Saelens *et al. EURASIP Journal on Wireless Communications and Networking* (2019) 2019:219
https://doi.org/10.1186/s13638-019-1502-5

EURASIP Journal on Wireless Communications and Networking

REVIEW Open Access

Impact of EU duty cycle and transmission power limitations for sub-GHz LPWAN SRDs: an overview and future challenges

Martijn Saelens*, Jeroen Hoebeke, Adnan Shahid and Eli De Poorter

Abstract

Long-range sub-GHz technologies such as LoRaWAN, SigFox, IEEE 802.15.4, and DASH7 are increasingly popular for academic research and daily life applications. However, especially in the European Union (EU), the use of their corresponding frequency bands are tightly regulated, since they must confirm to the short-range device (SRD) regulations. Regulations and standards for SRDs exist on various levels, from global to national, but are often a source of confusion. Not only are multiple institutes responsible for drafting legislation and regulations, depending on the type of document can these rules be informational or mandatory. Regulations also vary from region to region; for example, regulations in the United States of America (USA) rely on electrical field strength and harmonic strength, while EU regulations are based on duty cycle and maximum transmission power. A common misconception is the presence of a common 1% duty cycle, while in fact the duty cycle is frequency band-specific and can be loosened under certain circumstances. This paper clarifies the various regulations for the European region, the parties involved in drafting and enforcing regulation, and the impact on recent technologies such as SigFox, LoRaWAN, and DASH7. Furthermore, an overview is given of potential mitigation approaches to cope with the duty cycle constraints, as well as future research directions.

Keywords: IoT, LPWAN, SRD, Duty cycle, Legislation, Regulation, Frequency band, Spectrum, SigFox, LoRaWAN, DASH7

1 Introduction

The past decade has seen a large growth in the use of Low-Power Wide-Area Network (LPWAN) short-range devices (SRDs). To ensure compatibility over borders and cultivate the economical market and collaboration, harmonization of frequency bands for SRDs is needed. SRDs use unlicensed bands and must thus share access to radio spectrum with other devices. This requires regularization to assure fair spectrum access for all SRDs and to prevent harmful interference. Such regularization consists of limits on transmission power and duty cycle. As the amount of SRDs rises and regulatory bands become more contested, the effects of regulatory limits will become more and more relevant. For example, LoRa duty cycle limitations already impacts, among others, the throughput of the downlink communication, the (un)availability of acknowledgements, the feasibility of over the air firmware upgrades, geolocation inaccuracies, and scalability [1–4]. Several models predict that the probability of duty cycle violations during downlink communication will further increase, up to 20% for SigFox and 15% for LoRaWAN [5]. Similar impacts are expected for other technologies operating in sub-GHz radio frequency bands.

However, despite the large impact of these regulations, many researchers are unaware of the exact limits and are not aware of mitigation techniques they can apply. Various institutes have each implemented regulations on the availability of radio spectrum for SRDs and their usage restrictions. This fragmentation causes confusion and misconceptions for researchers and manufacturers alike.

---

*Correspondence: martijn.saelens@ugent.be
Department of Information Technology, Ghent University - imec - IDLab, Technologiepark Zwijnaarde 15, B-9052, Ghent, Belgium

Documentation is scattered among multiple sources and their jurisdiction is often unclear. For example, a generalized duty cycle of 1 or 10% is often mentioned (e.g., [6, 7]), while the actual regulations are more diverse and include other parameters such as maximum transmission power and the usage of polite spectrum access techniques. At the time of writing, there is no survey known to the author which gives an easily accessible overview of these regulations, their legal value, and where additional information about them can be found. This paper is a response to that vacuum and aims to provide an overview on the currently existing regulations for SRDs in the European region using the unlicensed frequency bands in the 863 to 870 MHz range. Although this paper focuses on LPWAN SRDs in the 863 to 870 MHz range, the insights and resources presented in this paper can be generalized to other frequency ranges as most of the documents described in this paper also contain information about other frequency ranges. Finally, the paper also discusses how these legislation constraints can serve as inspiration for future research.

The paper is divided into 6 sections. First, Section 2 provides examples regarding the impact of duty cycle limitations in recent scientific papers. Next, Section 3 gives a basic overview of the currently available frequency bands for SRDs in the 863 to 870 MHz range in the European region. This section discusses the regulatory demands for using these frequency bands, such as duty cycle limitations, and gives an overview about recent changes in the regulatory landscape, such as the newly opened frequency bands in the 874 to 876 MHz and 915 to 921 MHz range. The next section, Section 4, discusses how technologies such as SigFox, LoRaWAN, and DASH7 are impacted by the regulations. Next, an overview is given in Section 5 on future research challenges related to the regulations. The last section then contains the conclusion of this paper.

Additionally, to guide researchers through the regulatory landscape, 2 appendices are provided to give more insights in the drafting of regulation and the regulatory documents produced defining the regulations. Appendix A describes the various institutes involved and how they collaborate. Appendix B then delves deeper into the regulations and documents drafted by those institutes. This includes the official legislation provided by the EU and other often cited documents such as ERC Recommendation 70-03 and EN 300 220.

2 Related work

Although regulatory limitations have a significant impact on existing technologies, these are often overlooked and left unexplored in current scientific literature. For example, [8] proposes a sub-GHz network protocol based on IEEE 802.15.4g [9] for reliable industrial networks with delay guarantees, using source routing and path changes, but does not mention the regulatory limits and how they impact their proposed solution. Similarly, [10] presents an LPWAN multi-hop protocol using features such as multi-hop data-aggregation and Adaptive Power Control (APC), but does not discuss how the solutions would perform within regulatory limits.

Even when limitations are mentioned, analyzing the impact of regulations is often left for future research. For example, [11] describes network architectures for wireless connected shuttles in warehouses using IEEE 802.15.4 in the 868 MHz band, but only mentions that latency bounded operations are limited due to duty cycle operations. Another example, [12], describes a protocol to analyze power consumption at mains sockets. There, it is shown that radio duty cycle regulations are responsible for the limitation of the amount of clients connected to a master device, but the extend of this limitation is not verified with experimental data.

Recently, a small number of scientific papers have been published that aim to quantify the impact of regulatory limits. For example, [13] shows that the throughput of 802.11ah networks using high data rate, polling sequences, and packet sizes (e.g., healthcare use cases) is severely impacted by duty cycle restrictions. In the same way, duty cycle restrictions pose a difficult obstacle for real-time communication and further research is needed [6]. Pham [14], proposing a solution for quality of service (QoS) under duty cycle restrictions, and [15], introducing duty cycle aware real-time scheduling, both include mitigating actions and experimental data. Unfortunately, such papers are still rather the exception. At the moment, even commercial devices sometimes ignore the regulatory limits in real-world situations. For example, a measurement in [16] of the 868 MHz frequency band in Paris shows the presence of a violating interfering device. Similarly, [17] also shows the presence of duty cycle limit offenders during real-world measurements in the city of Aalborg, showing that the regulations are not always clear or overlooked.

3 An overview of the current sub-GHz duty cycle and power restrictions

This section gives a high-level overview of the available frequency bands for SRDs and their regulatory limits.

3.1 Available frequency bands

Sub-GHz technologies such as LoRaWAN and Sigfox can use several radio frequencies. Multiple overlapping frequency bands are available [18]. Some bands are application specific, whereas others are meant for non-specific devices. The bandwidth varies from 0.05 to 5 MHz. Each of the frequency bands specifies 2 parameters: the maximum allowed transmission power and the maximum allowed duty cycle ratio. An overview of the available frequency bands is shown in Fig. 1 and described in Table 1.

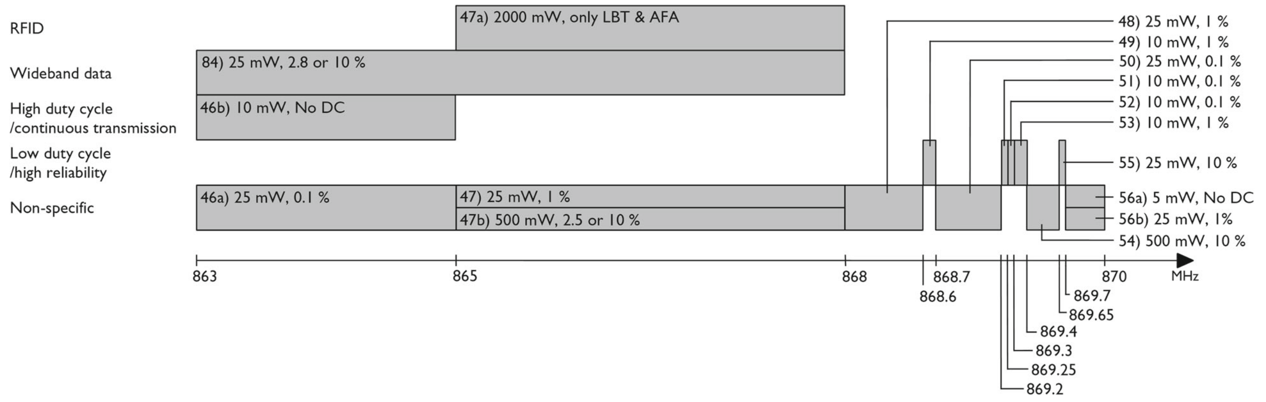

Fig. 1 A visual overview of the available frequency bands for SRDs in the 863 to 870 MHz range. The maximum transmission power (in mW) and maximum duty cycle (in %) are mentioned for each band

Table 1 An overview of the available frequency bands for SRDs in the 863 to 870 MHz range [18]

Nr.	Start freq. (MHz)	End freq. (MHz)	Bandwidth (MHz)	Category	Max TX power (mW) (e.r.p.)	Duty cycle
46a	863	865	2	Non-specific short-range devices	25	Polite access or 0.1%
46b	863	865	2	High duty cycle/continuous transmission devices	10	None
84	863	868	5	Wideband data	25	Polite access, and 10% (access point) or 2.8% (other devices)
47	865	868	3	Non-specific short-range devices	25	Polite access or 1%
47a	865	868	3	RFID	2000	Polite access only, no duty cycle
47b	865	868	3	Non-specific short-range devices	500	Polite access, and 10% (access point) or 2.5% (other devices)
48	868	868.6	0.6	Non-specific short-range devices	25	Polite access or 1%
49	868.6	868.7	0.1	Low duty cycle/high reliability devices	10	1%
50	868.7	869.2	0.5	Non-specific short-range devices	25	Polite access or 0.1%
51	869.2	869.25	0.05	Low duty cycle/high reliability devices	10	0.1%
52	869.25	869.3	0.05	Low duty cycle/high reliability devices	10	0.1%
53	869.3	869.4	0.1	Low duty cycle/high reliability devices	10	1.0%
54	869.4	869.65	0.25	Non-specific short-range devices	500	Polite access or 10%
55	869.65	869.7	0.05	Low duty cycle/high reliability devices	25	Polite access or 10%
56a	869.7	870	0.3	Non-specific short-range devices	5	None
56b	869.7	870	0.3	Non-specific short-range devices	25	Polite access or 1%

Currently, there are 5 types of frequency bands based on their application:

- *Radio Frequency Identification (RFID)* applications are based on tags and devices activating the tags for retrieval of information (1 frequency band).
- *Wideband data* applications use wideband modulation techniques (1 frequency band).
- *High duty cycle/continuous transmission* applications rely on low latency. For example, streaming and multimedia devices such as home entertainment systems, wireless headphones, wireless microphones, and assistive listening devices (1 frequency band).
- *Low duty/high reliability* applications are alarm and social alarm systems with a need for reliable communication (5 frequency bands).
- All other devices belong to the *non-specific* category (8 frequency bands).

3.2 Duty cycle limitations

Each of the frequency bands imposes limits to the maximum amount of time devices are allowed to transmit. These limits are defined in the form of (i) a duty cycle or (ii) polite spectrum access restrictions. The duty cycle is defined as the ratio of the cumulated sum of transmission time per observation period. This duty cycle limit is given by (1) where T_{obs} is the observation period and $\sum T_{\text{on}}$ the total allowed on air transmission time of the device within that period [18, 19]. The default duration of the observation period is 1 h, unless otherwise specified for the specific frequency band. Currently, all frequency bands use the default observation period of 1 h.

$$\text{DC}_{\text{max}} = \frac{\sum T_{\text{on}}}{T_{\text{obs}}} \tag{1}$$

Duty cycles range from 0.1% (3.6 s per hour) up to 10% (360 s per hour). Only transmission times of transmissions within that particular frequency band are included for the calculation of the duty cycle. This means that transmissions may occur in multiple bands simultaneously. By transmitting sequentially in multiple frequency bands, a larger maximum transmission time per hour can be achieved. The duty cycle does not have any restrictions how the transmissions should be spread out in time. It makes no distinction if transmission times are evenly spaced out or if the transmission time is used up at the beginning of the observation period and the rest of the interval waited out. The only thing that must be respected is the maximum duty cycle ratio itself. As such, devices are allowed to transmit using bursty traffic, e.g., transmitting 36 s and then waiting for 3564 s for a duty cycle of 1%. However, as the start of the observation period is not exactly defined, one must be cautious that such burst do not occur in the same observation period T_{obs} as shown in example c in Fig. 2.

3.3 Transmission power limitations

In addition to the duty cycle restrictions, there is also a limit on the transmission power. Transmission power limits range from 5 to 2000 mW. They are expressed in milliwatt (mW) or decibel-milliwatt (dBm). The conversion table for the most occurring maximum transmission power values is given in Table 2. The power values are defined here as Effective Radiated Power (ERP) values; the power that must be given to a reference half-wave dipole antenna to get the same electrical field strength as the actual device at the same distance in the direction of the antenna gain [20]. Another often used definition is Effective Isotropic Radiated Power (EIRP); the power that must be given to a reference isotropic antenna to get the

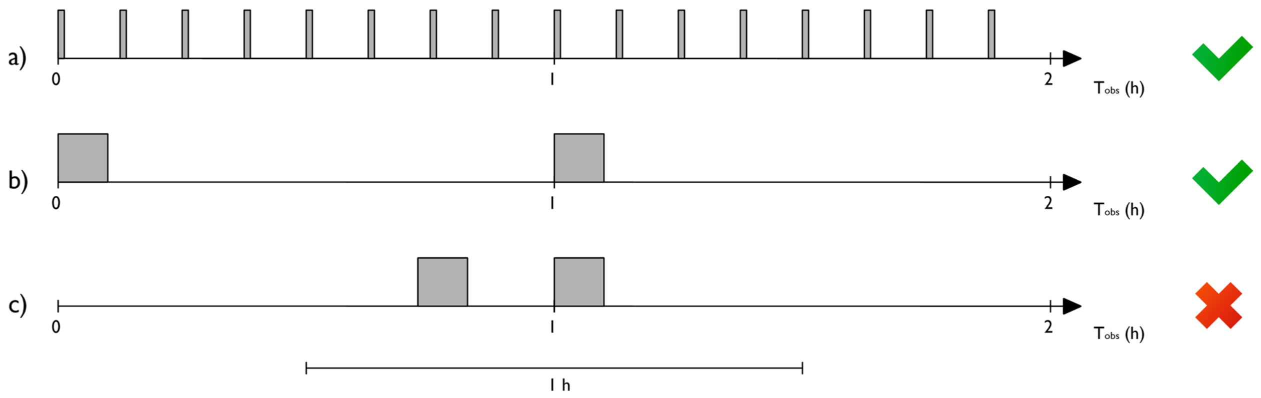

Fig. 2 Examples of how transmissions can be spread in time during the observation period T_{obs}. **a** Example of an evenly distributed spreading. **b** Example on the other hand of using all available transmission time in a single burst. **c** Also an example of using all available transmission time in a single burst, but due to the offset in the burst are there actually 2 burst in a single observation period T_{obs}. Therefore, the device in example **c** does not conform to the duty cycle regulations

Table 2 The most occurring maximum transmission power values in mW and dBm

mW	dBm
5	7
10	10
25	14
500	27
2000	33

The values have been rounded to often used integers

same electrical field strength as the actual device at the same distance. The EIRP and ERP can be converted into each other using (2) if the powers are expressed in dBm.

$$P_{\mathrm{EIRP}} = P_{\mathrm{ERP}} + 2.15\ \mathrm{dB} \qquad (2)$$

APC is required in frequency band $47\mathrm{b}_{(865\ \mathrm{MHz})}$[1] (see Section 3.5 and Table 3). This implies that an SRD adapts its transmission power when communicating to another SRD. The peak transmission power at the minimum setting of APC should not exceed 7 dBm ERP [21]. Although APC requires bi-directional communication to find out the used transmission powers, it is not defined how this should be implemented. Technologies for APC do exist, such as Adaptive Transmission Power Control (ATPC) [22], but are often solely focused on transmission quality and energy consumption instead of regulations.

3.4 Polite spectrum access

When an application uses polite spectrum access, the duty cycle restrictions are loosened. Polite spectrum access encompasses 2 aspects: Listen Before Talk (LBT) and Adaptive Frequency Agility (AFA) [21]. LBT defines that the device must listen if the medium is already in use by a Clear Channel Assessment (CCA) check. When the medium is in use, the device must wait a random backoff interval or change the frequency before checking again. The latter is called AFA. When these 2 aspects are implemented, the duty cycle is loosened to 100 s of cumulative transmission time per hour for each possible interval of 200 kHz, which corresponds to a duty cycle ratio of 2.7%. Since the regulations do not define the start and end point of these 200 kHz boundaries, all possible 200 kHz intervals should be considered[2]. Note that as a consequence, using polite spectrum access techniques is not beneficial for certain bands, for example $54_{(869.4\ \mathrm{MHz})}$ and $55_{(869.65\ \mathrm{MHz})}$, since these have duty cycle limitations of 10% which is higher than the 2.7% with polite spectrum access. A notable downside of polite spectrum access techniques is additional complexity, which often translates into increased hardware costs. For this reason, technologies such as LoRaWAN and SigFox do not support CCA and hence do not support polite spectrum access.

