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Technology agnostic regulatory criteria for licence-exempt spectrum

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Abstract

Purpose – *Spectrum regulations have major impact on the development and deployment of innovative technologies. Current regulations for license-exempt radio spectrum generally are given in terms of technology-related criteria. This paper aims to propose a set of metrics that can be used to define technology-agnostic spectrum regulations which encourage rather than restrict technology innovation.*

Design/methodology/approach – *This paper builds on and expands two other papers on regulatory criteria for license-exempt spectrum which define metrics for spectrum loading and spectrum sharing efficiency. Here, we add metrics for Block Edge Masks and for medium access adaptivity. This gives a complete toolset for the management of radio spectrum.*

Findings – *Because of the diversity of use of license-exempt spectrum, performance criteria must be formulated in terms that abstract from the details of equipment properties. Instead, they must be formulated in terms of spectrum utilization dimensions: RF power, time and frequency occupation. The result is a concise set of metrics that can be applied to the regulation or management of shared spectrum.*

Research limitations/implications – *The mathematics used in this paper deal with high-level parameters and may ignore factors that are important in certain cases and may require refinement.*

Practical implications – *The implications of the proposed metrics include an increase emphasis on the objectives of spectrum policy and on measures to assure efficient spectrum utilization both within frequency bands and between adjacent bands.*

Social implications – *There are no social implications the authors are aware of.*

Originality/value – *The originality of this work lies in recognizing that the extreme variety of devices and mode of operation deployed in license-exempt spectrum calls for spectrum management criteria that are technology agnostic.*

Keywords *Regulation, Wireless, License exempt, Spectrum management*

Paper type *Research paper*

1. Introduction

This paper proposes to expand the concept of generic radio regulation to the domain of short-range devices (SRDs) and licence-exempt spectrum (LE spectrum) based on block edge masks (BEMs) and in-band sharing criteria. Because of the great diversity of LE equipment, a new approach to in-band sharing is proposed which uses multi-dimensional metrics which are well suited for high-density, heterogeneous deployments of wireless devices.

The scope of this paper is horizontal sharing[1] of radio spectrum, i.e. sharing of the same frequency band by a population of devices with the same regulatory status[2]. No assumptions are made about the applications or the technologies used in a given frequency band.

Licence-exempt applications play an indispensable role in the daily lives of consumers, businesses and public organizations. A clear example can be found in Wi-Fi, which carries

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the majority of the world's data traffic (CISCO, 2017). However, the number of supporting applications is much broader, ranging from short-range RF identification tags to enter a building, baby monitors, wireless doorbells and intruder alarms, to city or region-wide networks supporting broadband data or machine-to-machine (M2M) connectivity. Recent studies for the European Commission (EC) estimated that there were 5.24 billion licence-exempt devices in the 28 member states of the European Union, rising to 75.38 billion by 2030. This represents a cumulative annual growth rate (CAGR) of 19.45 per cent (Tech4i2, 2015). With the emergence of M2M communications and the Internet of Things, driven by the promises of Big Data, the economic importance of SRDs is rapidly growing as a complement to mobile network based M2M or Internet of Things (IoT) communications.

Licence-exempt access is meant to provide easy and unencumbered access to spectrum. It is an important driver for innovation and its importance is recognized by the EU. The proposed Electronics Communications Code (EC, 2016, recital 113) which amends the current regulatory framework affirms the principle to use general authorizations to spectrum access in preference to individual licences for spectrum However, the European regulations for licence-exempt access to spectrum are still overly complex. The European SRD Decision (EC, 2013) defines a partially overlapping and/or inconsistent set of 59 subband definitions for the spectrum below 5GHz. Another part of the problem is that the SRD Decision exports the responsibility for certain regulatory requirements to harmonized standards. Although, the Radio Equipment Directive (EC, 2015), in theory, provides the possibility to enter the market without adhering to the applicable harmonized standard, it is in reality virtually impossible to enter the market without it. This further exacerbates the problem because these harmonised standards add another layer of technical requirements. For example, the harmonized standard for Wideband Data Transmission Systems operating in the 2.4GHz band contains 90 pages (ETSI, 2016b).

The current distribution of responsibilities in Europe between the regulatory bodies (e.g. the European Commission and the Electronic Communications Committee (ECC)) and the technical bodies (e.g. the European Telecommunications Standards Institute, ETSI) leaves much of the detailed technical work to the latter. This gives industry a major opportunity in shaping the *de facto* compliance criteria for the benefit of its members: it comes down to letting the butcher determine the minimum quality of the meat he sells. The complex and detailed set of technical criteria that are typical of harmonized compliance standards, constrain designer choice without contributing in a measurable sense to efficient use of spectrum. Compared to other jurisdictions, the legal restrictions on the use of licence-exempt spectrum in Europe are exceptional in their details and specificity. Therefore, Europe's wireless industry is at a disadvantage in world markets.

