Assessment of Spectrum Management Approaches to Private Industrial Networks

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Abstract. Ubiquitous connectivity is one of the foundational technologies enabling data sharing amongst participating components of an industrial internet of things (IIoT) system. The growing pressure to open the mobile market for location specific networks has resulted in new regional licensing and sharing-based models for spectrum access, to allow the emergence of local networks to serve different verticals. While the development of technical solutions for network performance is progressing, less attention has been paid to the spectrum management approaches for the new industrial networks and location specific service offerings. This paper examines solutions to problems currently faced by industry in acquiring spectrum to support the IIoT along with introducing a framework that should be accounted for when assessing the feasibility of the spectrum management approaches. The aspects of how spectrum is currently allocated and how it addresses the IIoT needs were assessed in six selected countries: Canada, Finland, France, Germany, Netherlands, UK and US.

Keywords: Industrial internet of things · LTE · Private networks · Spectrum management · Regulation · 5G

1 Introduction

The fourth industrial revolution, "Industry 4.0", is the next era in industrial production, aiming at improving significantly the flexibility, versatility, usability and efficiency of industrial manufacturing through integrating the internet of things (IoT) and related services in [1]. Intelligent networking can be used by companies for flexible production, optimized logistics, advanced use of data on various production processes. Ubiquitous connectivity is one of the foundational technologies enabling data sharing amongst participating components of an industrial IoT (IIoT) system [2].

Wireless communication, and in particular, the 5th generation mobile networks (5G), is an important means of achieving the required flexibility and efficiency of production [3]. The 5G will not only expand the broadband capabilities of mobile networks but has been designed to provide advanced wireless connectivity suitable for all vertical industries, such as the manufacturing, logistics, transportation, automotive and agricultural sectors. To achieve this, 5G supports three usage scenarios: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communications (URLLC) [4]. In some industrial use cases the

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required network performance and characteristics may be relatively similar to those of public mobile networks, while for some use cases the requirements may be significantly different, particularly related to required network availability, security and privacy [5]. Implementation and deployment of the distinct requirements of industrial applications can be delivered by private networks deployed directly by industrial organizations themselves, or by external service providers [6]. There are recent indications that industry players may prefer to set up their own networks, e.g., the German car manufacturers have shown a preference to operate their own private 5G networks, as they are reluctant to entrust their digitized operations and data to third parties, such as public mobile network operators (MNOs) [7]. If an industrial or a private network is deployed by an organization other than current mobile license holder, e.g., by a micro-operator [8], the organization needs to get access to suitable spectrum. [9] addressed the use of private long term evolution (LTE) networks for mission and business critical mobile broadband communications, analyzed the three plausible service delivery models, and highlighted the role of the spectrum management in assigning dedicated spectrum. Spectrum management aims at allocating spectrum to the right use, and high overall efficiency by assigning it to those who value it most. Ultimately, the spectrum management decisions are about maximizing the value of spectrum, its efficient utilization, and its benefits to society [10].

Traditionally, private mobile radio (PMR) systems have been deployed in specific, rather narrow bands, as the main service has been voice and narrowband data. Due to historical reasons the bands have been very much country specific. However, the spectrum demand has changed towards wider bandwidths to facilitate higher network capacities and higher bitrates. Wireless local area networks, (RLANs) have been used widely in industry environment as a solution to provide wideband local connectivity, but utilization of unlicensed bands and limitation to very short ranges do not often provide the required performance and quality of service (QoS). Instead, employment of standardized wide area technologies, such as LTE, and later 5G could better meet the performance requirements of industrial networks [11]. To date, most third generation partnership project (3GPP) defined LTE bands have been and are being made available for nationwide public mobile networks through competitive awarding, i.e. auctions, and the same approach has dominated the 5G spectrum release so far [12, 13]. Only a few countries have introduced regulatory frameworks for making spectrum available for individually authorized, locally deployed private LTE or 5G networks [14]. As one solution to overcome the spectrum scarcity, variants of 3GPP technologies have been developed suitable for deployment in the license exempt bands, especially to the 5 GHz RLAN bands. However, use of shared bands does not provide sufficient spectrum certainty and quality for all applications and use cases [15].