To be allowed to use the loosened duty cycle limit, devices implementing polite spectrum access techniques must also comply to other restrictions (Fig. 3) [21]. The CCA check must have a minimum duration of 160 µs. After this check, the device must wait for a *dead time* of maximum 5 ms before it may begin its transmission. The transmission itself has a maximum duration of 1 s or 4 s depending on the type of transmission. A transmission is defined as a continuous transmission or a burst of transmissions separated by intervals smaller than 5 ms. After the transmission, the application is banned from transmitting on that frequency for a minimum of 100 ms. It is however still allowed to use that interval for the next CCA interval or transmitting on other frequencies.

3.5 Frequency bands in practice

One of the most commonly used frequency bands is band $48_{(868\ \mathrm{MHz})}$ for non-specific SRDs. This is due to historical reasons: initially only a selection from the bands in Table 1 was available for non-specific SRDs, with heavier restricted duty cycle and power limitations [23]. Band $48_{(868\ \mathrm{MHz})}$ was the best candidate for LPWAN end devices, because it was the only band for non-specific SRDs with a 1% duty cycle ratio and at the same time a larger than average bandwidth of 600 kHz. Therefore, it became the band used by end devices of various popular technologies such as SigFox [24] and LoRaWAN [25]. Similarly, band $54_{(869.4\ \mathrm{MHz})}$ was selected by those technologies as the band for downlink communication by base stations, as it had the highest power and duty cycle limitations of all the then available frequency bands. Since a single base station needs to communicate with a large number of end devices, a large transmission power and higher duty cycle is important.

In addition to the above restrictions, several bands impose additional usage restrictions [18]. For example, some bands do not allow for analog video or audio, often with the exception of voice. Other examples are maximum allowed bandwidth limits, determined channel spacing, specific center frequencies or subchannels, or only allowing specific applications. Other documents, such as ERC Recommendation 70-03 [19], provide their own set of specific rules for certain frequency bands. The relevance and jurisdiction of each document is further elaborated on in Appendix B. An overview of these additional restrictions is given in Table 3.

3.6 EU regulatory institutes and documents

Various institutes on global, regional, and national level are responsible for SRD regulation. The International Telecommunication Union (ITU), on a global level, has not imposed any mandatory regulations, thus handing down this responsibility to institutes on a regional level. The ITU however defines some recommendations. For

Table 3 An overview of the extra restrictions on the available frequency bands for SRDs in the 863 to 870 MHz range [18]

Nr.	Start freq. (MHz)	End freq. (MHz)	Category	Other restrictions
46b	863	865	High duty cycle/continuous transmission devices	Only available to wireless audio and multimedia streaming devices
84	863	868	Wideband data	Only available for wideband SRDs in data networks
47	865	868	Non-specific short-range devices	Analog audio applications other than voice are excluded. Analog video applications are excluded
47a	865	868	RFID	Interrogator transmissions at 2 W e.r.p. are only permitted within the 4 channels centered at 865.7 MHz, 866.3 MHz, 866.9 MHz, and 867.5 MHz. Maximum bandwidth of 200 kHz
47b	865	868	Non-specific short-range devices	Only available for data networks. Transmissions only permitted within the bands 865.6-865.8 MHz, 866.2-866.4 MHz, 866.8-867.0 MHz, and 867.4-867.6 MHz. APC required alternatively other mitigation techniques with at least an equivalent level of spectrum compatibility
48	868	868.6	Non-specific short-range devices	Analog video applications are excluded
49	868.6	868.7	Low duty cycle/high reliability devices	Only available to alarm systems
50	868.7	869.2	Non-specific short-range devices	Analog video applications are excluded
51	869.2	869.25	Low duty cycle/high reliability devices	Only available to social alarm devices
52	869.25	869.3	Low duty cycle/high reliability devices	Only available to alarm systems
53	869.3	869.4	Low duty cycle/high reliability devices	Only available to alarm systems
54	869.4	869.65	Non-specific short-range devices	Analog video applications are excluded
55	869.65	869.7	Low duty cycle/high reliability devices	Only available to alarm systems
56a	869.7	870	Non-specific short-range devices	Audio and video applications are excluded
56b	869.7	870	Non-specific short-range devices	Analog audio applications other than voice are excluded. Analog video applications are excluded

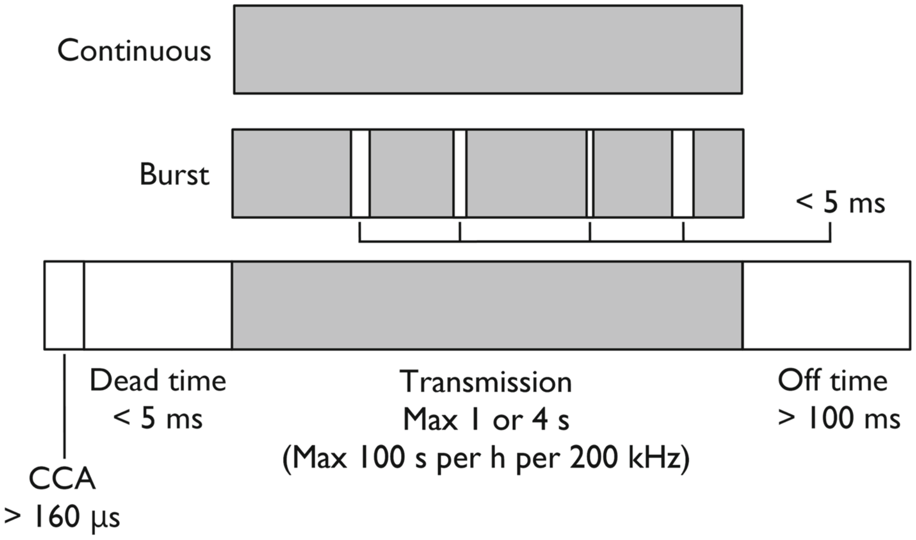

Fig. 3 A visual overview of the restrictions for polite spectrum access transmissions

example, Recommendation SM.1896 [26] recommends frequency ranges for the harmonization of SRDs. The ITU is also responsible for defining the license-free Industrial, Scientific and Medical (ISM) bands. Although the 863 to 870 MHz frequency range is often mistaken as an ISM band, it is actually not contained in any of the ISM bands defined for the European region, as shown in Table 8 in Appendix A.1.

At EU level, the SRD regulation is defined by the cooperation of 3 institutes: the European Commission (EC) for legislation, European Conference of Postal and Telecommunications Administrations (CEPT) for studies on technical measures, and European Telecommunications Standards Institute (ETSI) for standardization. The laws created by the EC are the only truly legally binding deliverables. Other documents often referred to in literature, such as ERC Recommendation 70-03 and the harmonized standard EN 300 220, are voluntarily but could offer advantages to manufacturers to create compliant radio equipment.

A thorough overview of all institutes involved in drafting LPWAN SRD regulation and their interactions with each other is provided in Appendix A. Appendix B.1 gives a full description of the EU legislatory acts relevant to LPWAN SRDs and their consequences. Deliverables ERC Recommendation 70-03 and EN 300 220 are further elaborated in Appendix B.2.

3.7 Recent evolutions

CEPT is mandated by the EC to yearly evaluate the frequency allocation table in EU law [18] and to propose modifications if necessary [27]. The latest CEPT Report [28] contains among others multiple alterations and additions to the frequency allocation table regarding SRDs in the 800+ MHz range:

- The extension of the frequency bands for SRDs with extra bands in the 862 to 863 MHz, 870 to 876 MHz, and 915 to 921 MHz ranges [29]. This introduces additional spectrum for SRDs and reduces the risk of interference and congestion in current bands. This has already been implemented by introducing additional frequency bands for SRDs in the 874 to 876 MHz and 915 to 921 MHz range.
- The definition of the duty cycle is broadened to allow for an individual observation time[3] per frequency band. The default is still 1 h, unless explicitly specified. This has already been implemented.
- The renaming of SRD categories. The frequency bands assigned to the low duty cycle/high reliability category are re-assigned to the non-specific SRD category, but keep the usage restrictions that these bands may only be used for (social) alarms. This usage restriction will be adapted later to more specific parameters (e.g., duty cycle, channeling, or access parameters) after more research has been conducted by CEPT and ETSI to allow for broadening the future usage based on technical parameters instead of application type. The frequency band belonging to the category low latency/continuous transmission will also be renamed to wireless audio and multimedia streaming systems.
- The merge with RFID regulation, introducing a frequency band for RFID. This has already been implemented by the addition of $47a_{(865\ \mathrm{MHz})}$.

The most notable suggestion of the CEPT report is the addition of extra frequency bands. The rising usage of SRDs and the increasing need for radio spectrum, caused CEPT to investigate for countermeasures against radio spectrum congestion and harmful interference. As a result, ranges 862 to 863 MHz, 870 to 876 MHz, and 915 to 921 MHz were selected for further research as these are mostly underused by CEPT member states [30, 31]. Furthermore, the 915 to 921 MHz range falls within the region 2 ISM band of the ITU, which has been adopted in various other parts of the world (e.g., Australia, New Zealand, Singapore, Vietnam, Malaysia, Japan, South Africa, and the USA). The usage of the 915 to 921 MHz frequency range thus improves global harmonization, and compatibility between EU members and other states. As a response, the EU has introduced 5 additional frequency bands in the 874 to 876 MHz and 915 to 921 MHz range: 2 for non-specific SRDs, 1 for wideband data applications, and 1 for RFID [32]. An overview of these bands can be seen in Tables 4 and 5, and Fig. 4.

Most of these recently added frequency bands were already in use by some member states for other applications, such as extension bands for Global System for Mobile communications for Railways (GSM-R) or for military use. Some member states are thus allowed to not implement some of these frequency bands in order to keep their usage of those frequency bands. This is possible as the Radio Spectrum Decision [33] dictates that EU regulation may not interfere with the usage of radio equipment by member states for governmental, security, or defense purposes. To reduce further fragmentation, EU Member states are therefore not allowed to introduce new uses in the 874.4 to 876 MHz and 919.4 to 921 MHz range.

4 Examples of LPWAN technologies and how they cope with duty cycle restrictions

Current technology on the market in the EU region must comply to the regulations described above. An overview of the use of frequency bands in the 863 to 870 MHz range by these technologies is given in Fig. 5. Additonally, an overview of the characteristics of uplink communication for these technologies is given in Table 6.

Table 4 An overview of the recently added frequency bands for SRDs in the 874 to 876 MHz and 915 to 921 MHz range [32]

Nr.	Start freq. (MHz)	End freq. (MHz)	Bandwidth (MHz)	Category	Max TX power (mW) (e.r.p.)	Duty cycle
1	874	874.4	0.4	Non-specific short-range devices	500	Polite access, and 10% (access point) or 2.5% (other devices)
2	917.4	919.4	2	Wideband data	25	Polite access, and 10% (access point) or 2.8% (other devices)
3	916.1	918.9	2.8	RFID	4000	Polite access only, no duty cycle
4	917.3	918.9	1.6	Non-specific short-range devices	500	Polite access, and 10% (access point) or 2.5% (other devices)
5	917.4	919.4	2	Non-specific short-range devices	25	Polite access and 1%

4.1 SigFox

SigFox is an Ultra Narrow Band (UNB) technology that uses a low rate of small-sized messages to achieve great distance [7, 24, 34, 35]. While it is mainly focused on uplink communication, it also supports a limited form of downlink communication. End devices communicate with SigFox base stations and their messages are pushed on the SigFox cloud. From here, they are delivered to the client infrastructure. The SigFox protocol is closed as the base stations and cloud are in the hands of SigFox operators and SigFox itself. Clients can use the SigFox network by buying a subscription. End devices of the client must be certified by SigFox to be able to use the SigFox network.

Up- and downlink communication each use a different modulation scheme and frequency range. Uplink communication uses a 192 kHz wide frequency interval from 868.034 to 868.226 MHz. All uplink communication thus falls into the range of the $48_{(868\ \mathrm{MHz})}$ frequency band with a limit of 25 mW transmission power and 0.1% duty cycle. As SigFox does not use polite spectrum access techniques, it is bound to the maximum transmission power and duty cycle of the frequency band. End devices use a transmission power up to 25 mW. In order to comply with the maximum allowed duty cycle, SigFox limits the maximum allowed transmissions for up- and downlink messages per day by its subscription model. The most extensive

Table 5 An overview of the extra restrictions on the recently added frequency bands for SRDs in the 874 to 876 MHz and 915 to 921 MHz range [32]

Nr.	Start freq. (MHz)	End freq. (MHz)	Category	Other restrictions
1	874	874.4	Non-specific short-range devices	Only available for data networks. All devices must be controlled by access points Maximum bandwidth of 200 kHz. APC required, alternatively other mitigation techniques with at least an equivalent level of spectrum compatibility
2	917.4	919.4	Wideband data	Only available for wideband SRDs in data networks. All devices must be controlled by access points. Maximum bandwidth of 1 MHz
3	916.1	918.9	RFID	Interrogator transmissions at 4 W e.r.p. are only permitted within the four channels centered at 916.3 MHz, 917.5 MHz, and 918.7 MHz. Maximum bandwidth of 400 kHz
4	917.3	918.9	Non-specific short-range devices	Only available for data networks. All devices must be controlled by access points Transmissions only permitted within the bands 917.3–917.7 MHz and 918.5–918.9 MHz. Maximum bandwidth of 200 kHz. APC required, alternatively other mitigation techniques with at least an equivalent level of spectrum compatibility
5	917.4	919.4	Non-specific short-range devices	Only available for wideband SRDs in data networks. All devices must be controlled by access points. Maximum bandwidth of 600 kHz

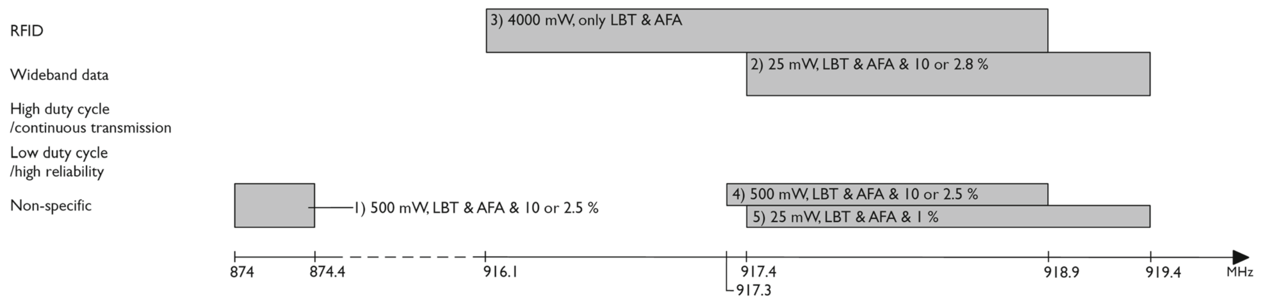

Fig. 4 A visual overview of the recently added frequency bands for SRDs in the 874 to 876 MHz and 915 to 921 MHz range. The maximum transmission power (in mW) and maximum duty cycle (in %) are mentioned for each band

subscription, the *platinum* model, allows for 140 up- and 4 downlink messages a day. When an uplink message is sent, it is transmitted 3 times on different frequencies one after another, as can be seen in Fig. 6. The frequency of each transmission is randomly selected within the 192 kHz wide interval, and each transmission uses only around 100 Hz of bandwidth. This scatters the messages in both the time and the frequency domain to avoid collisions with other transmissions. SigFox relies on the UNB character of its technology as a collision mitigation technique.

It takes about 6.24 s (T_m) to send a SigFox uplink message with a full payload *PL* of 12 bytes, totaling up to a message size *MS* of 26 bytes, and a data rate *DR* of 100 bps (3). By subscription limits, a device can send 140 uplink messages per day and thus have a daily on air time of 873.6 s. The duty cycle of 1% allows for a transmission time of 36 s per hour or 864 s per day. As can be seen from the results, SigFox actually allows 9.6 s of transmission time more than allowed by the regulatory limits. The subscription model does not explicitly mention a limit of uplink messages per hour. The 36 s allowed by the duty cycle allow for the transmission of 5.77 messages, which boils down to a limit of 5 messages per hour. SigFox actually overshoots the regulations to 6 messages per hour with 1.44 s per message, which can violate the regulatory limits if all messages are sent with a full payload. Ultimately, SigFox can blacklist end devices who regularly ignore the limits.

$$T_m = 3\left(\frac{8\text{MS}}{\text{DR}}\right) \tag{3}$$

SigFox base stations use frequency band $54_{(869.4\text{ MHz})}$ for downlink communication. The base stations profit from the high regulatory limits of this band. The high maximum allowed transmission power allows to send messages over larger distances, while the high duty cycle offers room for communication with a high number of devices. Although the small bandwidth is the biggest drawback of this frequency band, this has little impact on the operations of the base stations due to the UNB character of the communications.