This paper proposes a new approach that puts regulatory decision-making where it belongs: with regulatory authorities. Instead of developing regulation and compliance criteria in a bottom-up approach based on applications and equipment considerations, the new approach develops technology independent regulations and compliance criteria based on high-level economic and technology considerations. The new approach combines the Block Edge Masks concept (CEPT, 2009; Forde and Doyle, 2010) to regulate inter-band sharing criteria with in-band spectrum utilization metrics (Kruys *et al.*, 2016) that counter misuse and reward spectrum utilization efficiency. By carefully setting maximum and minimum limits for these metrics, efficient spectrum utilization is rewarded without restricting design freedom.

2. Policy considerations

2.1 Fairness and efficiency

The purpose of spectrum regulations is to implement a spectrum policy that typically is concerned with two very broad and difficult to quantify objectives: *fairness* and *efficiency* in the shared use of radio spectrum. In general, the meaning of *fair use* is intuitively understood but specifics prove difficult to define and agree on. Notably, in the case of a licence-exempt spectrum, a commonly accepted, broad definition of fair use has proven elusive. Similarly, the concept of fair spectrum sharing mechanisms for LE spectrum as proposed in Witvliet *et al.* (2012) nor ideas based on "Cognitive Radio" have resulted in useful designs or implementations (Tragos *et al.*, 2013).

Instead of seeking fair and optimum distribution of spectrum usage, *the avoidance of exclusion of use* may be considered a suitable and attainable alternative. Applied to spectrum sharing, fair use of shared spectrum requires that, within the limits of medium overload, no user can reasonably deny other users access to the shared spectrum.

Efficiency of spectrum use denotes the concept that the radio does not occupy more radio resources than necessary (given the state-of-the-art in technology) to accomplish its function. It seeks to maximize productive use of RF spectrum, regardless of scale. Spectrum sharing, as in all sharing, is a *non-zero sum game* in which the value of the sum varies with the rules by which the game is played – what degrees of freedom the players are allowed. There are two sides to efficiency: transmission efficiency and systems efficiency. The former denotes the number of bits per second per unit of spectrum; it is analogous to speed for cars, and it is typically touted by product brochures to entice buyers. Systems efficiency is a capacity measure expressed in bits per second per area. It is analogous to the fuel consumption per ton of weight of a vehicle; it includes both transmitter and receiver factors. Transmission efficiency varies inversely with transmission range and typically comes at a cost in systems efficiency, and, therefore plays a role in formulating the rules of the sharing game, e.g. in the form of regulatory *spectrum sharing efficiency* criteria.

2.2 The role of adaptivity

As noted above, *fair use* of shared spectrum requires that no user can deny other users access to the sharing domain. At low levels of use, sharing spectrum tends to present few problems, but when the number of users increases, there is a risk of overload situations – sometimes referred to as the tragedy of the (spectrum) commons. Preventing overload could be addressed through fixed or limited allocations to each of the users of the sharing domain. Although setting such limits do serve to prevent "winner take all" effects, it is inflexible and typically wasteful. Avoiding waste requires that no resource that is available is left unused when there is demand for that resource.

Systems sharing a spectrum resource have to adapt to local conditions; this is known as adaptive medium access (AMA). It serves the purpose of avoiding waste, but it pays the price of imperfect capacity allocation, and therefore some loss of efficiency. AMA is naturally related to the degree of spectrum use: a system using more spectrum resources than a given threshold must use adaptive medium access. The actual mechanism for AMA is not important because each of these mechanisms has its benefits and shortcomings (ECC, 2012). Imposing AMA on all equipment would be unfair, and therefore adaptive and non-adaptive medium accesses have to be accommodated in the same sharing space. Defining mechanisms of AMA does not belong to the scope of regulation. Instead, regulation should be concerned with the effectiveness of AMA, regardless how it is implemented. Here too, as in the case of the metrics for transmitter and receiver performance, a significant degree of abstraction is needed that allows implementations to evolve under the umbrella of generic requirements.

3. A new approach

The conventional approach to regulating the LE spectrum use is to set limits for frequency use and RF power levels, possibly complemented by restrictions in time. These regulatory limits are translated into detailed technical compliance requirements which frequently are application-specific or technology-specific. Equipment must be shown to meet these requirements before it can be sold and used. This approach has evolved over time and its inherent restrictions have become a burden on industry, as well as users.