While there are already some studies on suitable regulatory frameworks for local 5G deployments [16], more detailed studies on locally and temporary shared spectrum [17] and micro licensing and the associated regulatory framework [15], there is no preceding work and method to assess spectrum management approaches in the context of locally deployed IIoT networks. Furthermore, to the best knowledge of the authors, summary of the recent spectrum management approaches in this context has not been presented in the literature. This paper examines, what would be suitable spectrum management approaches facilitating deployment and operation of private and industrial networks to meet the requirements towards the 5G era. The focus is on use cases where private networks are deployed by industrial organizations for their own use and thus they need to get access to suitable spectrum on affordable terms. Information on studied spectrum management approaches have been collected both from public sources and directly from the regulators. This research addresses the planning and authorization processes which are key parts of the overall spectrum management process [18].

The rest of the paper is organized as follows. In Sect. 2, applications and their spectrum and regulatory requirements are discussed, and assessment framework introduced. Next, selected recent spectrum management approaches relevant for private industrial networks are described, assessed and regulatory recommendation given. Finally, conclusions are drawn in Sect. 4.

2 Spectrum and Regulatory Requirements of Private Industrial Networks

The 3GPP has analyzed use cases of vertical industries and defined a set of functional requirements and system parameters related to communication services for each use case in each domain [5, 19]. Several of the developed service performance requirements have an impact on preferred spectrum management approach. High communication service availability can be reached through exclusive access to dedicated spectrum assignments and through protection from harmful interference. Access to wide bandwidths is needed. The required service areas are typically geographically limited, covering one or several, local or regional areas, ranging from indoor coverage, up to few km^2. This means that frequency ranges below 4 GHz with sufficient transmit powers are preferred if outdoor coverage is required. Depending on the application, traffic may range from symmetric up to very asymmetric, in either direction requiring uplink/downlink ratio (UL/DL) flexibility from the technology, the deployment and the band regulation. Use of time division duplex (TDD) technology can provide the required duplex flexibility, though adjacent networks may need to be synchronized, which would limit the applicability. 5G Alliance for Connected Industries and Automation (5G-ACIA) [3] addresses major challenges of 5G, highlighting spectrum and operator models. In order to meet extremely demanding latency and reliability requirements, licensed spectrum and protection from harmful interference are highly preferred.

Investment cycles of vertical industries differ from cycles of the telecom industry: cycles for media and entertainment are typically shorter, ranging between 2–3 years, for automotive industry 7–8 years, energy, manufacturing and mechanical industries 25 years, and for oil & gas from 10 to 25 years [11]. Partly due to this difference, vertical industries may prefer to deploy their own networks. Furthermore, the timing for investing in wireless communications depends solely on their own business plans. For example, in the Netherlands, UtilityConnect [20] has deployed its own dedicated network for smart energy grid applications rather than relying on 3G or 4G networks which were considered too short-term solutions.

Vertical industries require the assurance that for their networks there will be a continuity of service, without unjustified price increases, spectrum re-farming or technology upgrades over their planned life span. On the other hand, deploying and operating a wireless networks for IIoT are not their core business, but an enabler for optimizing operations and productivity, enhancing security and safety, and improving planning and decision making.

This all means that the cost of spectrum should be affordable, suitable authorization process would be application based, and that the applications should be allowed to be submitted any time, based on the business need. It also means, that the license duration should be comparable to the investment cycle, and that overall regulatory certainty is needed for years to come. The key elements of the spectrum management approaches and the preferences are identified and summarized in Table 1.

Table 1. Spectrum management assessment framework.