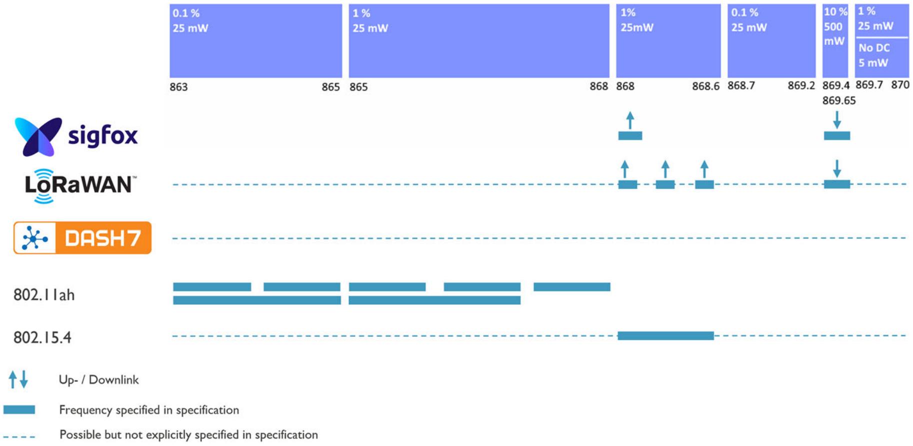

Fig. 5 An overview of the use of frequency bands in the 863 to 870 MHz range by various sub-GHz technologies

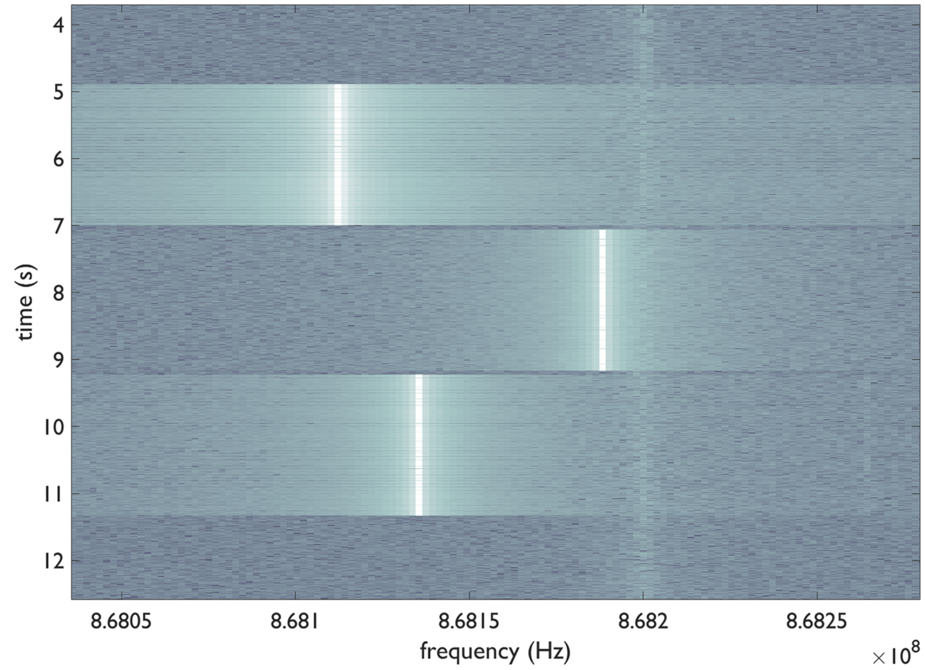

Fig. 6 A single SigFox message. Every message is transmitted 3 times on randomly selected frequencies one after another

4.2 LoRaWAN

LoRaWAN is a star-of-stars topology LPWAN technology based on the LoRa physical layer developed by Semtech [34, 36]. The LoRa layer uses Chirp Spread Spectrum (CSS) as modulation. Similar to SigFox, it allows for both up- and downlink communication, but with a strong optimization towards for uplink communication. The data rate of LoRaWAN transmissions can vary and can be adapted on the fly by the network to avoid packet loss or reduce power usage.

The LoRaWAN specification is split in a general [37] and regional document [25]. The general specification explains the inner workings of the protocol. As LoRaWAN aims to be used internationally, it must take into account the differences in regulations between various regions in the world. Therefore, all parameter values related to regional regulations have been moved to the regional specification. This supplements the general specification and prevents that a new version of the specification should be released for every change in regional regulation. Both the general and regional specification acknowledge the presence of spectrum regulation and remind the user that it is their responsibility to meet these regulations, aided by the information and parameter limits in the regional specification.

By the regional specifications, all LoRaWAN end devices in the EU region are required to support at least 3 default channels in the $48_{(868\ \mathrm{MHz})}$ frequency band for uplink communication, with center frequencies of 868.1, 868.3, and 868.5 MHz. Similar to SigFox, LoRaWAN does not use any polite spectrum access techniques. Although each uplink message is sent through a pseudo-randomly selected channel, this is not sufficient to be considered as an LBT & AFA polite spectrum access technique. End devices must therefore oblige to the 1% duty cycle limit. However, the regional specifications mention that all LoRaWAN devices in the EU region should be able to support channels in the whole 863 to 870 MHz range. This allows end devices to allocate channels in other frequency bands than $48_{(868\ \mathrm{MHz})}$ to reduce the constraints of the regulatory duty cycle limits. All EU LoRaWAN devices are required to be able to store 16 channels, with support for in total 8 different frequencies (including the default frequencies). Furthermore, the regional specifications specify the default maximum output power as 25 mW for end devices, which corresponds to the maximum output power of frequency band $48_{(868\ \mathrm{MHz})}$. Although the regional specifications also allow for an output power of 100 mW, the user is reminded that it is his responsibility to not exceed the regional regulatory limits. This value should hence only be used in frequency bands such as $54_{(869.4\ \mathrm{MHz})}$. Other parameters specified by the regional parameters for EU end devices are the preamble format, data rate and output power configurations, maximum payload sizes, and default settings.

The LoRa layer uses chirps to transmit symbols, as can be seen in Fig. 7. A chirp is an interval in which the transmission frequency is periodically increased. When it reaches the upper limit of the frequency channel, it overflows to the minimum limit and continues to

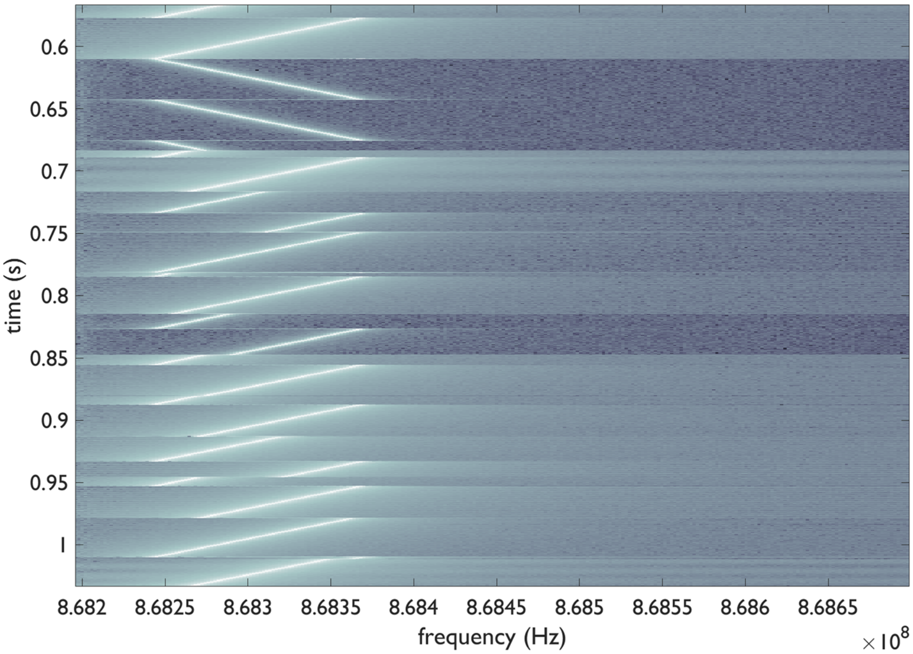

Fig. 7 An extract of a LoRaWAN message using CSS modulation

increase from there. The chirp is completed when the start frequency has been reached. Because of the spreading with spreading factor *SF*, every symbol will be a series of 2^{SF} chirps. Semtech sets the chirp speed equivalent to the used bandwidth, so a bandwidth BW of 100 kHz results in a chirp rate CR of 100 kcps. Using this information, the time on air for a single chirp can be calculated as BW^{-1}. The time T_s to transmit a single symbol is thus

$$T_s = \frac{2^{\mathrm{SF}}}{\mathrm{CR}} = \frac{2^{\mathrm{SF}}}{\mathrm{BW}} \tag{4}$$

The maximum time on air for a single LoRaWAN message can then be calculated using (5) (7) (8) [38, 39]. Equation (5) calculates the time on air of the preamble T_p, (7) the amount of symbols of the message n_m, and (8) the time on air T_m of the complete transmission.

$$T_p = (n_p + 4.25)T_s \tag{5}$$

$$n_t = \left\lceil \frac{8\mathrm{PL} - 4\mathrm{SF} + 28 + 16 - 20H}{4\mathrm{SF} - 8\mathrm{DE}} \right\rceil \tag{6}$$

$$n_m = 8 + \max((n_t(\mathrm{CR} + 4)), 0) \tag{7}$$

$$T_m = T_p + n_m T_s \tag{8}$$

The parameters are as follows:

- n_p is the amount of preamble symbols, which is 8 for EU end devices according to the regional specifications.
- PL indicates the number of payload bytes. The maximum payload size is defined in the regional specifications and ranges from 59 to 250 bytes for EU end devices depending on the use of repeaters and certain header fields.
- H is equal to 0 if the LoRa header is present, 1 otherwise. LoRaWAN always uses the header, so this should be 0.
- DE is 1 if low data rate optimization is enabled, 0 otherwise. This is used when SF is equal to 11 or 12, to account for oscillator drifts.
- CR is the coding rate and is often expressed as a ratio. Here, CR is a value in the range of 1 to 4 to calculate the coding rate as 4/(1 + CR).

The outcome of these equations can be used to get an estimate about the time on air per message and the amount of messages that can be sent within the duty cycle regulations. One must keep in mind that LoRaWAN transmissions cannot follow one after another directly. According to [37], an end device must wait to transmit until it has received a downlink transmission or the second receive window for downlink transmissions has passed. As shown in Fig. 8, each LoRaWAN uplink transmission is followed by two windows for downlink communication. The recommended values for RECEIVE_DELAY1 and RECEIVE_DELAY2, 1 s and 2 s respectively, are provided by the regional parameters [25]. A receive window must be at least long enough to be able to

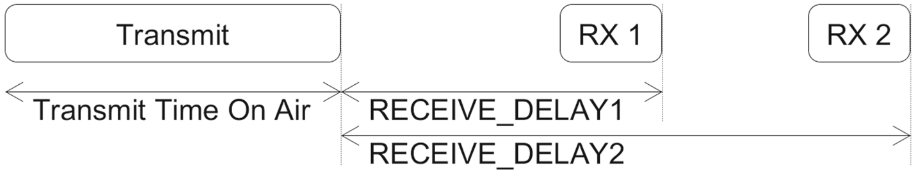

Fig. 8 A LoRaWAN uplink message, followed by its 2 receive windows for downlink communication [37]

detect a downlink preamble. The waiting time is not considered as transmission time T_{on} for the duty cycle regulations.

As downlink communication can only occur during the two downlink windows after an uplink transmission for class A devices, this could have a significant impact on the network. As soon as an end device has saturated its duty cycle, it cannot transmit uplink messages and thus not receive downlink messages. The communication is thus interrupted in both ways for the remainder of the duty cycle interval. As base stations are also limited to duty cycle regulations, it is unsure how many devices can be supported by a single station. Base stations answer in the same channel of the uplink message or a default channel in frequency band $54_{(869.4\ \mathrm{MHz})}$, depending if respectively the first or second downlink slot is used. The maximum amount of downlink messages according to duty cycle regulations thus depends on the end devices and their uplink frequency. When using class B end devices, which use extra slots for downlink communication, base stations also broadcast beacons in the default channel which also reduces the amount of possible downlink communication on the default channel.

4.3 DASH7

DASH7 is a full-stack solution based on RFID technology. According to the specification [40], DASH7 complies fully with regulations from all major regions. Contrary to SigFox and LoRaWAN, DASH7 uses LBT and AFA as polite spectrum access techniques to access the medium. This means that instead of having to adhere to the set duty cycle limit, DASH7 can benefit from the 100 s per 1 h per 200 kHz boundary described in Section 3.2.

DASH7 defines 3 types of channels: *lo-rate*, *normal*, and *hi-rate*. These types each have their own channel spacing, modulation, and data rate. The 863 to 870 MHz range is divided in 280 lo-rate channels with a width of 25 kHz and 207 normal/hi-rate channels with a width of 0.2 MHz. All normal and hi-rate channels fall within the frequency bands for non-specific SRDs, as shown in Table 7. However, a number of lo-rate channels also overlap with frequency bands reserved for low duty cycle/high reliability devices, as they fill the whole continuous 863 to 870 MHz range. Only DASH7 devices used as (social) alarms are allowed to function in those frequency bands. This applies to the ranges 868.6 to 868.7

Table 6 An overview of the characteristics of uplink communication by SigFox, LoRaWAN, and DASH7 [24, 25, 35, 37, 40]

	SigFox	LoRaWAN (according to EU regional parameters)	DASH7
Modulation	Differential Binary Phase Shift Keying (DBPSK)	CSS / CSS / Gaussian Frequency Shift Keying (GFSK)	2-GFSK
Max. total message size (bytes)	26	256	256
Max. payload size (bytes)	12	59 to 250	251
Data rate (kbps)	0.1	0.3 to 50	9.6 (lo-rate), 55.555 (normal), 166.667 (hi-rate)
Max. transmission power (mW)	25	100 (limited by the relevant regulatory limit, default 25 for end devices)	Limited by the relevant regulatory limit
Bandwidth (kHz)	0.1	125	25 (lo-rate), 200 (normal, hi-rate)
Freq. range (MHz)	868.034 to 868.226 (192 kHz)	863 to 869.95 (with default center frequencies at 868.1, 868.3, and 868.5 for uplink communication and 869.525 for downlink communication)	863 to 870 (lo-rate), 863 to 870 with the exception of 868.6 to 868.725, 868.925 to 868.975, 869.175 to 869.425, and 869.625 to 869.75 (normal, hi-rate)

Table 7 An overview of the normal/hi-rate DASH7 channels and the corresponding regulatory frequency bands

Channel Index	Start freq. (MHz)	Center freq. (MHz)	End freq. (MHz)	Regulatory freq. band
0	863	863.1	863.2	$46a_{(863\ \text{MHz})}$
8	863.2	863.3	863.4	$46a_{(863\ \text{MHz})}$
16	863.4	863.5	863.6	$46a_{(863\ \text{MHz})}$
⋮	⋮	⋮	⋮	$46a_{(863\ \text{MHz})}$, $47_{(865\ \text{MHz})}$, $47b_{(865\ \text{MHz})}$, and $48_{(868\ \text{MHz})}$
216	868.4	868.5	868.6	$48_{(868\ \text{MHz})}$
229	868.725	868.825	868.925	$50_{(868.7\ \text{MHz})}$
239	868.975	869.075	869.175	$50_{(868.7\ \text{MHz})}$
257	869.425	869.525	869.625	$54_{(869.4\ \text{MHz})}$
270	869.75	869.85	869.95	$56a_{(867.7\ \text{MHz})}$ and $56b_{(867.7\ \text{MHz})}$

MHz (channels 224 to 227), 869.2 to 869.4 MHz (channels 248 to 255), and 869.65 to 869.7 MHz (channels 266 and 267).

The loosened duty cycle interval conveniently matches the bandwidth of normal and hi-rate channels, thus allowing to make optimal use of the loosened duty cycle. However, most frequency bands designated for low duty cycle/high reliability devices do not permit the use of the 100 s duty cycle, thus disabling this optimization for some lo-rate channels.

5 Future research directions

In this section, we discuss some open problems and research challenges caused by EU regulatory restrictions for LPWAN SRDs. As the transmission power limitation is a simple fixed value, most of the challenges will revolve around the selection of regulatory frequency bands and coping with the duty cycle limit.

Although the technologies discussed up until now are well-known LPWAN technologies, the scope of this section will be expanded to include other non-LPWAN SRD technologies using the 863 to 870 MHz range. For example, the IPv6 over the Time Slotted Channel Hopping (TSCH) mode of IEEE 802.15.4e (6TiSCH) technology stack [41], shown in Fig. 9, and its various components such as among others IPv6 Routing Protocol for Low-Power (RPL) and Lossy Networks and TSCH are often used by SRDs in the 863 to 870 MHz range to create mesh networks. As these mesh networks use multi-hop communication and routing, they are more vulnerable to the negative effects of duty cycle regulations. A comparison between LPWAN and the 6TiSCH technology stack can be found in [43]. Furthermore, research is ongoing to mix both LPWAN and multi-hop communication protocols. For example, [44–47] present solutions to enable multi-hop communication on LoRa technology, where [48] also aims to enable RPL routing. Next, work is in progress by the IEEE 802.15 WPAN$^{\text{TM}}$ Task Group 4w (TG4w) [49] to amend IEEE 802.15.4 with LPWAN capabilities, naming the amendment IEEE 802.15.4w [50].

5.1 Impact on the network and higher layers

Saturation of duty cycled devices could have a significant effect on network performance. (i) When a receiving device is saturated, it will not be able to respond to any acknowledgements. This will be interpreted by the network as packet loss, leading to retransmissions and changes in network routing topology. (ii) In addition, duty cycle regulations could impose delays in network performance, as devices must be cautious when to send and how much. Measures such as spreading out messages during the duty cycle interval introduce a delay in network throughput, which could again lead to retransmissions. For example, this could occur when sending a Constrained Application Protocol (CoAP) GET request [51]. The upper CoAP layer at the sending device will time-out after a while due to a lack of a CoAP acknowledgement message and retransmit the CoAP GET request.