The new approach is application and technology agnostic. Instead of detailed technical compliance criteria, it uses two sets of multi-dimensional metrics that define the sharing space together with operational criteria for its usage. The dimensions of metrics are common to all radio technologies: transmission energy[3], frequency and time. The metrics that define the limits of the "spectrum resource" to be made available are called the statutory limits and include adjacent band sharing criteria in the form of BEMs. The operational criteria assure adequate spectrum sharing behaviour amongst the users of a given band (see Figure 1).

3.1 Statutory limits

3.1.1 In-band spectrum utilization limits. The in-band statutory limits define the total spectrum resource in terms of RF power, frequency and time. The statutory limits for a given band will depend on the applications foreseen, as well as on the existing or planned use of the adjacent frequency bands. Intended applications and mode of use of a given band will define each of these dimensions. For example, it may be considered necessary to limit the maximum RF power, the maximum bandwidth or the maximum duty cycle or combinations thereoff. The following examples clarify this.

In case of the 863-870MHz and the 2,400-2483.5MHz bands, the range of applications is wide and the RF power limits are low. The 2.4GHz band currently is covered by four different regulatory profiles: for non-specific short range devices, for wideband data Systems, for RFID devices[4] and for radio determination (i.e. radar) devices. The allowed RF power limits range from 10mW to 500mW. In the new approach, the statutory limits for the 2.4GHz band are simply the frequency range and the maximum RF power and maximum power density allowed.

A very different set of statutory limits would be needed for a frequency band dedicated to a different type of use, e.g. long range, low duty cycle use required for certain IoT applications. Here, bandwidth, as well as duty cycle limits, would be beneficial. For a licence-exempt frequency band dedicated to point-to-point applications, antenna directivity could be necessary to avoid interference amongst users of that band. Table I

Figure 1 Statutory limits and operational criteria

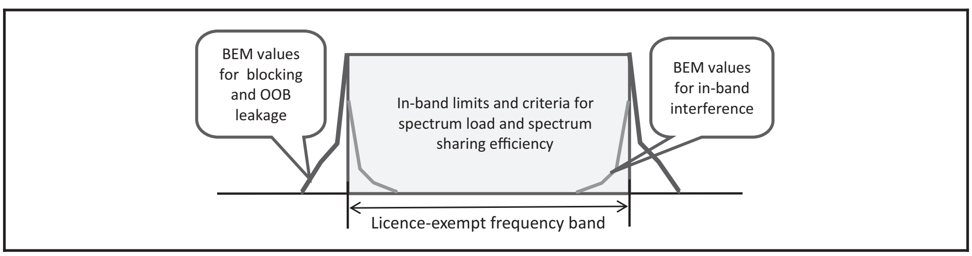


Table I Examples of in-band statutory limits for three popular SRD bands

SRD subband definitions	*43a-45c*	*46a-56b*	*57a-58*
Frequency range	433.05-434.79MHz	863-870MHz	2,400-2483.5MHz
	1.75MHz	7MHz	83.5MHz
RF power	10mW	25mW	100mW
RF power density	10mW/250kHz	25mW/250kHz	100mW/MHz
Duty cycle (%)	100	100	100
Occupied frequency	<l100kHz	<l7MHz	83.5MHz

gives some examples of statutory limits for three licence-exempt bands as defined in the current SRD Decision (EC, 2013).

The statutory limits need not diverge from the basic requirements given in the current regulations, but the operating requirements based on the load and efficiency metrics mentioned are a major departure from the current practice. Although the new approach is forward looking, its basis or starting points must be chosen so as to be compatible with the properties of equipment certified as compliant under the current approach.

3.1.2 Adjacent band interference parameters. The statutory limits set for a given frequency band imply its interference potential for the users of adjacent bands. In the mobile telecommunications domain, Block Edge Masks (BEMs) are the primary regulatory limits imposed on users of mobile telecommunications bands. BEMs specify the in-band power levels, as well as the degree of spillover allowed into the adjacent frequency range. Such BEMs may evolve towards dynamic forms that allow spectrum users to make optimal use of the available frequencies, given the presence of other spectrum users outside these frequencies. Dynamic BEMs are suitable for cases in which both sides – each a licensed entity – are able to interact with each other in some fashion so that mutually acceptable BEMs can be agreed on. However, in the case of licence-exempt spectrum, the entities are numerous and have different properties. Therefore, dynamic BEMs are not an option for managing adjacent band interference if licence-exempt spectrum is involved.

A BEM specification defines out-of-band emission restrictions, and by implication, potential interference levels in the adjacent bands. The parameters of the outbound BEM are the transmitted power and its decrease with increasing frequency distance from the band edge. For the receiving side, these translate into blocking levels and in-band interference which vary with physical distance *d*. This specification may be called the inbound BEM.