Spectrum management framework element	Private industrial network preference
Band type	Dedicated bands for applications requiring high spectrum quality, harmonized 3GPP bands for economies of scale
Bandwidth	Applicant defined: sufficient for wideband deployments
Spectrum availability	Full time, guaranteed
Harmful interference protection	Yes
Interference coordination	By regulator, through authorization conditions or automatic through technical solution
Sharing conditions	Stable, pre-defined
Technical or operational restrictions	Pre-defined, no substantial restrictions on network deployment or services
Location and overage area	Applicant defined: outdoor local or regional, indoor. One or multiple areas
Maximum transmit power	Sufficient for required local/regional outdoor and/or indoor coverage
Technology	Technology neutral approach, flexible duplex technology such as TDD allowed
Authorization method	Application based, time-to-air critical
Application timing	Submission any time, based on business need
Authorization duration	In line with investment cycle, typically long, e.g. 10 years
Cost/pricing	Fee, administrative one-off or annual fee, per license/area
Regulatory certainty	High, beyond authorization duration

3 Spectrum Management Approaches for Private Industrial Networks

In a few countries the spectrum management frameworks are already in place or are being defined for making dedicated spectrum available for wideband private networks. Furthermore, shared, license exempt bands are also widely available. The selected exemplary cases present spectrum management approaches in several countries on 2.3 GHz, 2.5 GHz and 3.5 GHz licensed frequency bands considered for LTE or 5G. The license exempt usage of the 5 GHz RLAN bands is also addressed for comparison. Information on studied spectrum management frameworks have been collected both from public national regulatory authority (NRA) sources and interviews.

3.1 Country Specific Spectrum Management Approaches

The C-Band in the Netherlands (NL)

The bands 3410–3500 MHz and 3700–3800 MHz are used by a military satellite earth station in the northern part of the country. In order to protect the incumbent users, those frequencies cannot be used for mobile services north from the Amsterdam – Zwolle line, while the rest of the C-band is available for commercial, nationwide mobile use. The bands are available for local broadband networks, including private LTE networks south from the line, with certain operational limitations [21]. For example, the emitted power towards north must be limited [22]. Deployment and operation of networks in those bands requires a license from the regulator. For the moment, the licenses are temporary, with the end date in 2022 for the higher band and in 2026 for the lower band. For every base station a separate license is needed with the maximum bandwidth of 40 MHz. This opportunity has been popular, more than 150 licenses have been issued and in some areas, like the Rotterdam harbor area, the bands are getting very occupied. As the authorization process is based on the first-come-first-served principle, in most popular areas it may not be possible to get a license. There are plans to remove the earth station from the band, and at the same time reorganize the use of the whole C-band. It seems that one option would be to re-farm the local networks to the 3700–3800 MHz band as planned in Germany and Sweden.

The C-Band in Germany (GER)

In Germany, the band 3400–3700 MHz will be auctioned in 2019 for public mobile networks whereas the band 3700–3800 MHz will be made available for regional and local assignments, based on application. The process allows applying for regional and local assignments not only at the time when the new regulatory frameworks comes to force, but also at a later date, flexibly and in line with the demand. There is currently a large amount of regional and local assignments in the 3400–3700 MHz band, with licenses expiring latest at the end of 2022. Those networks will be relocated to the 3700–3800 MHz band. The German regulator BNetzA has published the planned application procedure and the rules for the band 3700–3800 MHz [23]. Access to the band is based on application and requires an individual authorization from BNetzA. Operators having current access to licensed spectrum in 700–3700 MHz already are only eligible for a temporary access, in case there are unused parts in the 3700–3800 MHz band. License duration is 10 years, and the licenses are transferable.

According to the proposed rules the whole band 3700–3800 MHz will be available for indoor deployments. There are technical restrictions for ensuring that no harmful interference is created outside the facility. The band 3700–3780 MHz is reserved for outdoor regional deployments, and the 3780–3800 MHz for outdoor local deployments.

There are rules also for outdoor deployments to ensure that no harmful interference is created outside the defined coverage area. The locations and the area of the region can be defined based by the applicants. All assignments are based on 10 MHz blocks. The approach is service and technology neutral, though TDD is the only allowed duplex technology, and networks must be synchronized. National roaming is not mandated, but allowed. Efficient use of the assignment is required, also throughout a region, with a principle use-it-or-lose-it. There is a fee for the spectrum use.