Both effects cause a snowball effect, as retransmissions push other devices to their own saturation limits. If the sending device was also already on the verge of saturation, it could be pushed into saturation by the retransmissions. This effect could also be enhanced by the combination of multiple technologies demanding acknowledgements on different layers. For example, when the device uses both IEEE 802.15.4 and CoAP, then a CoAP retransmission will force multiple retransmissions on the IEEE 802.15.4 layer. Whenever a device reaches saturation, it is considered lost by the network and the routing information in the network must be adjusted. With non-LPWAN setups, the additional overhead by routing protocols such as RPL could cause a significant overhead, wasting the transmission time of several devices in the network [52–54] and forcing them to saturation. Similar effects could be seen

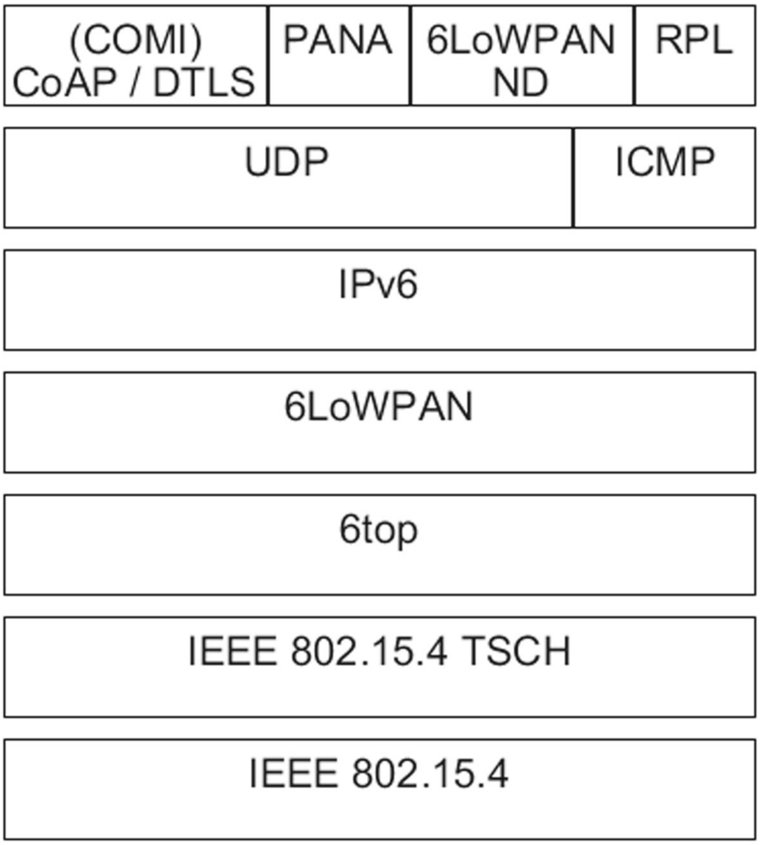

Fig. 9 An overview of the 6TiSCH stack [42]

when devices frequently drop in or out the network due to duty cycle regulations or other causes, resulting each time in routing adjustment overhead on the network.

5.2 The use of multiple frequency bands as a mitigation technique

As the duty cycle in each frequency band poses a limit, a solution would be to combine the use of different regulatory frequency bands. Unfortunately, this is not a possible solution for SigFox as SigFox uses only a single regulatory frequency band for uplink communication. At the contrary, LoRaWAN devices must be able to support channels in the whole 863 to 870 MHz range and are thus able to combine channels from multiple regulatory frequency bands. LoRaWAN devices are also capable of defining new channels through on-the-air updates, which could be used to migrate its traffic to other regulatory frequency bands. Similarly, DASH7 also supports channels in the 863 to 870 MHz range and is therefore also able to use multiple regulatory frequency bands.

As an example for non-LPWAN technologies, TSCH [55] could be improved to incorporate the use of multiple regulatory frequency bands. TSCH uses a slotframe where slots are assigned to pairs of devices. During each iteration of the slotframe, each slot is assigned a channel in a pseudo-randomly manner. However, the assignment of pairs of devices to slots and the definition of the bandwidth of channels and timings of the slotframe is left to the user. This leaves a possibility to adjust these parameters to the regulatory frequency bands. For example, the channels could be mapped to the bandwidth ranges of various regulatory frequency bands. Rizzi [56] proposes a LoRaWAN adaptation to apply a TSCH-like approach. This could bring these optimalisations to LPWAN technology, although this is not yet explicitly explored in [56].

Additionally, the 6TiSCH Operation Sublayer (6top) layer in the 6TiSCH stack allows devices to dynamically adjust the slotframe scheme in the TSCH slotframe by the use of a scheduling function [57]. The implementation of a scheduling function is left to the user. This scheduling function could be used to adapt the slotframe scheme to the duty cycle of each device. For example, devices who approach full saturation could be assigned less and less time slots in the slotframe scheme as they approach their point of saturation. This would force the device to reduce transmissions and would free up time slots in the slotframe scheme to other devices who are still far from their point of saturation.

Solutions have been proposed to extend TSCH with adaptive channel selection to omit channels with interference. Du and Roussos, Tavakoli et al., and Kotsiou et al. [58–60] blacklist undesirable channels based on interference. Such techniques could be adapted to blacklist channels for devices who are saturated in certain regulatory frequency bands. Another possible technique would be to incorporate additional input into the pseudo-randomly selection to reduce the assignments of channels belonging to regulatory frequency bands nearing saturation. Implementations for such adaptive channel selection already exist [61], but are not yet adapted to duty cycle regulations.

5.3 Possible actions for SRDs nearing saturation

As can be seen in Section 4, current technologies do not contain specific features to prevent any type of saturation or to reduce the impact of saturation on the network. SigFox simply limits the amount of messages due to their subscription model. As uplink communication happens in a single regulatory frequency band, SigFox devices can only be fully saturated. Once saturation is reached for a device, no more transmissions can occur from that device. Due to the proprietary character of SigFox, it is not possible to adapt its technology. LoRaWAN and DASH7 on the other hand leave it up to the user and upper layers to adhere to regulation and to prevent and respect saturation. However, DASH7 selects a channel prior before transmission and checks if the medium is accessible through Carrier-Sense Multiple Access Collision Avoidance (CSMA-CA). If the channel is in use, it retries the transmission process on another randomly selected channel. By editing this selection process to keep track of the transmission times to the different 200 kHz frequency intervals for polite spectrum access techniques, DASH7 could be adapted to better handle duty cycle regulations and prevent saturation. LoRaWAN also uses a pseudo-random channel hopping technique which could also be adapted to better suit the duty cycle regulations. By defining new channels through on-the-air updates, LoRaWAN could move its traffic to away from saturated regulatory frequency bands or change its physical layer (PHY) parameters when nearing saturation. Even on higher levels, mitigating actions can be developed. For example, when a device detects it is nearing saturation, it could alert its neighbors or a central authority. This would allow the network to change its routes or used frequency ranges to prevent cutting of a part of that network. There is still much room for further research into and the implementation of mitigating features regarding duty cycle limitations for such technologies. For example, models such as [62] are being proposed to adapt existing technologies to duty cycle regulations. Sandoval et al. [62] uses Markov Decision Processes (MDP) to derive an optimal transmission policy for LoRaWAN and SigFox to maximize the number of reported events according to their priority, while staying conform to the duty cycle regulations. This model is usable on constrained nodes, but currently only keeps a single regulatory frequency band in mind.

5.4 Efficient monitoring of duty cycled devices

Each SRD should at least be able to keep track of their own cumulative transmission time $\sum T_{\mathrm{on}}$ (1) per regulatory frequency band to prevent it from exceeding the regulatory duty cycle limits. This could also be used to detect nearing saturations and to use the last available transmission time for any mitigating actions.

To enable mitigating actions on a network level, it is essential to introduce monitoring on a higher level than the device itself. Such monitoring could be implemented in a centralized or decentralized manner. However, such monitoring solutions rely on additional wireless transmissions and thus could potentially increase the duty cycle problem. For example, [63] introduce a piggyback mechanism that integrates with IEEE 802.15.4 to retrieve network information. Since the act of collecting such information by itself also results in additional traffic, additional research is needed to analyze the overhead versus the benefits of centralized duty cycle monitoring in sub-GHz networks.

5.5 Heterogeneous spectrum monitoring

To collect spectrum data and to detect devices violating the regulatory limits, a central repository would be useful similar to tv-whitespace databases. However, rather than deploying additional devices, this repository should ideally be populated using the different heterogeneous devices that have already been deployed.

At the moment however, heterogeneous spectrum sensing still has its own challenges according to [64]. (i) As the spectrum sensing is done by different types of devices, the data of each of the devices could be stored in different types of formats (text, binary, ...) which makes it harder to aggregate and interpret the data. For example, there is often a lack of meta information containing device details such as the used technology, a description of the involved devices, and used signals. This could be mitigated by the introduction of a uniform storage mechanism. Next, (ii) the measuring resolution could be different between the various sensing devices in both the time and frequency domain. Collected data could therefore not be meaningful compared to one another, which makes it difficult to process and interpret. Therefore, effort should be put in defining a common resolution. (iii) In a similar way, there is often a mismatch in calibration between the different devices, thus defining the need for a common calibration reference to calibrate all the devices. Finally, (iv) as the different devices generate a large amount of data, there is a need for an efficient processing method to handle this data. Liu et al. [64] proposes methodologies to cope with some of these challenges.

5.6 Impact of PHY parameters

As the duty cycle limits the transmission time T_{on} of a device (1), one should also take into consideration the parameters of the physical layer. For example, IEEE 802.15.4-2015 [55] enabled devices can choose various PHY parameters. Smart Utility Network (SUN) Frequency Shift Keying (FSK) devices can choose from three operating modes; 50, 100, or 200 kbps. A larger data rate means shorter transmission times per message, but reduces the transmission range. One must also not forget the additional PHY fields attached to the transmission as these also contribute to the transmission time, such as among others the preamble, Start-of-Frame Delimiter (SFD), PHY header, and Forward Error Correction (FEC). The same goes for technologies such as LoRaWAN and DASH7. LoRaWAN can adapt its data rate on the fly, thus changing the time on air for its messages. DASH7 also has access to 3 different types of channel classes with a different data rate for each. These constructs can be leveraged to create adaptive PHYs in regard to their duty cycle status. Further research is still needed to automatically characterize the throughput, range, and duty cycle trade-offs and to automatically adjust the PHY parameters while keeping in mind these constraints.

Another solution would be the construction of SRDs with multiple PHYs, so that the device could switch to a different PHY depending on traffic needs and duty cycle limits. According to [16], this comes with its own challenges such as adaptations to routing protocols, the need for hand-over mechanisms, challenges for optimization, and a need for a virtualized LPWAN interface. Famaey et al. [65] proposes an architecture that uses such a multimodal device.

As already mentioned, the IEEE is currently developing an LPWAN amendment to the IEEE 802.15.4 standard, called IEEE 802.15.4w, which is based on the low-energy, critical infrastructure monitoring (LECIM) FSK PHY modulation scheme [50] already present in IEEE 802.15.4. IEEE 802.15.4w will introduce features such as frequency-hopping spread spectrum (FHSS) and low-density parity check (LDPC). It is expected that devices using IEEE 802.15.4 will be able to adapt to IEEE 802.15.4w by software modifications only. Currently, there is little academic literature on the IEEE 802.15.4w protocol and its performance, thus leaving opportunities for further research.

6 Conclusions

This paper gave an overview of the available frequency bands for various categories of SRDs. These frequency bands are specified by maximum duty cycle and maximum transmission power parameters. To remedy the duty cycle restriction, it is possible to use a combination of different frequency bands, or to use polite spectrum techniques. The latter reduces the duty cycle to 2.7% per 200 kHz interval, but is also bound to timing parameters. Eventually, we looked at the recent alterations to the regulations which mainly involve the addition of extra frequency bands in the 874 to 876 MHz and 915 to 921 MHz ranges.

Next, we have discussed 3 commonly used technologies and how they cope with the regulations. SigFox depends on a subscription model to keep the transmission time within duty cycle restrictions. The LoRaWAN specification mentions that it is the user's responsibility to respect the regulations. Its specification is split in a general and a regional part. The regional specification describes various parameters and settings for each region to help the user to comply to SRD regulation. DASH7 also relies on the user to respect the regulatory restrictions. Contrary to SigFox and LoRaWAN does DASH7 rely on polite spectrum techniques; therefore, it is able to use the loosened duty cycle restriction.

Additionally, we have identified some open research challenges regarding the regulatory limits, such as the impact on higher layers, mitigating the duty cycle restriction by using multiple frequency bands together, possible actions for when an SRD nears saturation, how SRDs violating the regulations can be detected, adaptations necessary to heterogeneous spectrum monitoring, and the impact of PHY parameters on duty cycle restricted SRDs.

Finally, more information regarding the relevant institutes and legislation can be found in Appendix A and B, allowing researchers to find relevant rulings in the sometimes confusion range of documents that is available.

We hope that this paper will be useful for researchers and manufacturers to find their way through the regulatory landscape, to achieve the best possible performance while remaining compliant to EU SRD regulations, and to inspire them towards relevant research driven by the imposed constraints.

Endnotes

[1] This paper uses the following notation for frequency bands in Tables 1 and 3: $number_{(start\ frequency\ \mathrm{MHz})}$. For example, band 48 from 868 to 868.6 MHz will be noted as $48_{(868\ \mathrm{MHz})}$.

[2] Similar to the issue of T_{obs} in the time domain for the duty cycle restriction, as shown in Fig. 2.

[3] T_{obs} in (1)

Appendix A: Institutes involved in drafting EU regulations for SRDs

The law for spectrum allocation in EU member states is the result of different institutes on various levels. (i) At the top level, global standardization institutes issue global standards and regulations in the form of international treaties. (ii) At European level, those treaties are implemented in EU law and then converted into national law by EU member states. (iii) Each member state has a National Regulatory Authority (NRA) for monitoring spectrum usage and enforcing regulation.

A.1 Global

The most prominent global institute for spectrum management is the ITU. The ITU is the United Nations specialized agency for information and communication technologies since 1949 [66]. It has been founded in 1865 and at the moment contains around 1000 members. Among those members are 193 countries, meaning that almost every country in the world is a member of ITU [67]. The ITU is composed out of 3 sectors: the Radiocommunication Sector (ITU-R), the Telecommunication Standardization Sector (ITU-T), and the Telecommunication Development Sector (ITU-D). Of these sectors, the ITU-R is responsible for the allocation of the radio spectrum.

The allocation of radio spectrum by the ITU-R is defined in the Radio Regulations (ITU-RR) [68]. This collection of documents is reviewed, appended, or revised every 3 to 4 years during a World Radiocommunication Conference (WRC). The ITU-RR divides the world into 3 large regions as shown in Fig. 10, where the EU belongs to region 1. Article 5 of the ITU-RR contains the frequency allocations.

Table 8 An overview of the ISM frequency bands defined by the ITU-RR [68]

Start freq.	End freq.	Center freq.	Remarks
6.765 MHz	6.795 MHz	6.780 MHz	
433.05 MHz	434.79 MHz	433.92 MHz	Only in most countries belonging to region 1
61 GHz	61.5 GHz	61.25 GHz	
122 GHz	123 GHz	122.5 GHz	
244 GHz	246 GHz	245 GHz	
13.553 MHz	13.567 MHz	13.560 MHz	
26.957 MHz	27.283 MHz	27.120 MHz	
40.66 MHz	40.70 MHz	40.68 MHz	
902 MHz	928 MHz	915 MHz	Only in region 2
2.400 GHz	2.500 GHz	2.450 GHz	
5.725 GHz	5.875 GHz	5.800 GHz	
24 GHz	24.25 GHz	24.125 GHz	

The ITU-RR defines the license-free ISM frequency bands, which are often used by SRDs because of their license-free nature. The 863 to 870 MHz frequency range is often mistaken as an ISM band, but is actually not contained in any of the ISM bands for region 1. A full overview of the ISM bands can be found in Table 8.

As a matter of fact, SRDs as a whole are not considered as a radio service according to article 1 of the ITU-RR [69, 70];

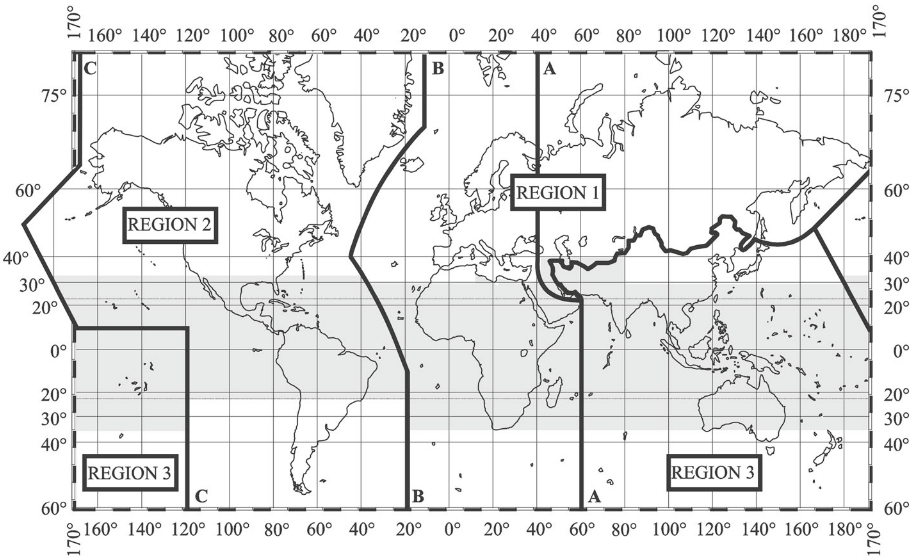

Fig. 10 The 3 regions defined by the ITU-RR [68]

thus, the regulations and frequency allocations of the ITU-RR do not apply to SRDs. The ITU-R has no mandatory regulations regarding SRDs. Resolution 54 [71] states that although global or regional harmonization could offer multiple benefits, radio spectrum regulation regarding SRDs is currently still considered a matter for national administrations. The resolution also declares that studies regarding the radio spectrum usage of SRDs should be continued, including participation of various standardization, industrial, and scientific organizations so that global or regional harmonization could be achieved in the future.

The studies conducted as result of the resolution 54 have lead to various ITU-R Reports and Recommendations. *Recommendations* are a voluntary set of international technical standards prepared by consensus, while a *Report* is a statement by an ITU Study Group (SG) regarding a specific matter or results from studies [67]. Neither of these types of documents force any regulation to ITU member states. These ITU-R deliverables regarding SRDs often provide useful overviews and insights. An overview of the most influential ITU-R deliverables is given here:

- *Report SM.2153* [72] by the Spectrum Management SG describes the technical and operational parameters of SRDs and how they access and use the radio spectrum. It includes among others a definition of SRDs, an overview of possible applications, commonly used frequency ranges, and maximum transmission power and an overview of various regional and national regulations from around the world.
- *Recommendation SM.1896* [26] recommends frequency ranges for the harmonization of SRDs. The Recommendation designates the frequency range from 862 to 875 MHz as available for region 1 and some countries of region 3.
- *Recommendation SM.2103* [73] provides a recommended categorization of SRDs for global harmonization.