The shape of this mask can be straightforward and hides the properties of the underlying emissions. The use of guard bands adds further complexity, and therefore, this subject is left for later work. For the purposes of this discussion, it is sufficient to note that the statutory limits for a given frequency band have to include the outbound BEM. Table II gives examples of the basic parameters for the outbound and inbound BEMs.

The definitions for frequencies f1 through f4 accommodate different bandwidths – up to a point. The values given here are examples only.

Together with the in-band limits, the adjacent band limits provide all the information necessary for adjacent band compatibility assessments. Establishing the statutory limits for a given frequency band is a complex spectrum management task that requires expertise in spectrum engineering as well as in frequency management.

Table II Examples of statutory limits for adjacent band interference

SRD subband definitions	*43a-45c*	*46a-56b*	*57a-58*
Frequency range	433.05-434.79MHz	863-870MHz	2,400-2483,5MHz
OOB leakage			
@ f1 = MIN (150% BW, 5MHz)	−26dBm/100kHz	−26dBm/100kHz	−16dBm/MHz
@ f2 = MIN (250% BW, 10MHz)	−36dBm/100kHz	−36dBm/100kHz	−26dBm/MHz
Interference ref distance (m)	1	1	4
Blocking tolerance level (dBm)	−40	−40	−40
In-band interference tolerance			
@ f3 = MIN (150% BW, 10MHz)	−26dBm/100kHz	−26dBm/100kHz	−16dBm/MHz
@ f4 = MIN (250% BW, 20MHz)	−36dBm/100kHz	−36dBm/100kHz	−26dBm/MHz

3.2 Operational criteria: Metrics for device behaviour

The statutory limits define the sharing space, the operational criteria constrain in-band spectrum sharing behaviour. Given the relative scarcity of the LE spectrum, large device populations sharing the same frequency range will be the rule rather than the exception. One implication of dealing with heterogeneous device populations is that the properties of individual devices must be abstracted in such a way that behaviour criteria cover transmitters and receivers for a wide range of devices. A second implication is that interference must be abstracted as well so that it can be taken into account in formulating new regulatory requirements that address efficient use of the available spectrum. Both of these implications are addressed in Kruys *et al.* (2016) which proposes two such abstractions: multi-dimensional metrics for spectrum load and spectrum sharing efficiency that take into account a number of normalized – and therefore technology agnostic – parameters. These include RF power spectral density, median duty cycle, occupied frequency range and signal-to-interference ratio. Spectrum load and spectrum sharing efficiency can be considered as maximum, respectively minimum *operational criteria* imposed on all devices operating in a given frequency band. The maximum load metric protects spectrum users against each other; the minimum efficiency metric keeps inefficient devices off the market.

3.2.1 The spectrum load metric. The spectrum load metric[5] is an operational requirement that is imposed on all to assure a minimum of fairness amongst spectrum users. It is the product of three parameters: RF power density, median duty cycle and occupied frequency range. Within the maximum set by regulation, developers are free to choose values for the individual parameters. The dimensions of the spectrum load metric are those of the power spectral density: W/Hz

$$L_{SP} = PD^{\frac{2}{PLE}} \cdot DC_m \cdot U_f \text{ W/Hz} \quad (1)$$

The choice of these parameters is motivated as follows. Because of the heterogeneous device population, the normalized RF power has to be expressed as a power spectral density *PD* in a convenient bandwidth. Path loss exponent *PLE* adjusts the spectrum load for propagation losses. The median duty cycle DC_m expresses the value most frequently used rather than an infrequently occurring maximum duty cycle. The U_f parameter gives the ratio between the actual operational frequency range and the statutory frequency range. To account for variable frequency technologies such as frequency hopping, this value is multiplied by the frequency occupation probability expressed in terms of the same bandwidth as used in the power spectral density. This occupation probability is required to model frequency hopping equipment correctly[6].

Table III shows the relative spectrum load values as a percentage of the sharing space for different types of 2.4GHz SRDs under indoor propagation conditions. The statutory limits (in bold) are those of Table I.