The 3.6 GHz WBS Band in Canada (CAN)

The band 3650–3700 MHz is designated in Canada for wireless broadband service (WBS) and fixed and mobile systems fulfilling regulator ISED's technical requirements [24, 25] are permitted. Deployed technologies include WiMax and LTE, which have been adjusted to comply with the specific requirements of the band. Licenses are issued on all-come all-served basis for Tier 4 service areas and there is a service area specific annual fee for the license. The licenses will expire on March 31 of each year, and will generally be renewable upon payment of required fees. The eligibility is not restricted.

The band is shared between all the WBS licensees within the service area, and the licensees are expected to cooperate to identify and resolve possible interference problems by themselves. To assist in facilitating cooperation and coordination, ISED has developed a publicly accessible spectrum management system database (SMS) showing both current license and site-specific data. Licensees will be required to upload their information to the database at least six weeks before putting a site to service and keep it up to date. In addition to coordination between the WBS licensees, they must ensure that no harmful interference is created towards incumbents deployed in the adjacent band and meet coordination distance requirements from the Canada-US border. A public consultation was conducted in 2018 [26], which addressed among other things also the possible need to develop the WBS band regulation further. To date, conclusions based on the responses have not been published.

The 2.6 GHz in France (FRA)

The 3GPP band 38 (2570–2620 MHz) had been planned for public mobile networks, but was not licensed because of the lack of market demand. Therefore, its suitability for wideband PMR networks was investigated through several trials and two public consultations were held. The trials showed that the band 38 is suitable for private LTE networks, and the first consultations concluded that a 40 MHz sub-band, 2575–2615 MHz, could cover the spectrum needs of superfast PMR. It seems that regulator ARCEP has to look in more detail to the case where demand exceeding the supply, particularly what would be the regulatory approach if there is a need to deploy several networks in the same geographical area, aiming to utilize the same band. According to the working assumptions [27] the aim is to grant access to blocs of 10, 15 or 20 MHz, in limited geographical areas and for maximum ten years licenses. Each applicant would have to specify the requested coverage area and justify the spectrum needs within that area. Compliance with the technical conditions of the EU would be required [28], e.g. the use of TDD would be required and the maximum field level at the edge of coverage area is restricted.

The 2.3 GHz band in Finland (FIN)

The 2.3 GHz band is identified globally for IMT [29] and the European regulation by the CEPT and the EU is in place [30]. However, in many European countries the band is used by various incumbents, and removing them would be difficult or impractical. As there are still spectrum resources unused by the incumbents the CEPT has defined a possible regulatory approach for administrations that would prefer to deploy public mobile networks in the band in shared manner employing the licensed shared access (LSA) concept [31].

In Finland the 2.3 GHz band is not designated for public mobile use. The main incumbent primary usage in the band is operation of wireless cameras. The use of the cameras is individually authorized, and the license allows operation of wireless cameras anywhere in the country. The number of cameras is very limited, so there are unused spectrum resources all over the country, in places where the cameras are not in use. Mobile networks could access the band on a secondary basis, but the public mobile network operators in Finland have not shown interest towards accessing the band, especially since the areas to be protected could change over the time and that the remaining areas available for mobile networks would also change consequently. Moreover, a rather complex LSA solution should be employed and still there could be restrictions on the spectrum availability for the mobile network. Private LTE networks could possibly be deployed and operated in rural and remote locations without complex coordination or severe operational restrictions.

Shared Access Mobile Bands in the UK (UK)

The UK regulator Ofcom has published a consultation on shared access in the 3.8–4.2 GHz band, in a portion of the 2.3 GHz band (2390–2400 MHz) and in the 1800 MHz shared spectrum (1781.7–1785 MHz paired with 1876.7–1880 MHz) [32]. The proposed approach is to provide spectrum for local networks in locations unused by other licensed users. The Ofcom proposes a single authorization approach for all three bands. As the bandwidth in the 1800 MHz band is rather limited, this paper addresses only the first two bands. The consultation includes also an interesting regulatory proposal to allow access to the unused parts of the bands awarded to public mobile networks, but that case is not analyzed in this paper further.