A.2 European region

Since the ITU does not provide regulations for SRDs on a global level, regulation must take place on a regional level. The regulations for SRDs in the EU region is the result of a triangle of cooperation of 3 institutes, namely the CEPT, the EC, and the ETSI. These institutes each have their role in drafting law, harmonizing spectrum allocation, and developing standards. This section describes each institute, their responsibility, and how they collaborate with the other institutes.

A.2.1 European Commission

The EC is the heart of the EU. Among other things, it defines the EU policy and takes the initiative for drafting EU legislation proposals. The EU policy for radio spectrum allocation is unified in a single document called the *Radio Spectrum Policy Programme* [74]. It was drafted for the first time in 2012 and can be considered as the road map for a wireless Europe for the next multiple years with an eye on the future. It aims to lay out a policy programme for the planning and harmonization of radio spectrum to create a single digital market. The efficient use of radio spectrum should be maximized by introducing greater flexibility and analyzing the need to free, reallocate, or create frequency bands. Harmful interference and fragmentation of the market should be avoided by the introduction of harmonizing technical measures and standards. To foster the internal EU market, attention should be paid to competition and innovation. Spectrum should therefore be available for the introduction of new technologies, while member states will collaborate with research and academic institutes to further development of existing and new technologies. Effort should also be made to reduce the environmental footprint. In order to keep track of the market needs, trends, and possible improvements in spectrum allocation, an inventory will be kept identifying the uses of spectrum. As competition is important for the well being of the market, it is vital that member states actively keep competition fair and effective. Therefore, member states are allowed to amend, limit, add conditions, reserve, and refuse rights to frequency bands or the transfer thereof, at the same time promoting the coexistence of technologies and services. Member states are allowed to impose sanctions to ensure fair competition and optimal spectrum use. The programme also defines that member states should follow EU standpoints in international agreements or negotiations and that the EU should always aim to promote compatible policies in neighboring or third countries if possible. As most often the case for radio spectrum regulation, the Programme does not apply to matters regarding public order, safety, and defense.

When there is a need for legislation, the EC will draft a proposal and submit it to the European Parliament and Council. If accepted, the legislation will be published in the *Official Journal of the European Union* (OJEU) [75, 76]. The EU distinguishes between various kinds of legal acts [76]:

- *Regulations* are effective immediately for all EU members and citizens.
- *Directives* must be translated into national law by a certain deadline.
- A *Decision* applies only to whom it is addressed and is similar to regulations directly applicable. Possible addressees include member states, companies, organizations, and individuals.

- Non-binding acts, such as *recommendations* and *opinions*, serve only to inform or express the EU views.

EU legislation follows the *subsidiarity principle*, which specifies that legislation must be applied as local as possible [75]. If there is no need for EU wide legislation, then it must be deferred to the EU members themselves on a national level. Most EU legislation for spectrum management are decisions addressed to all member states.

Because of the importance of correct and relevant legislation, it is necessary for the EC to inform themselves thoroughly. EU legislative acts often lay down the general principles and give the EC power to implement more specific additional acts. These acts are divided into 2 different kinds, namely implementing and delegated acts [77]:

- When the EC wants to introduce an *implementing act*, it is obligated by EU law to consult a Committee comprised of representatives from each member state. This allows the member states to provide input into the drafting of implementing acts. Committees can prevent the adoption of an implementing act [78]. For radio spectrum matters, this Committee is the Radio Spectrum Committee (RSC) which is mainly focused on the development of technical measures for harmonizing legislation [33].
- *Delegated acts* may not alter essential elements of the law and serve to clarify definitions, objective, scopes, etc. Therefore is a consultation by a Committee not required. The regulations for delegated acts are limited to Article 290 in the Treaty on the Functioning of the European Union (TFEU) [77]. Nevertheless, it is of high importance for the EC to ask input from experts for delegated acts through an advisory group (a Commission Expert Group (CEG)) [79]. The input of a CEG is only consultive and not binding for the EC. The Radio Spectrum Policy Group (RSPG) is the CEG for radio spectrum policy and offers opinions to the EC for non-technical matters involving the radio spectrum allocation [80]. This mainly revolves around the EU policy for radio spectrum allocation by an economic, political, cultural, strategic, health, and social viewpoint. The members are the representatives of the member states ministries and NRAs, although representatives of certain countries and organizations such as CEPT and ETSI are also welcome as observers.

The RSPG generally handles radio spectrum matters on a more high level plane compared to the RSC, which generally handles only technical implementing measures. Contrary to the RSC, the RSPG does not have any legal power to prevent the implementation of an act, as it is only an advisory group.

A.2.2 CEPT/ECC

CEPT was founded in 1959 to improve relations and cooperation between national postal and telecommunication administrations. It is composed out of 3 committees: the European Committee for Postal Regulation (CERP), the Committee for ITU Policy (Com-ITU), and the Electronic Communications Committee (ECC). CEPT currently has 48 members (the NRA of each country), covering the European continent and including all EU members [81]. This is an ideal position to harmonize not only within the EU, but also with its border states.

The CEPT/ECC’s main priority is to harmonize the use of limited radio- and telecommunication resources, such as radio spectrum and satellite orbits [82]. The EC can issue mandates to the CEPT to conduct studies or give opinions on the technical side of harmonizing measures in legislation proposals [83], and also represent the interests of the EU on an international level at the ITU. The CEPT/ECC can issue 6 types of documents [84]:

- *ECC Decisions* are issued to harmonize the limited resources. These decisions are non-binding, but are based on consensus and thus often implemented by the CEPT member states. These CEPT/ECC decisions are synchronized with EC legislation as the latter are binding for all the EU member states.
- *ECC Recommendations* are a form of advice for member state NRAs, showing the viewpoints and opinions of the CEPT/ECC regarding harmonization.
- *ECC Reports* contain the results of studies.
- *CEPT Reports* are sent as an answer to mandates issued by the EC. They contain the results of requested studies and are often used by the EC as a base for legislation proposals.
- *European Common Proposals (ECP)* are submitted to the ITU to represent the EU viewpoints.
- *ECC multi-annual strategic plans.*

An overview of these document and how they interact with the EC and ETSI is shown in Fig. 11. All CEPT/ECC deliverables can be found publicly online [85].

A.2.3 ETSI

In 1988, CEPT created ETSI to separate the task of regulation from standardization [69]. ETSI is appointed by EU law as one of the 3 European Standardization Organizations (ESOs) [86]. Contrary to CEPT, which only consist of member state NRAs on the European continent, ETSI also includes as members manufacturers, researchers, economic operators, and various other kinds

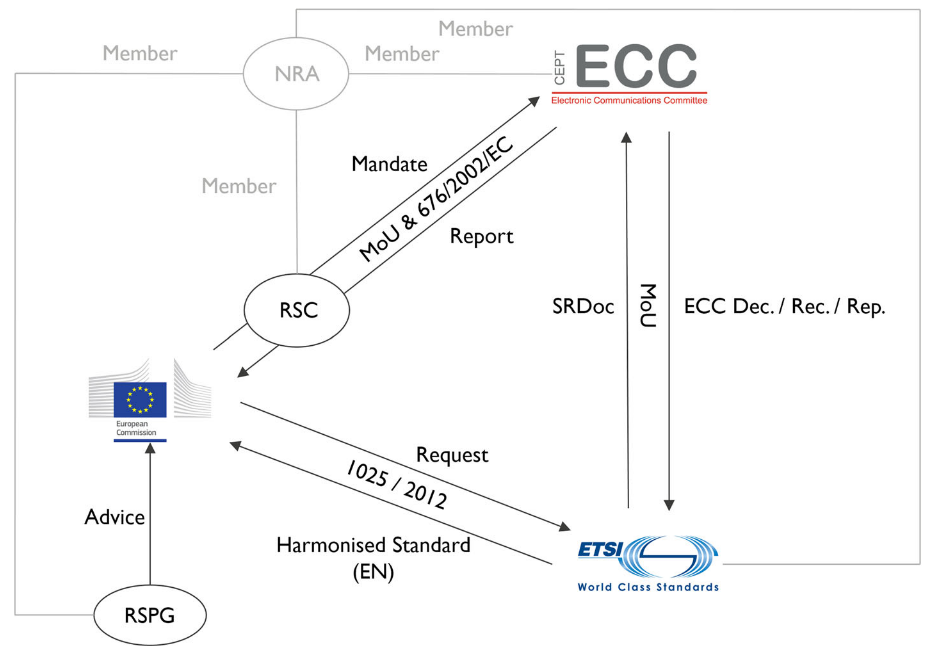

Fig. 11 An overview of EC, CEPT, and ETSI interaction

of organizations and institutes from all over the world. Currently, ETSI has over 800 members from 68 countries. Its standards are created by consensus and are used throughout the world [87, 88]. As ETSI is merely a standardization organization, its standards are entirely voluntarily. ETSI is also responsible for developing *harmonized standards*. A harmonized standard is a standard developed by one of the 3 ESOs as a response on a request from the EC for harmonized legislation [86]. These standards can be recognized by the “EN” at the beginning of their name [89].

A.2.4 Interactions between the institutes

The EC, CEPT, and ETSI institutes form a triangle of cooperation and interaction as can be seen in Fig. 11. The EC takes initiative for legislation, CEPT conducts studies involving the shared use of spectrum, and ETSI drafts the European (harmonized) standards.

EC and CEPT The EC and CEPT have signed a Memorandum of Understanding (MoU) which allows the EC to issue mandates to CEPT [83]. When the EC wants to take initiative for developing harmonizing EU legislation, it can ask CEPT for advice or to undertake studies regarding technical implementing measures. The results of the work done by CEPT are then sent back in the form of CEPT reports. The EC works closely with the RSC during this process in order to retrieve input of the member states on the mandates to CEPT and drafts of the legislative acts, and with the RSPG for advice on non-technical and policy measures. The MoU therefore asks to allow representatives of CEPT to take part in meetings of the RSC and RSPG. Vice versa are EC representatives allowed at relevant meetings of the CEPT/ECC. This cooperation is reflected in EU law [33, 80] and CEPT/ECC rules of procedure [84]. An overview of all mandates to CEPT from the EC can be found in [90, 91]. The MoU also encourages the exchange of information and experience between the two institutes.

EC and ETSI The collaboration between EC and ETSI is defined in EU law instead rather than an MoU [86]. ETSI can be requested by the EC to draft EU harmonizing standards. These harmonizing standards are then officially published in the OJEU [92].

CEPT and ETSI Aside from the mandates and requests from the EC to CEPT and ETSI, there is also an MoU between CEPT and ETSI [93]. In this MoU, each institute’s responsibilities and the need for close collaboration has been recorded. It states that the two institutes are complementary: CEPT is responsible for regulating and harmonizing the use of radio spectrum, while ETSI is responsible for standardization. Deliverables from both organizations should not contradict each other and must be mutually acceptable. The institutes will co-operate closely together, exchange information, and invite representatives from the other on relevant meetings. The MoU also contains an annex describing the procedures for cooperation. These protocols imply that whenever one of the institutes is developing a deliverable, it should inform the other institute when a new deliverable or modification to an existing deliverable of that other institute is needed. When ETSI is developing a standard with spectrum sharing issues or in need for spectrum (re)allocation, it can issue an System Reference Document (SRDoc) to CEPT describing the issue. CEPT/ECC will then investigate the matter, conducting the necessary studies or (re)allocating radio spectrum if necessary. The results of studies are sent back to ETSI in the form of ECC Reports, the (re)allocation of radio spectrum in the form of ECC Decisions or Recommendations [92]. During the whole process there is a strong interaction with feedback from both institutes. Both institutes keep a relationship matrix, which shows how they co-operate [94]. A full overview of the cooperation procedure for standardization and regulation by CEPT and ETSI can be found in [92].

A.3 National

In order to regulate radio spectrum, each state has an NRA on a national level. A list of all EU NRAs can be found in Table 9. Often (depending on the state) is the NRA involved on both global, regional, and national level [96, 97]. This allows states to have input in global and regional standardization and regulation, which can offer economical benefits. For example, the Belgian NRA, Belgian Institute for Postal Services and Telecommunications (BIPT), is involved in all 3 layers [96]. On a global level, BIPT is a member of the ITU. Regionally, BIPT is a member of CEPT/ECC, ETSI, RSC, and RSPG. Nationally, BIPT is by law designated as the institute for managing the radio spectrum.

Appendix B: Legislatory acts, recommendations, and standards for SRDs in the EU

The complexity of sub-GHz SRD law arises from the fact that the EU regulation is spread out over a number of EU laws. This section offers an overview of these laws and their implications.

B.1 European legal acts

All EU regulation for the use and allocation of radio spectrum is laid down in EU law. An overview of the most important laws concerning radio spectrum can be found in Fig. 12.

B.1.1 Decision 676/2002/EC (Radio Spectrum Decision)

Decision 676/2002/EC on a regulatory framework for radio spectrum policy in the European Community [33], also known as the *Radio Spectrum Decision*, is a cornerstone for SRD regulation in EU law. The Decision has some influential consequences: (i) radio spectrum regulation should occur on a EU level instead of national, (ii) mandates can be issued to CEPT as described in Appendix: Section A.2.4, (iii) it contains the legal basis for the creation of the RSC, (iv) all member states must publish their national radio frequency table to the public, and (v) it describes the policy for member states involved in international organizations regarding radio spectrum such as the ITU.

B.1.2 Decision 2000/299/EC

According to Decision 2000/299/EC [98], radio equipment can be allocated to 2 different classes, which are simply named *class 1* and *class 2*. Class 1 contains all the radio equipment that can be used throughout the whole EU without any restrictions. Any radio equipment that has been applied a restriction by an EU member state belongs to class 2. The Alert Sign has been assigned as the Equipment Class Identifier for class 2, as shown in Fig. 13. Class 2 devices must contain a table on the packaging, including the sign shown in Fig. 14, indicating which member state has put any restrictions on this device [99]. Affixing the Equipment Class Identifier is no longer required by EU law.

Table 9 An overview of the NRAs in the EU [95]

Country	NRA	Website
Austria	RTR	www.rtr.at
Belgium	BIPT	www.bipt.be
Bulgaria	CRC	www.crc.bg
Croatia	HAKOM	www.hakom.hr
Cyprus	OCECPR	www.ocecpr.org.cy
Czech Republic	CTU	www.ctu.eu
Denmark	DBA	www.danishbusinessauthority.dk
Estonia	ETRA	www.tja.ee
France	ARCEP	www.arcep.fr
Finland	FICORA	www.traficom.fi/fi
German	BNetzA	www.bundesnetzagentur.de
Greece	EETT	www.eett.gr
Hungary	NMHH	www.nmhh.hu
Ireland	ComReg	www.comreg.ie
Italy	AGCOM	www.agcom.it
Latvia	SPRK	www.sprk.gov.lv
Lithuania	RRT	www.rrt.lt
Luxembourg	ILR	www.ilr.public.lu
Malta	MCA	www.mca.org.mt
The Netherlands	ACM	www.acm.nl
Poland	UKE	www.uke.gov.pl/
Portugal	ANACOM	www.anacom.pt
Romania	ANCOM	www.ancom.org.ro
Slovakia	RU	www.teleoff.gov.sk
Slovenia	AKOS	www.akos-rs.si
Spain	CNMC	www.cnmc.es
Sweden	PTS	www.pts.se
The UK	Ofcom	www.ofcom.org.uk

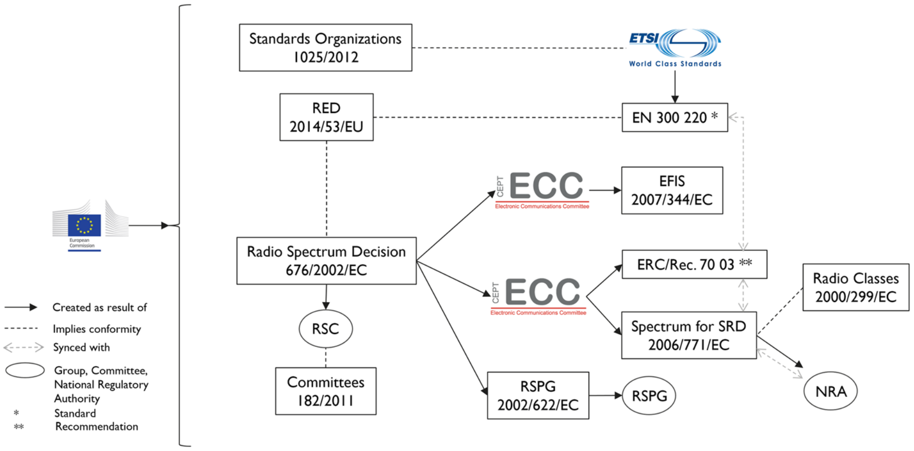

Fig. 12 An overview of the most notable EU laws regarding SRD regulation and how they are related

An indicative and non-exhaustive list listing the radio equipment for both Equipment Classes is publicly available online at [100]. The class 1 list contains an entry for each non-specific, alarm, social alarm, wireless streaming, RFID, and wideband data frequency band for SRDs mentioned in Table 1. Currently, there are no entries for SRDs in the 863 to 870 MHz range in the class 2 list, meaning that all SRDs using the frequency bands of Table 1 can be used throughout the whole EU without any restrictions.