Table III Spectrum load figures for popular 2.4GHz SRD technologies

						PLE = 3.3		
	Frequency range (MHz)	*Pout (mW)*	*BW (MHz)*	*PD_e in mW/MHz*	*DC_m (%)*	*U_f (%)*	*L_{sp} (mW/MHz)*	*L_{spr} (dB)*
Statutory limits	*83.5*	*100*	NA	*100*	*100*	*100*	NA	0
Wi-Fi-11g-20	83.5	100.0	18.0	5.56	80	21.6	0.488	−15.2
Wi-Fi-11n-20 (3 × 3)	83.5	100.0	18.0	5.56	80	21.6	0.488	−15.2
Wi-Fi-11ac-80	83.5	100.0	78.0	1.28	80	93.4	0.869	−12.7
BT Cl1	83.5	100.0	1.0	100.00	80	1.1	0.150	−20.4
BT-LE	83.5	10.0	2.0	5.00	80	2.3	0.049	−25.2
ZigBee	83.5	10.0	2.0	5,00	10	2.4	0.006	−34.1
SRD VLDC	83.5	100.0	2.0	50.00	1	2.4	0.003	−38.0

Table III suggests that a spectrum load requirement for a given frequency band should be in the order of 0.5mW/MHz, or approximately −15dB below the theoretical maximum, so as to discourage "heavy users". The optimal value depends on the applications foreseen and the desired spectrum sharing efficiency: the latter can be used to discourage inefficient spectrum use. This is covered in more detail below.

Setting the medium access adaptivity threshold a factor 10 below the spectrum load limit assures that only low-load spectrum users are allowed to operate without adaptivity.

Note that, by taking the ratio of the actual value and the statutory limit for PD, the spectrum load metric becomes a dimensionless figure.

3.2.2 The spectrum sharing efficiency metric. The efficiency of spectrum utilization is a subject much research largely motivated by the economics of mobile telecommunications. Most, if not all, of the publications on the subject deal with homogeneous device populations operating in licensed spectrum (Rysavy, 2014; FCC, 2011; Lee, 2008; ITU-R, 2017). Very little has been done on extending such metrics to licence-exempt spectrum populated by a heterogeneous device population. Lee (2008) proposes a spectrum efficiency metric based on the ratio of user traffic to licensed spectrum occupancy only.

For licence-exempt spectrum, a metric is needed that accommodates a wide range of device behaviours sharing the same spectrum without any coordination. This metric is called the *spectrum sharing efficiency metric.* It expresses the net transmission rate of a system in a busy environment relative to its spectrum occupancy, taking into account the presence of background interference. A key factor in this metric is the signal to interference ratio (SIR) because it determines the spectrum re-use distance between systems. Other factors include the transmission rate, the net protocol efficiency, the radiated RF power, the spectrum occupancy[7], implementation margin H and the prevailing channel conditions for given path loss exponent; this generalization may not be applicable to all environments, but given the inherent uncertainty about actual path loss conditions, it is adequate for many licence-exempt cases. The result is given in equation (2):

$$M_{she} = \frac{(E_{prot} \cdot E_o)}{PD^{\frac{2}{PLE}} \cdot U_f \cdot 10^{\left(\frac{2(SIR+H+RBI)}{10.PLE}\right)}} b/s/W \tag{2}$$

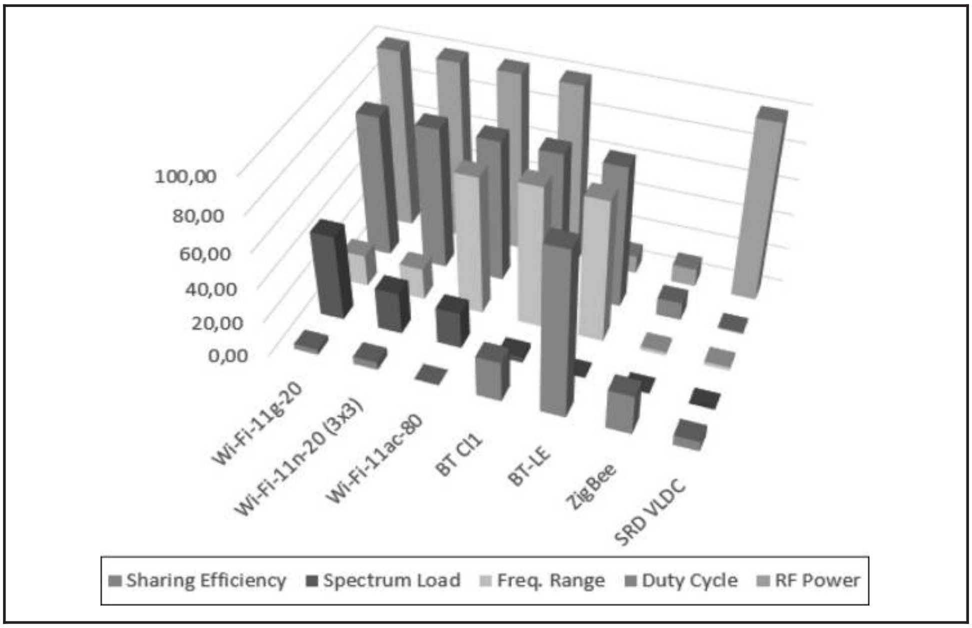
The inclusion of the terms $PD^{2/PLE}$ and U_f in equation (2) makes it clear that the sharing efficiency requirement for a given frequency band can be met in various ways – including the trading of occupied frequency for *SIR* or transmission rate for RF power spectral density. Because of the impact of the propagation conditions, equations (2) and (3) include the path loss exponent *PLE*. Which PLE value is applied to a given frequency band is a regulatory decision.

