated connections.

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