PUBLIC SAFETY COMMUNICATIONS

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Wireless communications technologies play an irreplaceable role in emergency and disaster relief situations. It is generally acknowledged that the existing public safety (PS) wireless communications facilities frequently fall short of meeting users' needs in many critical situations. Emergency scenarios usually lead to exceptionally high traffic loads, and the lack of network capacity is one of the major limitations to overcome. In this context, this article first discusses about several dimensions that enable increased capacity in emergency scenarios, and then the attention is placed on the role of spectrum sharing as one of these key dimensions. In this regard, a comprehensive view of possible spectrum-sharing models for emergency communications is developed. The key principles underlying each sharing model are given, and its applicability is described through illustrative examples, where it is made evident that cognitive radio (CR) technology constitutes a major technological enabler for their realization. Finally, a discussion on the feasibility of each of the spectrum sharing models is addressed.

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Introduction

Wireless communication scenarios are characterized by the coexistence of a variety of radio-communication systems. Wireless networks differ from each other in the specific air interface technology, supported services, bit-rate capabilities, coverage, mobility support, and so on. While different applications and needs have led to the deployment of such heterogeneous networks (e.g., commercial cellular systems, ad hoc networks, and PS), all of them respond to society's fundamental demand for communications.

Wireless communications technologies play an irreplaceable role to satisfy public protection and disaster relief (PPDR) operational needs in emergency situations. Appropriate communications among first responders, authorities, and citizens are crucial. Even though the PS community's technological needs have been understood for a long time, the capabilities of current PS communications systems [e.g., private/professional mobile radio (PMR)] are still lagging behind to that available in commercial mobile networks [1]. Some of the major limitations of PS communications systems in emergency and disaster relief scenarios are as follows:

- *Lack of Interoperability*: The diversity of technologies used by PS organizations often inhibits the cooperation between different agencies. As a result, first responders are frequently required to manage several separate (often incompatible) radio-communication systems.
- *Lack of Support for Broadband Data Rates*: The evolution of PS operations has created the need for applications where large amounts of data are exchanged between first responders or between the tactical frontline responders and multiple levels of a hierarchical command structure. Data-intensive multimedia applications include real-time access to critical data, such as high-resolution maps or floor plans, and on-field live video transmission from cameras on helmets to a central unit, telemedicine, and so on.
- *Lack of Network Capacity in Emergency Scenarios*: While the PMR network operators have optimized the use of their communications systems in their day-to-day service, the situation dramatically changes when an emergency causes additional stress for the system (and the operators). Emergency scenarios usually lead to exceptionally high traffic loads that a single wireless communication system may not be able to support.

Based on these observations, it is evident that more efficient and effective advanced wireless communication solutions than today's PMR systems are needed. Focusing on the lack of capacity during emergencies, it can be said that due to the unpredictable nature of an incident in time, place, and scale, it is not possible to either associate a detailed resource plan in advance or rely on a worst-case capacity deployment of PS communications facilities. A usual problem during a major incident is shortage in radio resources to cope with PS communications [2]. In this framework, this article first introduces a general discussion on the dimensions that may enable capacity extension. Then, the attention is placed on the role of spectrum sharing as a means of capacity extension. The remainder of the article is devoted to further develop this dimension. In particular, an analysis of the spectrum availability in emergency scenarios is initially carried out to categorize the different types of spectrum sources that might be potentially used for emergency communications. The resulting categorization is used to identify five possible spectrum sharing models intended to bring additional capacity for PPDR communications. The key principles behind these sharing models are explained, and their applicability is described through examples in the context of an illustrative incident scenario. Finally, a discussion on the suitability of the identified spectrum sharing models is provided, considering organizational and operational aspects of potential sharing users as well as relevant technical and regulatory initiatives that can contribute to pave the way toward their adoption.

Enhanced Capacity in Emergencies Through Spectrum Sharing

Let's consider a PS network (PSN) composed of several base stations, each covering an area of S km^2. A given air interface technology, exhibiting a certain spectral efficiency E b/s/Hz, is used. A cell is assigned a certain spectrum amount of B Hz. Thus, the capacity deployed is $B \times E/S$ b/s/km^2. The PSN network has been designed and dimensioned for a certain density, U users/km^2, assuming that each one of them generate an average traffic T b/s/user so that $B \times E/S = U \times T$. When an emergency occurs, both the number of users present in the scenario U^* and the traffic generated T^* suddenly increase and, consequently, the network runs short of capacity (i.e., $B \times E/S < U^* \times T^*$). Conceptually and from the previous simplified view, the equilibrium could be reestablished by increasing B, increasing E, and/or reducing S.