The 3.8–4.2 GHz band is currently being used by several incumbent services, but in addition the band could be used for private networks as there are unused spectrum resources. The band is next to the 3.4–3.8 GHz band, which has been identified as a pioneer 5G band in Europe and several countries are looking to expanding the 5G deployments also to the 3.8–4.2 GHz band. The highest 10 MHz of the 2.3 GHz band are used currently for military applications, and also there is room for local network deployments. The 2.3 GHz band 40 is already widely used for 4G deployments, especially in Asia, and therefore, LTE equipment is widely available.

The access to the bands is planned to be individually authorized, allowing operation in a certain location. Two types of licenses are defined: a low power license allowing operation of a low power base station within a 50 m radius circle and a medium power license for operating a medium power base station in a rural area. The applicants would need to specify the bands they would like to access, as well as the planned locations. The Ofcom would then assess for each application the interference to and from other licensees in the band, based on coordination methodology and parameters proposed by them and make the assignments on a first come first served basis. This approach would provide certainty for the spectrum access and a possibility to provide QoS. The license fees would be cost based administrative fees, charged annually on a per area based or on a per base station basis, amount depending on the used bandwidth: the original proposal being £80 per 10 MHz. In the current proposals the Ofcom would deal with coordination between the licensees, but they intend to explore the potential for introducing dynamic spectrum access (DSA) in the proposed three shared access bands.

The 3.5 GHz CBRS Band for PAL Use in the Unites States (US)
In the US the band 3550–3700 MHz is being made available for citizens broadband radio service (CBRS) [33]. The band is currently used by several incumbent services, but there are unused spectrum resources in the band. The CBRS users comprise of two tiers of users: priority access license (PAL, tier 2) users and general authorized access (GAA, tier 3) users. Spectrum for PAL users is auctioned in 10 MHz pieces and one licensee can hold up to 4 PAL channels, i.e. up to 40 MHz. The authorizations are regional. The PAL authorization allows PAL licensees to access the spectrum resources available from the incumbents, while the incumbents must be protected from harmful interference. The rules allow the PAL licensees to lease their spectrum within their PAL area, which is beyond their deployment coverage. For example, in an industrial area a PAL holder may lease one or more of their channels to industrial enterprises. Spectrum not used by incumbents or by a PAL licensee is available for general authorized access (GAA) users on an unlicensed, shared basis. The amount of GAA spectrum may vary based upon variations incumbent and PAL usage; furthermore, unlicensed GAA users may experience harmful interference from other GAA users.

For both GAA and PAL, the base stations (CBSD) must register with a spectrum access system (SAS) and request a spectrum grant. The SAS will identify suitable spectrum for the CBSDs while ensuring that higher tier users are protected from harmful interference from lower tier users. The CBRS band could be suitable for IIoT, because the PAL licenses may allow a path for acquiring exclusive spectrum for regional use and GAA allows for a no cost option for non-mission critical services. The leasing rules for CBRS PALs provide also a potentially lower cost option for enterprises to lease spectrum at their facility.

The 5 GHz RLAN Bands (5G RLAN)
The International Telecommunication Union, Radiocommunication Sector (ITU-R) has identified the bands 5150–5350 MHz and 5470–5725 MHz globally for wireless access systems (WAS), including radio local area networks (RLAN). There are also several incumbent applications deployed in those bands, and the deployment of WASs must not cause harmful interference to the incumbent applications. Therefore, a number of technical and operational restrictions have been defined, such as maximum transmit power, restriction to indoor use in part of the bands and restrictions on antenna pattern [34] as well as required interference mitigation methods, such as dynamic frequency selection (DFS), transmit power control (TPC) and listen-before-talk protocol (LBT) to facilitate coexistence both with incumbent applications and among WASs sharing the band [35]. The global regulation is reflected, e.g. to Europe, and similar restrictions apply. Systems compliant with the ETSI standards [36] are allowed to be deployed in

the 5 GHz RLAN bands within the EU and the CEPT. Also, the FCC has defined their technical requirements. LTE-U [37] and MulteFire [38] are LTE based technologies that are designed to be compliant with the regulatory requirements in the 5 GHz bands. RLAN networks can be deployed in the 5 GHz bands under a general authorization, and this applies in most countries also to compliant LTE based networks for private and industrial applications.