B.1.3 Decision 2006/771/EC

As the amount of SRDs on the internal market expanded, it became apparent that harmonization was needed to ensure compatibility across borders, prevent harmful interference, and reduce production costs. Therefore,

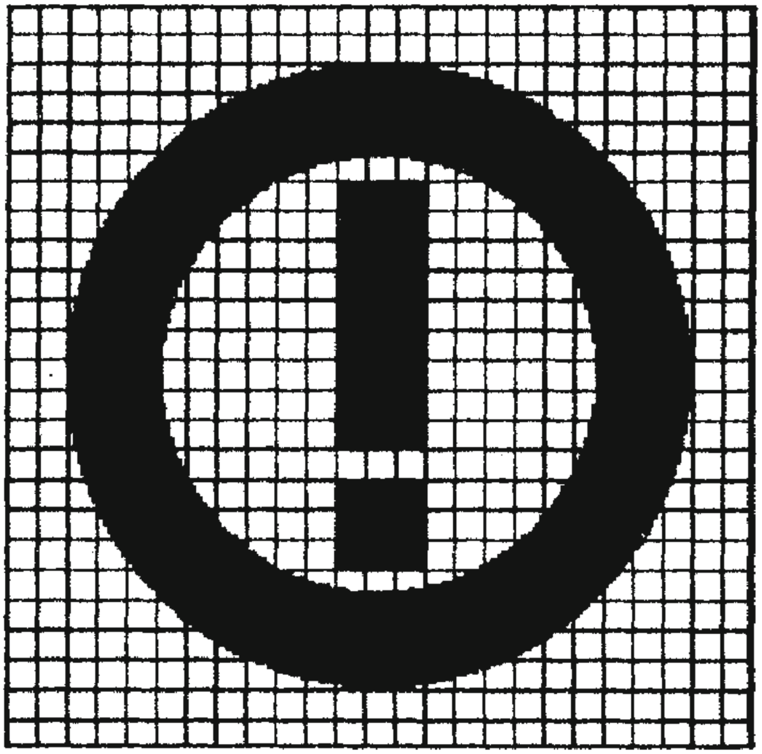

Fig. 13 The Equipment Class Identifier for class 2 radio equipment [98]

Fig. 14 The sign for radio equipment under restrictions in one or more member states [99]

Decision 2006/771/EC [18] has been drafted for the legal harmonization of frequency bands for SRDs throughout the EU. The annex of this Decision contains a frequency allocation table for the range of 9 kHz to 246 GHz. This table is the only frequency allocation table with legal value [4], contrary to the tables in other documents described in Appendix: Section B.2 which have none. SRDs compliant with the specified frequency ranges and their parameters are classified as class 1 devices and may thus be used throughout the whole EU. All frequency ranges from the table are available in all EU member states, as enforced by the Decision. Member states are allowed to loosen the restrictions or make available other frequency ranges. However, SRDs using those restrictions or frequency ranges cannot operate in the whole EU and are consequently classified as a class 2 device.

The table specifies the following parameters for each frequency band:

- The category of SRD to which the band is assigned
- The maximum transmission power, maximum field strength, or maximum power density
- Additional parameters such as duty cycle, channeling, access, or occupation rules
- Extra usage restrictions

The frequency ranges from the frequency allocation table within the range of 863 to 870 MHz are displayed in Fig. 1 and Tables 1 and 3.

This Decision also acknowledges the low-power and short-range nature of SRDs and defines their position in relation to other radiocommunication services. Due to their nature, SRDs are allowed to share frequency bands with other radiocommunication services. It is the responsibility of SRDs to protect themselves from interference of such services and to avoid causing harmful interference to those services. The radiocommunication services have priority and should thus not be obligated to protect themselves from SRD interference.

Decision 2006/771/EC is a direct result of the Radio Spectrum Decision, as it came into existence through a mandate to CEPT [101]. Later on, a permanent mandate was issued to CEPT to update the Decision on a yearly basis [27].

B.1.4 Decision 2018/1538

Recently, additional frequency bands have been allocated to SRDs through Decision 2018/1538 [32], as described in Section 3.7. Due to the usage of bandwidth in the 874 to 876 MHz and 915 to 921 MHz range by EU member states for public order, security, and defense purposes, a different and more flexible approach is needed rather than adding the new frequency bands to Decision 2006/771/EC. After all, the Radio Spectrum Decision dictates that EU regulations may not intervene with the member state regulations regarding public order, security, and defense purposes. The aim of this decision is to prevent further fragmentation of the frequency bands in this range, while providing greater flexibility to member states regarding frequency bands for public order, security, defense, and railway purposes.

B.1.5 Decision 2007/344/EC

The purpose of Decision 2007/344/EC [102] is to introduce a single access point with a common format and level of detail for all available information about radio spectrum allocation in the EU. This single access point, named ERO Frequency Information System (EFIS), is publicly available on the internet [103] and contains all available radio spectrum information for each EU and CEPT member state. It is a handy tool for manufacturers, researchers, and other interested users for looking up or comparing radio spectrum allocations from different EU and CEPT member states. EFIS is hosted by the European Communications Office (ECO), the office supporting CEPT. It is not the purpose of EFIS to replace the NRA's national databases, but to complement them. The NRAs still keep maintaining their own radio spectrum information databases, but must send updates to EFIS twice per year.

The Decision is a direct consequence of the Radio Spectrum Decision, as that mentioned that all member states should publicly publish their frequency allocation table and all other available information for the use of radio spectrum, and keep this up to date. EFIS was then selected after the EC mandated CEPT to investigate if it was indeed suitable to fulfill that task [104].

B.1.6 Decision 2002/622/EC

Decision 2002/622/EC [80] announces the establishment of the RSPG as an advisory group for assisting the EC in matters about radio spectrum policy on EU and international level. The decision defines the members of the RSPG as one expert of each member state. It is also allowed to invite observers, such as CEPT and ETSI, and encouraged to consult with other interested parties such as market operators and consumers.

B.1.7 Directive 2014/53/EU (RED)

Directive 2014/53/EU [105], also known as the *Radio Equipment Directive (RED)*, specifies the essential requirements radio equipment must meet in order to be allowed on the EU market. All radio equipment in order with the Directive may be made available and move freely throughout the whole EU market[5]. Radio equipment considered compliant with the relevant harmonized standards is also considered compliant with the essential requirements of this Directive. This *presumption of conformity* offers a great advantage for manufacturers: when the radio equipment complies with the relevant harmonized standards, such as EN 300 220, it can be put on the EU wide market. The relevant harmonized standards can be found in the OJEU [106].

These essential requirements for radio equipment are defined in 3 parts. First, the radio equipment must be safe to use and may not present any risk to persons or animals. Next, radio equipment must use the radio spectrum as efficient as possible and prevent harmful interference. Finally, the radio equipment must comply with the following requirements depending on the class or category to which it belongs: it must be compatible with other radio equipment and accessories (e.g., chargers), it may not harm its network or abuse the network resources, the privacy of users must be respected, measures must be present to prevent fraud, it must provide access to emergency services, it must be accessible for persons with a disability, and only software compliant with the radio equipment may be loaded onto that equipment.

The Directive also defines the obligations of the manufacturers, importers, and distributors involved [6]. Manufacturers are responsible for the radio equipment they produce, the conformity assessment thereof, and the drafting of the technical documentation of the equipment. When radio equipment is deemed compliant with the requirements through assessment, the manufacturer will draft an EU declaration of conformity and affix the Conformité Européenne, or European Conformity (CE) marking shown in Fig. 15. Aside from assessment, manufacturers are also subject to other obligations. These obligations are among others: (i) radio equipment must be usable in at least 1 member state without breaking regulations. (ii) Member states imposing restrictions on the equipment must also be listed on the packaging. (iii) The equipment must also be affixed with an identification of the equipment (e.g., a serial number) and the manufacturers' contact details and (iv) be accompanied with various documents including (a copy of) the declaration of conformity, technical documentation, instructions, a description of the components or accessories, safety information, and information of the used frequency bands and maximum transmission power. (v) Manufacturers are also obliged to keep the technical documentation and declaration of conformity for a period of 10 years. (vi) Manufacturers must cooperate with national authorities and provide all relevant documents when requested to prove the conformity of the equipment. (vii) It is the manufacturers responsibility to keep radio equipment or to be produced radio equipment of the assessed type, compliant in the event of a change in technical specifications of the equipment or of harmonized standards. If radio equipment no longer complies with this directive, it must be investigated and monitored by the manufacturer. Additionally, distributors must be informed and a register of complaints can be kept. When necessary, manufacturers must take corrective measures or remove the equipment

Fig. 15 The CE marking. This marking declares that radio equipment complies with EU regulation and therefore may be freely distributed and used throughout the whole EU market

of the EU market. If the non-compliance presents a risk, national authorities must also be notified. Importers and distributors are bound by the similar demands as manufacturers. Importers are only allowed to import positively assessed radio equipment. It is the importers and distributors responsibility to ensure that the equipment is compliant, the manufacturer (and importer) has fulfilled its obligations, all required affixes and documents from the manufacturer are present, and the equipment stays compliant during storage or transport. Imported radio equipment must also be affixed by the importers contact details. Importers must also keep the declaration of conformity and technical specifications for 10 years. Just like manufacturers, importers and distributors are obliged to keep track of non-compliant radio equipment, to take corrective measures if necessary, to inform the distributors involved, and to cooperate with national authorities. Manufacturers, importers, and distributors must keep track for 10 years who has supplied them and who they have supplied with radio equipment.

The conformity assessment procedures can be performed by either the manufacturer itself or a conformity assessment body. When harmonized standards are not or only partially used, compliance with certain requirements can only be assessed through a conformity assessment body. The annexes of the Directive describe 4 types of conformity assessment procedures. In the case of a negative assessment by an assessment body, the assessment body can ask to take corrective actions. If these are not sufficient, the assessment body can refuse or recall approval. An appeal procedure is available in case the assessment is contested. The technical documentation must contain enough information and details to check if the equipment is compliant to this Directive and the requirements. If the technical documentation is not adequate, manufacturers or importers can be asked to have the equipment tested for compliance to the requirements by an external party at their own expense. Conformity assessment bodies can also be notified by market surveillance authorities in case of non-compliance or risk, and have the authority to restrict the equipment from the EU market. The Directive also specifies regulations for conformity assessment bodies and each member state's national accreditation body to assess and monitor those conformity assessment bodies. These regulations include that all bodies must be objective, free from conflict of interest, have sufficient means and capable personnel, be up to date, exchange information, and respect confidentiality. All conformity assessment bodies are listed publicly by the EC [107].

B.1.8 Regulation 1025/2012

Regulation 1025/2012 [86] lays down the rules regarding standardization organizations and procedures in the EU and appoints ETSI as one of the 3 European standardization organizations. The Regulation also defines the right of the EC to send requests to the European standardization organizations to draft harmonizing standards. Harmonized standards should be drafted with the needs of the market and public interest in mind and be based on consensus. The development of standards must happen in a transparent manner and also involve all interested parties during various stages of the development. This includes research centers, universities, enterprises, consumer organizations, environmental and social parties, public authorities, and market surveillance authorities. Drafts of standards, and other deliverables, must be distributed to other European and national standardization organizations, to allow other standardization organizations to comment on the draft or deliverable. When the harmonized standard is adopted, it will be published in the OJEU by the EC. National standardization organizations are not allowed to impose standards which impede EU harmonization and must remove national standards if they conflict with new harmonized standards. Member states are however allowed to object against a harmonized standard, which can lead to the addition of restrictions on the standard or its withdrawal.

Standardization organizations must work in a transparent manner according to the Regulation. For example, all European and national standardization organizations must publicly publish their annual work programme. This programme defines among others the standards or other deliverables which will be worked on during that year or were adopted in the previous work programme.

B.2 Recommendations and standards

Next to the official EU law, a few other documents are often mentioned regarding the allocation of radio spectrum. This section takes a closer look at those documents, their implications, and jurisdiction.

B.2.1 ERC 70 03

In 1997, CEPT has issued a recommendation for the allocation of radio spectrum for SRDs. This document, called *ERC Recommendation 70-03* [19], gives the opinion of the CEPT/ECC on how the radio spectrum should be allocated. The recommendation in itself has rather little power to impose or force the implementation of the harmonizing frequency bands and their restrictions, as CEPT members are free to choose whether or not to implement CEPT or ECC deliverables [108]. The recommendation is also merely a recommendation, which implies that the implementation is encouraged, but entirely voluntarily. The harmonized frequencies in the Recommendation used to be defined in ECC decisions, but were repealed in 2008 as they became obsolete through EU harmonized standards [109]. The Recommendation is updated and synchronized with the frequency allocation tables in both Decision 2006/771/EC and EN 300 220 and thus corresponds with EU law. This synchronization is done deliberately because many CEPT members are also EU member states, which are obliged to uphold EU law. Members are encouraged, but not required to uphold to the more extensive Recommendation's restrictions as long as they stay within EU law. Although the recommendation has only a small legal impact, it is cited in multiple papers and online sources. This demonstrates the Recommendation's true power, namely providing the otherwise scattered information regarding radio spectrum allocation in a single clear and publicly available document.

The recommendation also contains 14 annexes and 5 appendices. While the recommendation itself expresses the need for harmonization and prevention of harmful interference on a high level, the most relevant and contributing information is actually contained in the annexes and appendices which make up the bulk of the recommendation. Each annex contains a frequency allocation table defining the frequency bands for SRDs belonging to a certain application type. The frequency bands in the Recommendation mainly conform to the frequency bands specified in Decision 2006/771/EC with some minor changes which are mostly more restrictive. Only the following annexes contain frequency bands in the 863 to 870 MHz range:

- *Annex 1: Non-specific SRDs*. This annex contains all the frequency bands of Decision 2006/771/EC for non-specific SRDs with the exception of $47b_{(865\ \mathrm{MHz})}$, which is defined in annex 2. A major difference with Decision 2006/771/EC is the split of the non-specific frequency bands for the 863 to 870 MHz into a (i) FHSS, (ii) Direct Sequence Spread Spectrum (DSSS) or other wideband technique, and (iii) non-spread spectrum band. The FHSS and non-spread spectrum bands also specify certain bandwidth conditions not present in Decision 2006/771/EC. The DSSS or other wideband techniques have a power density limit, while there are no such limits in Decision 2006/771/EC. The duty cycle in the frequency band for DSSS or other wideband techniques can be increased to 1% if certain conditions regarding bandwidth and power are met, but this does not apply for the FHSS and non-spread spectrum bands. Another notable difference is that restrictions as in Table 3 are generalized in the Restriction over all non-specific frequency bands in the 863 to 869.2 MHz range. This generalized restriction allows only digital audio and video with a maximum bandwidth of 300 kHz and analog and digital voice applications with a maximum bandwidth of 25 kHz. This differs with Decision 2006/771/EC, where frequency bands for non-specific SRDs often exclude analog audio or video applications without exceptions based on bandwidth, and do not have bandwidth conditions for audio and video applications using digital modulation. Additional, $56\text{b}_{(869.7\text{ MHz})}$ is more heavily restricted than in Decision 2006/771/EC as only voice is allowed under certain conditions, such as maximum bandwidth of 25 kHz, polite spectrum access, and maximum transmission time of 1 min per transmission.

- *Annex 2: Tracking, tracing, and data acquisition.* This annex contains band $47\text{b}_{(865\text{ MHz})}$ from Decision 2006/771/EC without modifications.
- *Annex 3: Wideband data transmission systems.* This annex contains the wideband data transmission band $84_{(863\text{ MHz})}$ from Decision 2006/771/EC without modifications.
- *Annex 7: Alarms.* This annex contains all the low duty cycle/high reliability bands $51_{(869.2\text{ MHz})}$, $52_{(869.25\text{ MHz})}$, $53_{(869.3\text{ MHz})}$, and $55_{(869.65\text{ MHz})}$ from decision 2006/771/EC without modifications.
- *Annex 10: Radio microphone applications including Assistive Listening Devices (ALD), wireless audio, and multimedia streaming systems.* This annex contains the high duty cycle/continuous transmission band $46\text{b}_{(863\text{ MHz})}$ from decision 2006/771/EC without modifications.
- *Annex 11: RFID.* The RFID annex contains a frequency band equivalent to band $47\text{a}_{(865\text{ MHz})}$ from Decision 2006/771/EC, with the addition of a maximum continuous interrogation time of 4 s and a dead time of 100 ms between interrogation transmissions in the same channel. It also contains frequency bands corresponding to the frequency bands in the repealed Decision 2006/804/EC, which are still allowed for RFID interrogation devices made before the repeal.

Table 10 The duty cycle categories defined in ERC Recommendation 70-03 [19]

Name	Duty cycle (%)	Maximum allowed continuous transmission time (s)
Very low	$\leq 0.1\%$	0.72
Low	$\leq 1\%$	3.6
High	$\leq 10\%$	36
Very high	Up to 100%	–

Following the annexes are the appendices of which appendix 1 (*National Implementation*), 3 (*National Restrictions*), and 5 (*Duty Cycle Categories*) are the most interesting. Appendix 1 (*National Implementation*) provides a matrix with all frequency bands as rows and all CEPT members as columns. The appendix gives an overview of which CEPT members have implemented which frequency bands fully, partially, or not at all. Appendix 3 (*National Restrictions*) lists for each frequency band all CEPT members that have only implemented the frequency band partially or not at all, together with a description of the limitation and the reason thereof. The last appendix, appendix 5 (*Duty Cycle Categories*), contains the only recommendation in all of the EU, CEPT, and ETSI documentation regarding radio spectrum regulation for the maximum allowed continuous transmission time for SRDs not using LBT and AFA. An overview can be seen in Table 10. For example, transmissions in the low category are recommended to have a duration less or equal than 3.6 s. As the duty cycle of 1% only allows for 36 s of transmission time during 1 h, only 10 continuous messages of 3.6 s can be sent.