The previous observation provides some principles that are applicable in a long-term view to support PPDR communications with increased capacity to face emergency situations: availability of more spectrum (therefore, increase B), adoption of more spectrally efficient radio technologies for PS (therefore, increase E), and deployment of a large number of network sites (therefore, reduce S), particularly if broadband data rates are to be provided. Since the availability of economical investment in the public sector is limited, progressing on any of these three directions poses serious challenges to public administrations in charge of PPDR communications facilities.

The focus of this article is on the spectrum component. Traditionally, the spectrum used for PPDR communications has been assigned following an administrative spectrum management model and is exclusively restricted to PPDR use (no other uses than PPDR are allowed). The administrative spectrum management model is also known as the *command and control model*, whereby spectrum regulatory authorities determine how different parts of the spectrum will be used, i.e., its allocation, and by whom it could be used, i.e., its assignment. While likely being an effective solution for satisfying public sector spectrum needs, this model is believed to result in a rigid and nonefficient allocation of the spectrum [3]. As a matter of fact, the allocation of new dedicated spectrum to satisfy increasingly data-intensive PPDR operational needs is nowadays a challenging issue for spectrum regulatory authorities [4]. One important handicap is that suitable spectrum bands needed to build cost-effective PSNs are the same highly valued bands demanded by the commercial market to provide key services such as TV broadcasting and third-generation or fourth-generation mobile communications. In addition, the harmonization of PPDR spectrum bands across countries, as pursued in Europe to facilitate cross-border interoperability and an economy of scale for PPDR communications equipment, adds even more complexity to the allocation of spectrum for PPDR. The overall result is a limited availability of PPDR spectrum that is typically fragmented across several bands (very high frequency, UHF, 5 GHz) and owned and operated by a number of different PPDR organizations in an exclusive manner.

The limited availability and current usage models of PPDR spectrum can definitively constitute a bottleneck in some emergency scenarios where extraordinary traffic loads may arise. Therefore, innovative approaches are needed to 1) provide enough PPDR spectrums to satisfy stringent spectrum demanding operational needs in major incidents and, at the same time, 2) avoid a low utilization of spectrum allocated for PPDR that may not be necessary for daily operations.

In this context, the introduction of spectrum sharing principles is believed to be an essential step toward achieving enhanced capacity in emergency scenarios, enabling better PPDR communications and, ultimately, improving overall spectrum utilization. Spectrum sharing refers to the application of technical methods and operational procedures to permit multiple users to coexist in the same region of spectrum [5]. Coexistence may be achieved by numerous methods such as coordinating time usage, geographic separation, frequency separation, directive antennas, orthogonal modulations, and so on. In the past, the employment of these spectrum sharing mechanisms has typically been on a static, preplanned basis, whereas future advanced radio systems are intended to support a more dynamic, even real time, use of the spectrum (i.e., dynamic spectrum access). In this context, CR technology able to adapt, in a dynamic and flexibly manner, the spectrum utilization of PS communications equipment is anticipated to constitute a key technological enabler for the realization of most forms of spectrum sharing. We note that PPDR communication systems based on spectrum sharing still must validate the severe operational requirements [6] of PPDR organizations in terms of resilience, service availability, security, and timing constraints.

Analysis of Spectrum Availability in Emergency Scenarios

Emergencies and major incidents often require the participation of several emergency services (e.g., law enforcement, fire and rescue, medical assistance, and so on) and generally include the involvement, either directly or indirectly, of large numbers of first responders. Major disasters (e.g., earthquakes, hurricanes, chemical factory explosions, and so on) can impact extensive geographical areas and cross borders, both physical and administrative and involving PPDR agencies from different jurisdictions. In addition to local PPDR agencies, major incidents often require the help of out-of-area emergency support units. Communications facilities used in the incident are those available to local agencies for their day-to-day communications. These facilities mainly consist of PMR networks that are either exclusively used by a single PPDR agency or shared by a number of them. In addition to permanent network infrastructures, fast deployable equipment can also be brought to the affected area to establish incident area networks (IANs) for real-time mission-critical voice, video, and data, and sensor communications. Also, the PS personnel often rely on communications over the public mobile networks to complement their dedicated systems.

In an illustrative emergency scenario intended to guide the discussion in this article, it is assumed that in an incident area two separate PSNs, denoted as PSN 1 and PSN 2, are deployed. These networks will provide PPDR services to local PPDR agencies (e.g., local police, fire and rescue units, and so on) as well as some of the arriving out-of-area emergency support units (e.g., fire brigades from nearby locations). It is considered that some out-of-area emergency teams arriving at the incident have their own dedicated PSN, termed as PSN 3, although it is assumed that there is no coverage of this network in the incident area (e.g., specialized units that do not operate in the incident area but displaced to help). In addition to PPDR communications facilities, a communication infrastructure devoted to support non-PS services (e.g., broadcast transmitters, commercial cellular network, military point-to-point links, and so on), denoted with the generic name Network 4, is also considered to operate in the incident area.