3.2 Spectrum Management Approach Summary and Assessment

This section compares and assesses selected spectrum management approaches based on the analysis framework introduced in Sect. 2. A summary is depicted in Table 2. The key areas of the proposed spectrum management assessment framework are authorization, spectrum assignment, co-ordination, cost/pricing and regulatory certainty.

Table 2. Assessment of country specific spectrum management approaches.

Spectrum management framework element	Netherlands C-band	Canada WBS band	Germany 3.7 GHz	France 2.6 GHz	UK Shared 3.8 and 2.3 GHz	Finland 2.3 GHz	US CBRS PAL/GAA	RLAN 5 GHz
Band type	+	+	+	+	+	+	+/+	−
Bandwidth	+	+	+	+	+	+	+/+	+
Spectrum availability	+	−	+	+	+	−	−/−	−
Protection from harmful interference	+	−	+	+	+	−	+/−	−
Interference coordination	+	−	+	+	+	−	+/+	+
Sharing conditions	+	+	+	+	+	−	+/+	−
Technical or operational restrictions	+	+	+	+	+	−	+/−	−
Location and coverage area	+	+	+	+	−	+	+/+	+
Maximum transmit power	+	+	+	+	−	+	+/+	−
Technology	+	+	+	+	+	+	+/+	+
Authorization method	+	+	+	+	+	+	−/+	+
Application timing	+	+	+	+	+	+	−/+	+
Authorization duration	−	+	+	+	−	TBD	+/+	+
Cost/pricing	+	+	+	TBD	+	+	−/+	+
Regulatory certainty	−	−	+	+	+	−	+/+	+

In all presented country specific cases there are specific bands designated for private networks and the access is **individually authorized.** In some cases, there are incumbents having primary rights to the band, which means that private networks as secondary users are not allowed to cause harmful interference to the primary users (UK, FIN, US). In the unlicensed 5 GHz RLAN case, there are also incumbents requiring protection, which is reflected in technical and operational restrictions on the private networks. Furthermore, there are several other technologies allowed to share the 5 GHz bands horizontally with the private networks, which may restrict the spectrum availability and certainty. In all example cases, there is room for sufficient **bandwidths**. Dedicated access to a band together with protection from harmful interference provides the highest **spectrum availability** (NL, GER, UK).

Several **coordination approaches** are employed: only the first entrant may get the access (NL, GER, UK), the regulator may do the coordination when a new entrant submits an authorization application (UK), the entrant may need to prove that there is no harmful interference towards incumbents (FIN), the licensees have to coordinate among them in case of interference (CAN) or coordination is done by technical means (US). In Germany the designated band is wide, and it is partitioned for regional and local outdoor deployments, both shared with indoor deployments. This approach allows geographically parallel networks. For 5 GHz RLAN unlicensed bands the coordination is covered by technical and operational restrictions for vertical sharing and by LBT protocol for horizontal sharing.

The **maximum transmit power** is sufficient for various coverage requirements and deployments in the 3GPP defined LTE bands, except in the shared use case (UK). In parts of the 5 GHz RLAN bands the transmit power is limited to 200 mW, and operation is limited to indoor environment (not applicable in the US).

UL/DL flexibility is possible in all cases, as the bands are unpaired and the use of TDD is either possible or required (GER, FRA). In most cases adjacent networks may need to be synchronized, which would limit the UL/DL flexibility. In Canada and in Finland the networks may be located a significant distance apart from each other, so that synchronization may not be needed.

Application based individual **authorization** without timing restrictions for submission is widely employed (NL, CAN, GER, FIN, UK). If the principle is first-come-first-served, late applicants may be left without access to spectrum, especially if the available bandwidth does not support deployment of several geographically overlapping networks (NL, FRA, UK). If the principle is all-come-all-served, there may be coexistence problems due to overlapping networks, unless there is a specific coordination approach or process (CAN). The coordination process could be performed by the regulator (UK), or be on the responsibility of the licensees (CAN).

The **license duration** should be rather long, and in line with verticals' investment cycles. The longest offered license periods are 10 years (GER, FRA). On the other hand, in one case the license period is only one year, but the **license renewal** is done simply by paying the next year's fees (CAN). In the US CBRS band licenses are for ten years with possibility of renewal. In other cases the renewal approach is not defined, which undermines the regulatory certainty.