B.2.2 EN 300 220

As the result of a request from the EC, ETSI drafted a harmonized standard called EN 300 220 for SRDs in the 25 to 1000 MHz range [110]. The standard consists of 4 parts from EN 300 220-1 to EN 300 220-4. EN 300 220-1 [21] contains mainly the technical specifications and procedures to test conformance to the standard. Part 2 [111] is the actual harmonized standard for non-specific SRDs. Part 3 is divided into 2 parts itself of which both are harmonized standards for the low duty cycle/high reliability alarm frequency bands: 3-1 [112] handles the social alarm band and 3-2 [113] the other alarm bands. Finally, part 4 [114] contains the harmonized standard for metering devices operating in the 169.4 to 169.475 MHz band.

The EN 300 220 standard aims to fulfill the essential requirements described in the RED. This connection between the standard and the RED is the true advantage of EN 300 220. This is a valuable asset for manufacturers, as the implementation of the EN 300 220 standard in their SRDs and solutions is an easy way to comply to EU regulation. It is not mandatory to implement the EN 300 220 standard to fulfill the essential requirements, but then, its conformity must be proven and tested otherwise. EN 300 220-3-2 to EN 300 220-4 each cover the

Table 11 The CCA threshold defined in EN 300 220-1 [21] based on an antenna gain of 0 dB relative to a dipole

Transmission power (mW)	CCA threshold
< 100 mW	15 dB above S_p
Between 100 and 500 mW	11 dB above S_p

essential requirements for that type of SRDs (non-specific or (social) alarms), based on the technical specifications described in EN 300 220-1. Annex A of each document gives the relationship between the standard and the essential requirements of the RED.

The most interesting section in EN 300 220-1 [21] is Section 5.21 (*polite spectrum access*), as this is the only occurrence of specific regulations for devices using LBT and AFA. All timing parameters and the alternative duty cycle ratio defined in Section 3.2 and Fig. 3 originate from this section. It also specifies other parameters like the CCA threshold: only when no signals are received with a signal strength above the threshold during the CCA check is the medium considered free and available for transmission. The threshold is categorized by the transmission power, as can be seen in Table 11, and depends on the receiver sensitivity S_p which can be calculated using the receiver bandwidth R_b (9). Unfortunately, not all parameters have been defined clearly. One example are the boundaries of the 200 kHz intervals for the alternative duty cycle. Another is the maximum continuous transmission time which can be 1 s or 4 s depending on the application. Regular transmissions only have a maximum duration of 1 s, while the 4 s limit is reserved for polling sequences and transmission dialogs. However, there is currently no precise definition when a transmission can be categorized as a polling sequence or transmission dialog. In the same way, there is no list of specific algorithms for LBT or AFA accepted by the standard: LBT is simply defined as an CCA check followed by a random backoff time period or frequency change, and AFA can be implemented in various ways but should try to avoid channels occupied by other devices.

$$S_p = 10\log(R_b) - 117 \tag{9}$$

Parts EN 300 220-2 to EN 300 220-4 are the actual harmonized standards and almost exclusively refer to EN 300 220-1 for descriptions, limits, and conformance procedures. The standardized frequency allocations can be found mostly in their annexes:

- *EN 300 220-2 annex B* contains the regulatory limits for non-specific SRDs in the EU market, categorized as class 1 devices, in the form of a frequency allocation table. It is kept in sync with Decision 2006/771/EC. The frequency bands in the annex are at the moment of writing which is not yet updated to the current version of Decision 2006/771/EC, meaning that for example $47b_{(865\ \mathrm{MHz})}$ is not yet added. Additionally, frequency bands regarding RFID and wideband data applications are not included in EN 300 220. Even without the differences due to updated legislation, there are some differences between EN 300 220-1 and Decision 2006/771/EC, resembling the differences between ERC Recommendation 70-03 and Decision 2006/771/EC. For example, EN 300 220-2 mentions no usage restrictions regarding audio and video in the whole 863 to 869.65 MHz range, in contrast to the exclusions of analog audio and/or video mentioned in Decision 2006/771/EC. There is also no restriction for analog video in $54_{(869.4\ \mathrm{MHz})}$ or any mention of the allowance for voice applications in $56a_{(869.7\ \mathrm{MHz})}$ as there is in Decision 2006/771/EC. Additionally, EN 300 220-2 is more restrictive for $46a_{(863\ \mathrm{MHz})}$, as it limits the bandwidth for audio and video to 300 kHz while such restriction is not enforced by Decision 2006/771/EC.
- *EN 300 220-2 annex C* also has a frequency allocation table, but for frequency bands not harmonized in the EU or for non EU members. The frequency bands here largely correspond with the equivalent frequency bands mentioned in annex 1 of ERC Recommendation 70-03. The difference is that ERC Recommendation 70-03 describes the frequency bands with notes, while EN 300 220-2 describes these explicitly in its spectrum table. Minor differences for example are the replacement of audio/video bandwidth limitations of FHSS frequency bands by a maximum allowed occupied bandwidth based on the amount of channels, and the definition of wideband as a minimum occupied bandwidth of 200 kHz in EN 300 220-2.
- *EN 300 220-3-1 section 4.2* contains the frequency band for social alarms, which corresponds entirely with the low duty cycle/high reliability band $51_{(869.2\ \mathrm{MHz})}$ from Decision 2006/771/EC.
- *EN 300 220-3-2 annex B* contains the frequency bands for alarms, which correspond entirely with low duty cycle/high reliability bands $49_{(868\ \mathrm{MHz})}$, $52_{(869.25\ \mathrm{MHz})}$, $53_{(869.3\ \mathrm{MHz})}$, and $53_{(869.65\ \mathrm{MHz})}$ from Decision 2006/771/EC.

Abbreviations

6LoWPAN: IPv6 over Low-Power Wireless Personal Area Network; 6TiSCH: IPv6 over the TSCH mode of IEEE 802.15.4e; 6top: 6TiSCH operation sublayer; AFA: Adaptive Frequency Agility; ALD: Assistive Listening Devices; APC: Adaptive Power Control; ATPC: Adaptive Transmission Power Control; BIPT: Belgian Institute for Postal Services and Telecommunications; CCA: Clear Channel Assessment; CE: Conformité Européenne, or European conformity; CEG: Commission expert group; CEPT: European Conference of Postal and Telecommunications Administrations; CERP: European Committee for Postal Regulation; CoAP: Constrained Application Protocol; Com-ITU: Committee for ITU Policy; CSMA-CA: Carrier-sense multiple access collision avoidance; CSS: Chirp Spread Spectrum; DBPSK: Differential Binary Phase Shift Keying; DC: Duty cycle; DSSS: Direct Sequence Spread Spectrum; EBA: European Broadcasting Area; EC: European Commission; ECC: Electronic Communications Committee; ECO: European Communications Office; ECP: European Common Proposals; EFIS: ERO Frequency Information System; EIRP: Effective Isotropic Radiated Power; ERO: European Radiocommunications Office; ERP: Effective Radiated Power; ESO: European Standards Organization; ETSI: European Telecommunications Standards Institute; EU: European Union; e.r.p.: Effective Radiated Power; FEC: Forward Error Correction; FHSS: Frequency Hopping Spread Spectrum; FSK: Frequency Shift Keying; GFSK: Gaussian Frequency Shift

Keying; GSM-R: Global System for Mobile Communications for Railways; IoT: Internet of Things; ISM: Industrial, Scientific and Medical; ITU: International Telecommunication Union; ITU-D: Telecommunication Development Sector; ITU-R: Radiocommunication Sector; ITU-RR: Radio Regulations; ITU-T: Telecommunication Standardization Sector; LBT: Listen Before Talk; LDPC: Low-Density Parity Check; LECIM: Low-Energy, Critical Infrastructure Monitoring; LPWAN: Low-Power Wide-Area Networks; MDP: Markov Decision Processes; MoU: Memorandum of Understanding; NRA: National Regulatory Authority; OJEU: *Official Journal of the European Union*; PHY: Physical layer; QoS: Quality of service; RED: Radio Equipment Directive; RFID: Radio Frequency Identification; RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks; RSC: Radio Spectrum Committee; RSPG: Radio Spectrum Policy Group; RSPP: Radio Spectrum Policy Programme; SFD: Start-of-Frame Delimiter; SG: Study group; SRD: Short-range device; SRDoc: System Reference Document; SUN: Smart Utility Network; TG4w: IEEE 802.15 WPAN^{TM} Task Group 4w; TFEU: Treaty on the Functioning of the European Union; TSCH: Time Slotted Channel Hopping; UNB: Ultra Narrow Band; USA: United States of America; WRC: World Radiocommunication Conference

Authors' contributions

EDP was responsible for the conceptualization and project administration. MS was responsible for the investigation. AS was responsible for the resources. JH and EDP were responsible for the supervision of the study. MS was responsible for the visualization, writing, and original draft of the manuscript. MS and EDP were responsible for the writing, review, and editing of the manuscript. All authors read and approved the final manuscript.

Funding

This work has been partly funded by the IDEAL-IoT (Intelligent DEnse And Longe range IoT networks) SBO project, funded by the FWO-V (Fund for Scientific Research-Flanders) under grant agreement #S004017N.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 6 December 2018 Accepted: 24 June 2019

References

1. J. M. Marais, R. Malekian, A. M. Abu-Mahfouz, in *2017 IEEE AFRICON*. LoRa and LoRaWAN testbeds: a review, (2017), pp. 1496–1501. https://doi.org/10.1109/AFRCON.2017.8095703
2. K. Mikhaylov, J. Petaejaejaervi, T. Haenninen, in *European Wireless 2016; 22th European Wireless Conference*. Analysis of capacity and scalability of the LoRa low power wide area network technology (VDE, Berlin, 2016), pp. 1–6. https://www.vde-verlag.de/
3. A. Pop, U. Raza, P. Kulkarni, M. Sooriyabandara, Does bidirectional traffic do more harm than good in LoRaWAN based LPWA networks?. CoRR. **abs/1704.04174** (2017). 1704.04174
4. F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, T. Watteyne, Understanding the limits of LoRaWAN. IEEE Commun. Mag. **55**(9), 34–40 (2017). https://doi.org/10.1109/MCOM.2017.1600613
5. B. Vejlgaard, M. Lauridsen, H. Nguyen, I. Z. Kovacs, P. Mogensen, M. Sorensen, in *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*. Coverage and capacity analysis of Sigfox, LoRa, GPRS, and NB-IoT, (2017), pp. 1–5. https://doi.org/10.1109/VTCSpring.2017.8108666
6. D. Ismail, M. Rahman, A. Saifullah, in *Proceedings of the Workshop Program of the 19th International Conference on Distributed Computing and Networking. Workshops ICDCN '18*. Low-power wide-area networks: opportunities, challenges, and directions (ACM, New York, 2018), pp. 8–186. https://doi.org/10.1145/3170521.3170529
7. K. E. Nolan, W. Guibene, M. Y. Kelly, in *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*. An evaluation of low power wide area network technologies for the Internet of Things, (2016), pp. 439–444. https://doi.org/10.1109/IWCMC.2016.7577098
8. Y. Kawamoto, Y. Kado, in *2016 TRON Symposium (TRONSHOW)*. NES-SOURCE: indoor small-scale wireless control network protocol that has a communication failure point avoidance function, (2016), pp. 1–7. https://doi.org/10.1109/TRONSHOW.2016.7842884
9. IEEE standard for local and metropolitan area networks–part 15.4: low-rate wireless personal area networks (LR-WPANs) amendment 3: physical layer (PHY) specifications for low-data-rate, wireless, smart metering utility networks. IEEE Std 802.15.4g-2012 (Amendment to IEEE Std 802.15.4-2011), 1–252 (2012). https://doi.org/10.1109/IEEESTD.2012.6190698
10. T. Adame, S. Barrachina, B. Bellalta, A. Bel, HARE: supporting efficient uplink multi-hop communications in self-organizing LPWANs. CoRR. **abs/1701.04673** (2017). 1701.04673
11. A. Karaağaç, J. Haxhibeqiri, W. Joseph, I. Moerman, J. Hoebeke, in *2017 IEEE 13th International Workshop on Factory Communication Systems (WFCS)*. Wireless industrial communication for connected shuttle systems in warehouses, (2017), pp. 1–4. https://doi.org/10.1109/WFCS.2017.7991971
12. M. Altmann, P. Schlegl, K. Volbert, in *2015 12th International Workshop on Intelligent Solutions in Embedded Systems (WISES)*. A low-power wireless system for energy consumption analysis at mains sockets (IEEE, Piscataway, 2015), pp. 79–84. https://www.ieee.org/
13. M. Qutab-ud-din, A. Hazmi, L. F. D. Carpio, A. Goekceoglu, B. Badihi, P. Amin, A. Larmo, M. Valkama, in *European Wireless 2016; 22th European Wireless Conference*. Duty cycle challenges of IEEE 802.11ah networks in M2M and IoT applications (VDE, Berlin, 2016), pp. 1–7. https://www.vde-verlag.de/
14. C. Pham, QoS for long-range wireless sensors under duty-cycle regulations with shared activity time usage. ACM Trans. Sen. Netw. **12**(4), 33–13331 (2016). https://doi.org/10.1145/2979678
15. M. T. Islam, B. Islam, S. Nirjon, in *2018 14th International Conference on Distributed Computing in Sensor Systems (DCOSS)*. Duty-cycle-aware real-time scheduling of wireless links in low power wans (IEEE, Piscataway, 2018), pp. 53–60
16. E. De Poorter, J. Hoebeke, M. Strobbe, I. Moerman, S. Latr´e, M. Weyn, B. Lannoo, J. Famaey, Sub-GHz LPWAN network coexistence, management and virtualization: an overview and open research challenges. Wirel. Pers. Commun. **95**(1), 187–213 (2017). https://doi.org/10.1007/s11277-017-4419-5
17. M. Lauridsen, B. Vejlgaard, I. Z. Kovacs, H. Nguyen, P. Mogensen, in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*. Interference measurements in the European 868 MHz ISM band with focus on LoRa and SigFox, (2017), pp. 1–6. https://doi.org/10.1109/WCNC.2017.7925650
18. European Union, Commission Decision of 9 November 2006 on harmonisation of the radio spectrum for use by short-range devices (2006). 2006/771/EC. Consolidated version of August 2017
19. CEPT/ECC, ERC Recommendation 70-03 Relating to the use of short range devices (SRD) (1997). https://www.ecodocdb.dk/download/Archive/25c41779-cd6e/4206d0ad-1909/Rec7003.pdf
20. M. Loy, R. Karingattil, L. Williams, ISM-band and short range device regulatory compliance overview (2005). http://www.ti.com/lit/an/swra048/swra048.pdf
21. ETSI, Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 1: Technical characteristics and methods of measurement (2017). https://www.etsi.org/deliver/etsi_en/300200_300299/30022001/03.01.01_60/en_30022001v030101p.pdf
22. S. Lin, F. Miao, J. Zhang, G. Zhou, L. Gu, T. He, J. A. Stankovic, S. Son, G. J. Pappas, ATPC: adaptive transmission power control for wireless sensor networks. ACM Trans. Sen. Netw. **12**(1), 6–1631 (2016). https://doi.org/10.1145/2746342
23. European Union, Commission Decision of 9 November 2006 on harmonisation of the radio spectrum for use by short-range devices (2006). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02006D0771(01)-20080611
24. SigFox, Sigfox technical overview (2017). https://storage.sbg1.cloud.ovh.net/v1/AUTH_669d7dfced0b44518cb186841d7cbd75/dev_medias/build_technicalOverview.pdf
25. LoRa Alliance Technical Committee, LoRaWAN™ Regional Parameters (2016). https://www.mdpi.com/1424-8220/17/10/2364
26. International Telecommunication Union, Recommendation ITU-R SM.1896: frequency ranges for global or regional harmonization of short-range devices (2011). https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1896-0-201111-S!!PDF-E.pdf
27. European Union, Permanent mandate to CEPT regarding the annual update of the technical annex of the Commission Decision on the