The term *RBI* models the background interference at the receiver: a higher level of background interference has the same effect as a higher SIR for the same transmission rate: a reduction in spectrum sharing efficiency. In the LE spectrum, the in-band interference consists primarily of the transmissions of other SRDs, including transmissions of adaptive SRDs that do not detect other spectrum users[8]. The value of the RBI parameter will have to be determined on the basis of real-world observations and expectations of device properties and densities. Incorporating RBI in the sharing efficiency assessment removes the need for the specification and measuring of conventional receiver compliance criteria.

Figure 2 makes use of equations (1) and (2) to focus on the essential property of the sharing efficiency metric: demonstrating the interaction of the transmitter power, the receiver SIR, path loss conditions and background interference.

Figure 2 does not show the effect of transmission rate adaptivity: as the transmission rate drops, the SIR drops as well and tolerance for interference, and therefore the sharing efficiency increases[9].

Figure 2 Spectrum load and sharing efficiency for popular SRD technologies



3.2.3 The adaptive medium access metric. AMA is perceived as a panacea that assures efficient but uncoordinated use of radio spectrum. Although this perception is not correct, AMA is a necessary function in licence-exempt spectrum. This paper is not the place to describe or even list AMA mechanism and their qualities, instead the focus will be on function and effect.

The function of AMA is not to improve spectrum capacity or efficiency but to avoid interference amongst the systems operating in a given sharing space using adaptive means that are aware of local conditions. The awareness requires extracting information from the environment, the adaptivity requires adjustment of medium access to minimize interference caused:

- The required information can be obtained directly, e.g. by sensing the medium at transmitter (and receiver) or indirectly, e.g. by monitoring own throughput. Which method is the best depends on equipment properties, as well as on circumstances. Regardless of the method chosen, there is always a significant degree of uncertainty in the information obtained, and this limits the effectiveness of AMA.
- The method of adaptation likewise depends on equipment properties but also on the tolerance for interference of other users of the sharing space.

Owing to the diversity of SRD equipment properties and usage, defining one or a few methods of AMA is not sufficient and restricts novel implementations (ETSI, 2016b). Avoiding such restrictions while maintaining compliance with the intent of the regulation requires a switch in focus from mechanism to effectiveness is crucial. The effectiveness of AMA functionality is easily measured by looking for its effect instead of measuring the details of its operation. This approach has the inherent advantage of being open-ended and future-proof.

An essential element of the AMA operation is the threshold[10] that triggers AMA behaviour. In the case of direct medium sensing, the threshold can be the energy level required as trigger. In the case of indirect detection methods, the rate of transmission error or failure may be used. Which type of threshold is adequate depends to a large extent on the typical mode of operation, including the operating range: at short range, transmitter and receiver may have roughly the same view of the shared medium; at long range, this is not the case. Therefore, medium sensing may work reasonably well[11] at short range, but transmission success rate monitoring will be more effective at long range. A suitable threshold definition takes into account the detection method used. For direct sensing methods, the threshold can be related to RF power level on the medium.

$$TH_{dir} = (-nn + \Delta)\ \text{dBm/MHz} \tag{3}$$

Here, $-nn$ is the baseline detection threshold for a given nominal transmitter power spectral density. Modifier Δ allows the threshold to be relaxed for lower power levels.

For indirect methods, a minimum number of events has to be monitored before the threshold can be considered to be exceeded. This threshold can be modified with the median duty cycle: a higher duty cycle requires a lower error rate as trigger for adaptive action:

$$TH_{ind} = \frac{Tx_{err}}{Tx_{suc}} > m\ .\ DC_m \tag{4}$$

Here, m is fixed regulatory parameter that is specific for a given frequency band.

In addition, assessing AMA performance in an implementation-neutral manner requires metrics that address the time aspect of the adaptive behaviour in two ways: the response time t_{rsp} and the revisit time t_{rvt}, the latter being the time between successive instances of medium access.

Both are related to the normal behaviour of the equipment: a high duty cycle calls for a short response time, a low duty cycle allows for a longer response time. The revisit time depends on the channel conditions: a busy channel requires a longer revisit time. Some standards recognize the problem of AMA that is aware of the medium load and specify an application-specific solution – the harmonised EN for the ITS band (ETSI, 2016a) is one example[12]. For a licence-exempt frequency band, a non-specific solution is needed.