Spectrum cost should be affordable, and therefore nationwide authorizations and competitive award methods are not suitable for authorization of locally deployed private networks. In most of the presented cases, there is a fee for the spectrum access, which is a preferred choice. The fee can depend on coverage area population (CAN), or on used bandwidth (UK). In one case auctions are used (US CBRS PAL), but the unused spectrum resources can be leased. Moreover, the cost of additional environmental sensing capability (ESC) monitoring and SAS control equipment provided by the SAS operator, and possibly by a third-party ESC operator will be passed on to end users through higher service fees.

The **regulatory certainty** is highest if there is a newly confirmed spectrum management framework and licenses are granted for a long period, preferably longer than the investment cycle of the licensee (GER, US). In some cases there is a spectrum management framework in place, but at the same time ongoing or planned process to review the framework (NL, CAN). Also, the licenses may be granted for shorter period, e.g. three years or one year, which may reduce the certainty. In two cases early proposals for a spectrum management framework have been published, but major changes are possible (FRA, UK).

3.3 Discussion

Based on the assessment results, several recommendations can be drawn. The heterogeneity of industrial use cases, applications and requirements leads to a flexibility requirement in spectrum award and use. For mission critical applications, and applications requiring high QoS, individual authorizations and protection from harmful interference are required. The authorizations should be based on applications, and submissions should be allowed any time, based on the business need. The applicant should be allowed to define the required bandwidth and coverage area. The preferred license duration should be aligned with the licensee’s investment cycle, and for industrial networks 10 years would be desirable with renewal option. Only reasonable administrative fees should be applied, on a yearly basis or per transmitter where practical. Spectrum should be made available from harmonized 3GPP bands in a suitable frequency range, for most cases below 5 GHz, on exclusive basis, and the bandwidth of the designation should allow deployment of more than one network in a location. Band segmentation, e.g. between local and regional deployments, and sharing between indoor and outdoor deployments should be considered. In all cases the maximum field strengths at the coverage edge could be defined as a coordination method. The complexity of the spectrum monitoring and control system should be minimized as well as the related services fees. UL/DL asymmetry should be facilitated through employment of TDD duplexing, and network synchronization should be required only in locations where it is required for coexistence reasons. Where synchronization is needed, the UL/DL ratio should be defined in a manner that takes into account the requirements of all affected networks.

4 Conclusions

The emergence of digital automation and enabling local high-quality private networks have the potential of improving the productivity and efficiency of vertical industries, promoting innovation and competition in the market and advancing society in totally new ways. There is an increasing interest for the deployment of local high-quality networks by different stakeholders to complement MNOs' networks especially for industrial vertical specific service delivery. This paper has highlighted the importance of understanding the different approaches for spectrum management in the context of the upcoming IIoT networks, whose deployment will be location specific to complement the previous generations that addressed wide-area coverage.

We have defined an assessment framework to consider the specifics arising from local IIoT networks operating in regionally licensed and shared spectrum bands, and assessed lately introduced spectrum management approaches in eight selected real-life cases. To do so, we have first identified the key elements of spectrum management approached based on a literature review focusing on the spectrum planning and authorization processes from the views of the vertical industries and a local private operator. It is critical to consider the authorization, spectrum assignment, coordination, cost/pricing approaches as well as the regulatory certainty. After that we have provided a case study of the recent spectrum authorization decisions in different countries and analyzed the decisions from the viewpoints of the identified key elements of spectrum management framework. Our analysis has shown that different countries have adopted different spectrum management approaches, which ultimately define who can enter the IIoT market and benefit from the related business models. Some of the first decisions have been taken to facilitate networks for verticals in regional license areas and to promote vertical specific service delivery through the possibility to establish local private networks by different stakeholders. Results showed that the, most promising approaches being proposed by Germany and France.

From technology perspective future work is needed on the reducing the complexity of coexistence management while improving the accuracy and certainty e.g. through propagation modelling and 3D clutter databases. On the policy and business future research could consider the valuation and pricing of spectrum for local and regional assignments.

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