technical harmonisation of radio spectrum for use by short range devices (2006). http://ec.europa.eu/newsroom/dae/document.cfm?action=display&doc_id=7494
28. CEPT/ECC, In response to the EC permanent mandate on the "Annual update of the technical annex of the Commission Decision on the technical harmonisation of radio spectrum for use by short range devices" (2016). https://www.erodocdb.dk/download/08fc64c1-36ab/CEPTRep059.pdf
29. CEPT/ECC, Addendum to CEPT Report 59 (2017). https://www.erodocdb.dk/download/08fc64c1-36ab/CEPTRep059_Addendum.pdf
30. CEPT/ECC, Future Spectrum Demand for Short Range Devices in the UHF Frequency Bands (2014). https://www.erodocdb.dk/download/f584774b-c3c4/ECCREP189.PDF
31. CEPT/ECC, Co-existence studies for proposed SRD and RFID applications in the frequency band 870-876 MHz and 915-921 MHz (2013). https://www.erodocdb.dk/download/26ce1d81-2a81/ECCREP200.PDF
32. European Union, Commission Implementing Decision (EU) 2018/1538 of 11 October 2018 on the harmonisation of radio spectrum for use by short-range devices within the 874-876 and 915-921 MHz frequency bands (2018). https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32018D1538
33. European Union, Decision No 676/2002/EC of the European Parliament and of the Council of 7 March 2002 on a regulatory framework for radio spectrum policy in the European Community (Radio Spectrum Decision) (2002). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002D0676
34. U. Raza, P. Kulkarni, M. Sooriyabandara, Low power wide area networks: an overview. IEEE Commun. Surv. Tutor. **19**(2), 855–873 (2017). https://doi.org/10.1109/COMST.2017.2652320
35. J.-C. Zúñiga, B. Ponsard, SIGFOX System Description. Internet-Draft draft-zuniga-lpwan-sigfox-system-description-04, Internet Engineering Task Force (December 2017). Work in Progress. https://datatracker.ietf.org/doc/html/draft-zuniga-lpwan-sigfox-system-description-04
36. J. de Carvalho Silva, J. J. P. C. Rodrigues, A. M. Alberti, P. Solic, A. L. L. Aquino, in *2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech)*. LoRaWAN - a low power WAN protocol for Internet of Things: a review and opportunities (IEEE, Piscataway, 2017), pp. 1–6. https://www.ieee.org/
37. N. Sornin, M. Luis, T. Eirich, T. Kramp, O. Hersent, LoRaWAN™ Specification (2016)
38. Semtech Corporation, SX1272/3/6/7/8: LoRa ModemDesigner's Guide (2013). http://www.semtech.com/images/datasheet/LoraDesignGuide_STD.pdf
39. N. Blenn, F. A. Kuipers, Lorawan in the wild: measurements from the things network. CoRR. **abs/1706.03086** (2017). 1706.03086
40. DASH7™ Alliance, DASH7 Alliance Wireless Sensor and Actuator Network Protocol Version 1.1 (2017)
41. Q. Wang, X. Vilajosana, T. Watteyne, 6TiSCH Operation Sublayer Protocol (6P) (2018). Internet-Draft draft-ietf-6tisch-6top-protocol-12, Internet Engineering Task Force (2018). Work in Progress. https://datatracker.ietf.org/doc/html/draft-ietf-6tisch-6top-protocol-12. Accessed 11 Oct 2018
42. L. Thomas, R. Shalu, J. J. Daniel, S. V. R. Anand, M. Hegde, in *2017 9th International Conference on Communication Systems and Networks (COMSNETS)*. 6TiSCH operation sublayer (6top) implementation on contiki os, (2017), pp. 423–424. https://doi.org/10.1109/COMSNETS.2017.7945424
43. H. A. A. Al-Kashoash, A. H. Kemp, Comparison of 6LoWPAN and LPWAN for the Internet of Things. Australian Journal of Electrical and Electronics Engineering. **13**(4), 268–274 (2016). https://doi.org/10.1080/1448837X.2017.1409920
44. S. Thielemans, M. Bezunartea, K. Steenhaut, in *2017 Wireless Telecommunications Symposium (WTS)*. Establishing transparent IPv6 communication on LoRa based low power wide area networks (LPWANs), (2017), pp. 1–6. https://doi.org/10.1109/WTS.2017.7943535
45. A. Abrardo, A. Pozzebon, A multi-hop LoRa linear sensor network for the monitoring of underground environments: the case of the Medieval Aqueducts in Siena, Italy. Sensors. **19**(2) (2019). https://doi.org/10.3390/s19020402
46. M. Anedda, C. Desogus, M. Murroni, D. D. Giusto, G. Muntean, in *2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. An energy-efficient solution for multi-hop communications in Low Power Wide Area Networks, (2018), pp. 1–5. https://doi.org/10.1109/BMSB.2018.8436722
47. C. Liao, G. Zhu, D. Kuwabara, M. Suzuki, H. Morikawa, Multi-hop LoRa networks enabled by concurrent transmission. IEEE Access. **5**, 21430–21446 (2017). https://doi.org/10.1109/ACCESS.2017.2755858
48. B. Sartori, S. Thielemans, M. Bezunartea, A. Braeken, K. Steenhaut, in *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. Enabling RPL multihop communications based on LoRa, (2017), pp. 1–8. https://doi.org/10.1109/WiMOB.2017.8115756
49. IEEE, IEEE 802.15 WPAN^{TM} Task Group 4w (TG4w) Low Power Wide Area (LPWA) (2011). Available online: http://grouper.ieee.org/groups/802/15/pub/TG4w.html Accessed 23 May 2019
50. Standards news. IEEE Commun. Stand. Mag. **2**(4), 12–17 (2018). https://doi.org/10.1109/MCOMSTD.2018.8636827
51. Z. Shelby, K. Hartke, C. Bormann, The Constrained Application Protocol (CoAP). RFC Editor (2014). https://doi.org/10.17487/RFC7252. https://rfc-editor.org/rfc/rfc7252.txt
52. N. Accettura, L. A. Grieco, G. Boggia, P. Camarda, in *2011 IEEE International Conference on Mechatronics*. Performance analysis of the RPL routing protocol, (2011), pp. 767–772. https://doi.org/10.1109/ICMECH.2011.5971218
53. U. Kulau, S. Müller, S. Schildt, A. Martens, F. Büsching, L. Wolf, in *2017 IEEE 18th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. Energy efficiency impact of transient node failures when using RPL, (2017), pp. 1–6. https://doi.org/10.1109/WoWMoM.2017.7974283
54. K. Heurtefeux, H. Menouar, N. AbuAli, in *2013 IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. Experimental Evaluation of a Routing Protocol for WSNS: RPL robustness under study, (2013), pp. 491–498. https://doi.org/10.1109/WiMOB.2013.6673404
55. Ieee standard for low-rate wireless networks. IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011), 1–709 (2016). https://doi.org/10.1109/IEEESTD.2016.7460875
56. M. Rizzi, P. Ferrari, A. Flammini, E. Sisinni, M. Gidlund, in *2017 IEEE 13th International Workshop on Factory Communication Systems (WFCS)*. Using LoRa for industrial wireless networks, (2017), pp. 1–4. https://doi.org/10.1109/WFCS.2017.7991972
57. P. Thubert, An architecture for IPv6 over the TSCH mode of IEEE 802.15.4 (2018). Internet-Draft draft-ietf-6tisch-architecture-14, Internet Engineering Task Force (2018). Work in Progress. https://datatracker.ietf.org/doc/html/draft-ietf-6tisch-architecture-14. Accessed 19 Dec 2017
58. P. Du, G. Roussos, in *2012 4th Computer Science and Electronic Engineering Conference (CEEC)*. Adaptive time slotted channel hopping for wireless sensor networks, (2012), pp. 29–34. https://doi.org/10.1109/CEEC.2012.6375374
59. R. Tavakoli, M. Nabi, T. Basten, K. Goossens, in *2015 IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems*. Enhanced time-slotted channel hopping in WSNS using non-intrusive channel-quality estimation, (2015), pp. 217–225. https://doi.org/10.1109/MASS.2015.48
60. V. Kotsiou, G. Z. Papadopoulos, P. Chatzimisios, F. Theoleyre, in *Proceedings of the 20th ACM International Conference on Modelling, Analysis and Simulation of Wireless and Mobile Systems. MSWiM '17*. Label: link-based adaptive blacklisting technique for 6TiSCH wireless industrial networks (ACM, New York, 2017), pp. 25–33. https://doi.org/10.1145/3127540.3127541
61. P. Li, T. Vermeulen, H. Liy, S. Pollin, in *2015 International Symposium on Wireless Communication Systems (ISWCS)*. An adaptive channel selection scheme for reliable TSCH-based communication, (2015), pp. 511–515. https://doi.org/10.1109/ISWCS.2015.7454397
62. R. M. Sandoval, A. Garcia-Sanchez, J. Garcia-Haro, T. M. Chen, Optimal policy derivation for transmission duty-cycle constrained LPWAN. IEEE Internet of Things J. **5**(4), 3114–3125 (2018). https://doi.org/10.1109/JIOT.2018.2833289
63. D. Fanucchi, R. Knorr, B. Staehle, in *2015 IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. Impact of network monitoring in IEEE 802.15.4e-based wireless sensor networks, (2015), pp. 1–3. https://doi.org/10.1109/WoWMoM.2015.7158174
64. W. Liu, M. Chwalisz, C. Fortuna, E. De Poorter, J. Hauer, D. Pareit, L. Hollevoet, I. Moerman, Heterogeneous spectrum sensing: challenges and

methodologies. EURASIP J. Wirel. Commun. Netw. **2015**(1), 70 (2015). https://doi.org/10.1186/s13638-015-0291-8
65. J. Famaey, R. Berkvens, G. Ergeerts, E. D. Poorter, F. V. d. Abeele, T. Bolckmans, J. Hoebeke, M. Weyn, Flexible multimodal sub-gigahertz communication for heterogeneous internet of things applications. IEEE Commun. Mag. **56**(7), 146–153 (2018). https://doi.org/10.1109/MCOM.2018.1700655
66. United Nations, United Nations Treaty Series: treaties and international agreements registered or filed and recorded with the Secretariat of the United Nations. Vol. 30 (1949). https://treaties.un.org/doc/Publication/UNTS/Volume%2030/v30.pdf
67. International Telecommunication Union, Collection of the basic texts adopted by the Plenipotentiary Conference (2015). http://handle.itu.int/11.1004/020.1000/5.21.61.en.100
68. International Telecommunication Union, Radio Regulations: Articles. Vol. 1 (2016). http://www.itu.int/dms_pub/itu-r/opb/reg/R-REG-RR-2016-ZPF-E.zip
69. H. Mazar, *Radio Spectrum Management: Policies, Regulations and Techniques*. (Wiley, Hoboken, 2016)
70. A. Sendin, M. A. Sanchez-Fornie, I. Berganza, J. Simon, I. Urrutia, *Telecommunication Networks for the Smart Grid: Artech House power engineering series*. (Artech House Publishers, Norwood, 2016)
71. International Telecommunication Union, Resolution ITU-R 54-2: studies to achieve harmonization for short-range devices (2015). https://www.itu.int/dms_pub/itu-r/opb/res/R-RES-R.54-2-2015-PDF-E.pdf
72. International Telecommunication Union, Report ITU-R SM.2153-6: technical and operating parameters and spectrum use for short-range radiocommunication devices (2017). https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-SM.2153-6-2017-PDF-E.pdf
73. International Telecommunication Union, Recommendation ITU-R SM.2103-0: global harmonization of short-range devices categories (2017). https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.2103-0-201709-I!!PDF-E.pdf
74. European Union, Decision No 243/2012/EU of the European Parliament and of the Council of 14 March 2012 establishing a multiannual radio spectrum policy programme (2012). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012D0243
75. (Publications Office of the European Union, Luxembourg, 2014). https://doi.org/10.2775/11255
76. K.-D. Borchardt, *The ABC of EU law*. (Publications Office of the European Union, Luxembourg, 2016). https://doi.org/10.2775/953190
77. European Union: Consolidated Versions of the Treaty on European Union and the Treaty on the Functioning of the European Union (2016). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02016ME/TXT-20160901
78. European Union: Regulation (EU) No 182/2011 of the European Parliament and of the Council of 16 February 2011 laying down the rules and general principles concerning mechanisms for control by Member States of the Commission's exercise of implementing powers (2011). http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32011R0182
79. European Union: Communication from the Commission to the European Parliament and the Council; Implementation of Article 290 of the Treaty on the Functioning of the European Union. COM (2009) 673 final (2009). http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:52009DC0673
80. European Union: Commission Decision of 26 July 2002 establishing a Radio Spectrum Policy Group (2002). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02002D0622-20100107
81. CEPT, CEPT Background (2017). Available online: https://cept.org/cept/background Accessed 8 Dec 2017
82. CEPT/ECC, ECC All About Our Organisation; The Electronic Communications Committee (2017)
83. CEPT/ECC and European Union, Memorandum of Understanding Between the European Commission ("the Commission") and the European Conference of Postal and Telecommunications Administrations ("CEPT") (2004). https://cept.org/files/6682/MoU%20EC%20and%20CEPT.pdf
84. CEPT/ECC, *Rules of Procedure for the Electronic Communications Committee (and its subordinate entities)*, 15th edition. (CEPT/ECC, Copenhagen, 2017). https://cept.org/ecc/
85. CEPT, European Communications Office Documentation Database. Available online: http://www.ecodocdb.dk/ Accessed 10 Dec 2017.
86. European Union, Regulation (EU) No 1025/2012 of the European Parliament and of the Council of 25 October 2012 on European standardisation, amending Council Directives 89/686/EEC and 93/15/EEC and Directives 94/9/EC, 94/25/EC, 95/16/EC, 97/23/EC, 98/34/EC, 2004/22/EC, 2007/23/EC, 2009/23/EC and 2009/105/EC of the European Parliament and of the Council and repealing Council Decision 87/95/EEC and Decision No 1673/2006/EC of the European Parliament and of the Council (2012). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02012R1025-20151007
87. ETSI, Building the future: work programme 2017–2018 (2017). https://www.etsi.org/images/files/WorkProgramme/etsi-work-programme-2017-2018.pdf
88. ETSI, Long-term strategy 2016–2021 (2018). http://www.etsi.org/technologies-clusters/white-papers-and-brochures/etsi-long-term-strategy. Accessed 28 Feb 2018
89. ETSI, Role in Europe. Available online: http://www.etsi.org/about/what-we-are/role-in-europe Accessed 10 Dec 2017
90. European Union, CIRCABC - Radio Spectrum Committee (RSC). Available online: https://circabc.europa.eu/faces/jsp/extension/wai/navigation/container.jsp Accessed 11 Dec 2017
91. European Union, Radio spectrum CEPT mandates: list of EC mandates to CEPT (2014). Available online: https://ec.europa.eu/digital-single-market/en/news/radio-spectrum-cept-mandates-0 Accessed 11 Dec 2017
92. CEPT/ECC and ETSI, European process of standardisation and regulation for radiocommunications devices and systems - cooperation between CEPT/ECC and ETSI (2018). https://cept.org/files/7326/ECC-ETSI%20cooperation%20process-2018%20final.pdf
93. CEPT/ECC, ETSI: Memorandum of Understanding between the CEPT Electronics Communications Committee (ECC) and the European Telecommunications Standards Institute (ETSI) (2016). https://cept.org/files/6682/MoU%20ECC%20and%20ETSI%20-%20update%202016.pdf
94. CEPT/ECC and ETSI, ETSI-ECC cross reference matrix (2017). Available online: https://cept.org/files/7326/ETSI-ECC_cross_reference_matrix-October2017v3.xlsx Accessed 11 Dec 2017
95. European Union, National Regulatory Authorities (2018). Available online: https://ec.europa.eu/digital-single-market/en/national-regulatory-authorities Accessed 28 Aug 2018
96. BIPT, Telecommunications-Radio communications. Available online: http://www.bipt.be/en/operators/bipt/international-relations/telecommunications-radio-communications Accessed 11 Dec 2017
97. Ofcom, Spectrum (international work) (2010). Available online: https://www.ofcom.org.uk/about-ofcom/international/spectrum Accessed 11 Dec 2017
98. European Union, Commission Decision of 6 April 2000 establishing the initial classification of radio equipment and telecommunications terminal equipment and associated identifiers (2000). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32000D0299
99. European Union, Commission Implementing Regulation (EU) 2017/1354 of 20 July 2017 specifying how to present the information provided for in Article 10(10) of Directive 2014/53/EU of the European Parliament and of the Council (2017). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017R1354
100. CEPT, R&TTE and RE Equipment Classes (2014). Available online: https://www.efis.dk/sitecontent.jsp?sitecontent=RTTE_sub-classes Accessed 11 Jan 2018
101. European Union, Opinion of the RSC on a draft Commission Mandate to CEPT on SRD radio spectrum harmonisation (2004). https://ec.europa.eu/digital-single-market/en/news/radio-spectrum-ceptmandates-0
102. European Union, Commission Decision of 16 May 2007 on harmonised availability of information regarding spectrum use within the Community (2007). https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32007D0344
103. CEPT, ECO Frequency Information System. Available online: https://www.efis.dk/ Accessed 12 Jan 2018
104. European Union, Mandate to CEPT on the use of EFIS for publication and access to spectrum information within the Community (2005). https://ec.europa.eu/digital-single-market/en/news/radio-spectrum-ceptmandates-0
105. European Union, Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the

Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC (2014). https://eur-lex.europa.eu/legal-content/GA/TXT/?uri=celex:32014L0053

106. European Union, Commission communication in the framework of the implementation of Directive 2014/53/EU of the European Parliament and of the Council on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC (Publication of titles and references of harmonised standards under Union harmonisation legislation) (2017). https://eur-lex.europa.eu/legal-content/SV/TXT/?uri=CELEX:52017XC0512(04)
107. European Union, Nando (New Approach Notified and Designated Organisations) Information System. Available online: http://ec.europa.eu/growth/tools-databases/nando/ Accessed 13 Feb 2018
108. CEPT/ECC, *Working Methods for the Electronic Communications Committee (and its sub-ordinate entities)*, 28th edition. (CEPT/ECC, Copenhagen, 2017). https://cept.org/ecc/
109. CEPT/ECC, ECC Decision of 14 March 2008 on the withdrawal of ERC/DEC/(01)04, ERC/DEC/(01)09, ERC/DEC/(01)13, ERC/DEC/(01)15 and ERC/DEC(01)18 (2008). https://www.ecodocdb.dk/download/6e386e17-bc5d/ECCDEC0804.PDF
110. European Union, Commission Implementing Decision of 4.8.2015 on a standardisation request to the European Committee for Electrotechnical Standardisation and to the European Telecommunications Standards Institute as regards radio equipment in support of Directive 2014/53/EU of the European Parliament and of the Council (2015). https://ec.europa.eu/growth/toolsdatabases/mandates/index.cfm?fuseaction=search.detail&id=556#
111. ETSI, Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 2: Harmonised Standard for access to radio spectrum for non specific radio equipment (2018). https://www.etsi.org/deliver/etsi_en/300200_300299/30022002/03.02.01_60/en_30022002v030201p.pdf
112. ETSI, Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 3-1: Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU; Low duty cycle high reliability equipment, social alarms equipment operating on designated frequencies (869,200 MHz to 869,250 MHz) (2016). https://www.etsi.org/deliver/etsi_en/300200_300299/3002200301/02.01.01_60/en_3002200301v020101p.pdf
113. ETSI, Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 3-2: Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU; Wireless alarms operating in designated LDC/HR frequency bands 868,60 MHz to 868,70 MHz, 869,25 MHz to 869,40 MHz, 869,65 MHz to 869,70 MHz (2017). https://www.etsi.org/deliver/etsi_en/300200_300299/3002200302/01.01.01_60/en_3002200302v010101p.pdf
114. ETSI, Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 4: Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU; Metering devices operating in designated band 169,400 MHz to 169,475 MHz (2017). https://www.etsi.org/deliver/etsi_en/300200_300299/30022004/01.01.01_60/en_30022004v010101p.pdf

Publisher's Note