These considerations lead towards the following metrics for assessing AMA behaviour using three parameters: t_{rsp}, the delay before adaptive action is taken, t_{ivl}, the interval between successive transmit operations and β, the degree of medium occupation expected. In general, the response time is a device-dependent parameter that is related to the transmission interval, and therefore to the duty cycle of the device: higher duty cycles require a shorter response time. This is captured in equations (5) and (6):

$$t_{rsp} < \frac{1}{DC_m} t_{ivl} \tag{5}$$

$$t_{rvt} > \beta\ .\ t_{ivl} \tag{6}$$

For direct AMA methods, e.g. sensing-based methods, β depends on the observed channel load and on the allowed maximum channel load – i.e. the channel load β_{max} at which the channel is close to saturation, typically 70 per cent[13]. As the medium becomes more heavily used, free time decreases and β should increase. The threshold for medium-busy detection can be the same as the threshold for AMA activation:

$$\beta = \frac{t_{chocc}}{(1 - \beta_{max})\ .\ t_{chfree}} \tag{7}$$

For indirect AMA methods, β is the inverse of m in equation (4); it is the ratio of transmission success over transmission failures: the rate of transmission failures will go up with increasing medium occupation.

These metrics leave the designers much freedom to design AMA algorithms, while verification of compliance to the requirements, as stated, is easy. Given the wide range of characteristics of equipment typically using licence-exempt spectrum, it is not possible to set quantitative limits for the above metrics other than an absolute limit common to all users of the band. A generic limit on the response time, equal to the limit for continuous transmission time, would serve this purpose.

4. Applicability

The approach sketched above to technology agnostic and application neutral regulatory criteria supports a wide variety of systems that make use of licence-exempt radio spectrum. The examples described in the preceding reflect the majority of systems making use of unlicensed spectrum – two-way, point-to-point (PtP) communications. Other types of system making use of the LE spectrum include point-to-multipoint (PtMP) systems, one-way data transmission systems (OWD) systems used in remote controls, RFID systems, radar-based detection (RBD) systems and ultra-wide band (UWB) systems.

In the case of PtMP systems, spectrum load and sharing efficiency are clearly applicable metrics, but the implicit asymmetry in spectrum utilization between the central server and its clients suggests a different criterion. However, if one considers the collection of clients to be one "half" of the system and the central server the other "half", the asymmetry disappears[14]. Whether it makes sense to operate PtMP systems in the LE frequency bands shared with other, different types of system is another matter.

In case of RFID systems, the asymmetry is inherent in the technology. Where RFID systems share a frequency band with other systems, the *spectrum load limit for that band* should apply to the RFID interrogators, but the sharing efficiency metric is less relevant because the EIRP of the interrogators dominates the impact on other users of the band.

In the case of OWD systems, there is no defined receiver, and therefore, it could be argued that the sharing efficiency metric should not apply. However, the essential properties of the receiver are implied in the design of the transmitter, and therefore, the sharing efficiency metric is applicable.

In the case of RBD systems, there are no data transmitted, and therefore, the sharing efficiency metric does not apply.

Whereas in the preceding cases, the inbound and outbound BEMs determine band adjacency issues, in the case of UWB systems, there is band overlap, and in these overlapped bands, different protection criteria for other spectrum users may apply. As the outbound BEM is determined by the statutory limits, overlap between frequency bands can be addressed by statutory limits that reflect these protection criteria. In this way, the outbound BEM becomes a series of subband BEMs. Conversely, the inbound BEM for a UWB band will be series of BEMs that mirror the outbound BEMs of overlapped spectrum users. The maximum spectrum load allowed in a given "UWB band" can be based on the default parameters for this metric; similarly, the sharing efficiency metric and its parameters are applicable.

5. Implementation considerations

The adoption of the metrics proposed in this paper has significant implications[15] for the agencies involved in radio regulations and compliance assessment standards. For each licence-exempt frequency band, a set of statutory limits and operational criteria has to be generated, such that nullifying the compliance of equipment currently on the market is avoided.

The new approach shifts the burden of setting major spectrum parameters back to where they belong, i.e. to administration-led bodies. This task fits well with the available expertise and increases the scope of their work to include band-specific statutory limits and operational requirements. Such work requires an understanding of the intended applications, the projected density of devices as well as the operating conditions within the band and in the adjacent bands. Industry-led bodies should play a key role in providing the required information. Further, it requires taking into account the prevailing – or projected – conditions in a given band regarding in-band and out-of-band interference as given by the applicable BEMs.

The new approach removes the need for detailed intra-band spectrum sharing analysis of licence-exempt spectrum[16]. Instead, the task of product-level spectrum sharing analysis is shifted from technical bodies to the product designer who has to make the engineering choices that make his/her product fit the intended application, as well as the applicable regulatory constraints.

As a result, the task of developing harmonised standards for compliance assessment is greatly simplified. Instead of the elaboration of detailed, device-level parameters and methods of measurement, harmonised standards are needed that map the regulatory requirements to the parameters to be measured, the methods of measurement to be used and the procedures for compliance assessment. As with current assessment protocols, the basis for the assessment is formed by the manufacturers declarations of all relevant parameters which are verified in the measurement procedures.

Further, the enforcement of regulatory requirements is simplified because the measurements required for assessing the compliance are simple and can be performed on off-the-shelf products without expensive laboratory equipment.

The current process of spectrum allocation in the EU requires that industry contributes technological data and market information in the form of (ETSI) systems reference documents (SRdoc) as starting point for spectrum sharing studies and allocation decisions. To support the development of technology agnostic regulatory criteria, such SRDoc remain useful, but their perspective has to change focus towards the long-term use of frequency band and away from product-oriented technical detail.

6. Conclusion

The motivation for technology agnostic regulatory requirements for licence-exempt spectrum is the removal of unnecessary regulatory and compliance constraints and giving designers more freedom to innovate while preserving the efficient use of the available licence-exempt spectrum. This paper proposes to develop such metrics using stable, long-term inter-band criteria such as BEMs and intra-band operational requirements that constrain equipment operation such that spectrum efficiently used and shared, as required by the EC's Radio Equipment Directive.

The parameters that are required to determine compliance are the RF power, median duty cycle and the antenna directivity together with the transmission rate, protocol efficiency and the SIR for the given transmission rate together with the metrics for adaptive medium access. By combining parameters in multi-dimensional metrics, technology specifics are avoided and designer freedom is enhanced.

Adoption of this approach has consequences for the distribution of responsibilities between the ECC and industry as represented in ETSI and details of role of the bodies currently involved may change. The burden of such change has to be weighed against the potential benefits of adopting a truly technology agnostic regulatory and compliance regime for valuable licence-exempt spectrum.

Notes

1. Vertical sharing arrangements are not covered in this paper. Much licence-exempt spectrum is shared with incumbent services that have priority in the use of a given band. A well-known example of such a vertical sharing arrangement are wireless LANs and other access systems operating in the 5 GHz band which is allocated on a primary basis to radar applications. The operating requirements for licence-exempt use include the ability to detect active radar systems and avoid co-channel operation. The vertical sharing arrangement for the sub-GHz spectrum makes use of geo-location databases.

2. For licence-exempt spectrum users such as SRDs, the regulatory status is usually “no-protection, no interference” relative to other “radio services” (users) that have either a primary allocation or a secondary allocation for a given frequency range.
3. “Energy” equates to area of use and/or interference. This is worked out in more detail in subsequent sections.
4. RFID devices are the odd-man-out in this context – that part of the regulation has a historical background. Conflict with other types of use is avoided through geographic separation.
5. See Kruys *et al*. (2016) for the derivation of this metric.
6. This is true for frequency hopping only. In case of adaptive frequency agility, the change of operating frequency occurs much slower, and therefore, the frequency occupation range is the same as the actual bandwidth and the occupation probability is unity.
7. This form gives a more realistic result; in Kruys *et al*. (2016), the occupied frequency factor was not used.
8. This is a major source of interference in a heterogeneous environment. See Annex 1 of (ECC, 2012).
9. This is true for a fixed duty cycle – which implies that the effective throughput drops significantly (e.g. one-fifth in case of 802.11ac-80 at an SIR of 20dB). Even allowing for an increase duty cycle, there is a net gain in the sharing efficiency – thanks to the very large drop in SIR.
10. Current compliance criteria focus on this threshold instead of an assessment of effectiveness of the adaptive effect.
11. As shown in ECC (2012), sensing-based spectrum sharing is not adequate for assuring orderly medium access in licence-exempt spectrum.
12. For details, see ECC (2012), which describes algorithms for distributed congestion control.
13. In ETSI (2015), this is referred to as the channel busy ratio (CBR).
14. This is true for the simple, general case. For systems where multiple client devices share the uplink, it may be true as well – depending on the details of the uplink resource allocations.
15. This paper notes only some of the major implementation considerations concerning the adoption of technology agnostic regulatory criteria. A more detailed view would fill a separate paper.
16. Where vertical sharing is involved, – e.g. RLANs and radar systems in the 5GHz band – the regulatory operating requirements provide a stable, technology neutral reference for vertical sharing studies. The DFS requirements formulated in ITU-R Recommendation M.1652 are an early example of operating criteria for licence-exempt equipment that have been developed by regulatory authorities.

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