In this context, Figure 1 distinguishes the different types of spectrum that might be potentially used for emergency communications. Two distinguishing factors for the categorization of spectrum availability shown in Figure 1 are whether 1) individual spectrum rights of use exist or not and 2) spectrum rights are entitled to provide PS services or non-PS services. The use of radio frequencies is subject to individual rights that are granted to users by means of individual authorizations (e.g., through administrative models and traditional licensing procedures managed by spectrum regulatory authorities) or, alternatively, permitted through a general authorization (e.g., license-exempt bands where devices are mainly mandated to be compliant to some standards but no individual authorization is issued) [7]. Without any loss of

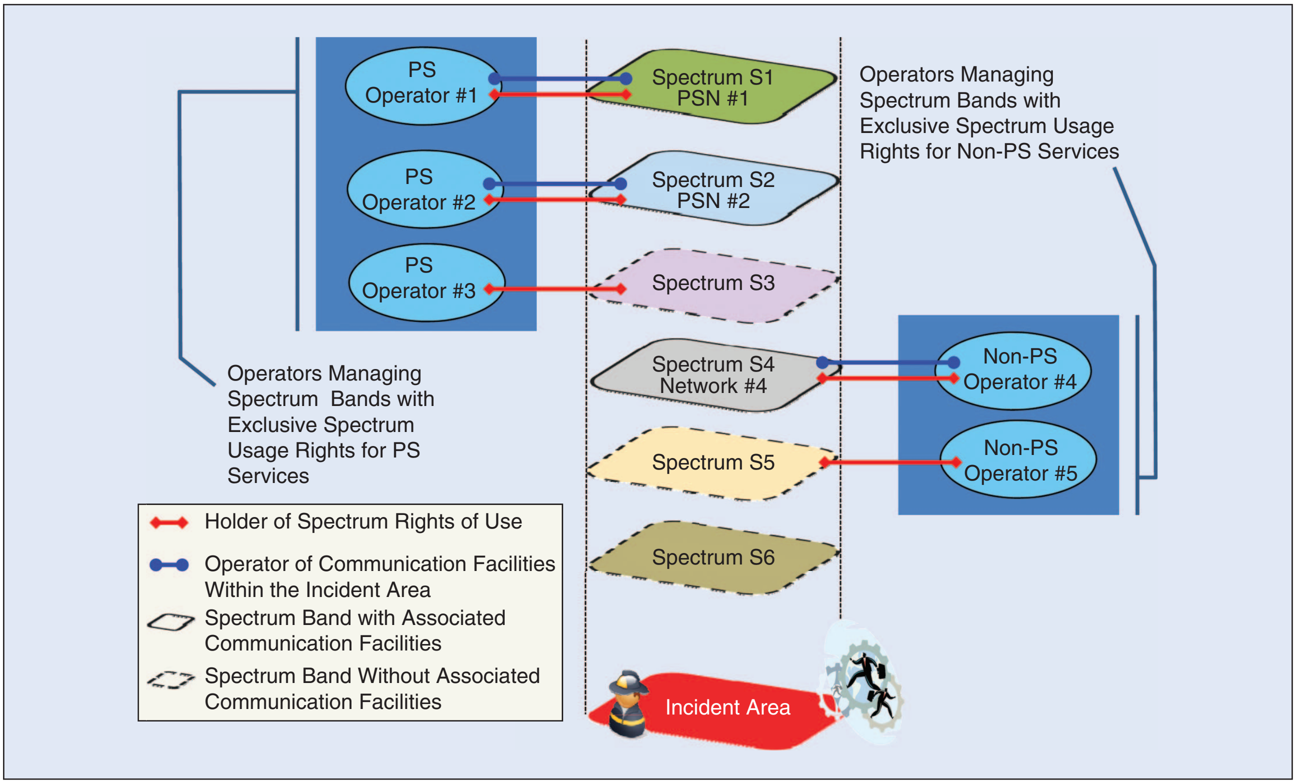

FIGURE 1 A categorization of spectrum availability in an incident area.

generality, individual rights of use, if any, are assumed hereafter to be directly held by the operators of the communications infrastructure (i.e., network operators). In addition, the categorization in Figure 1 also distinguishes whether network infrastructures (i.e., base stations) exploiting the spectrum are deployed in the incident area or not.

On this basis, Figure 1 identifies the following spectrum options:

- *Spectrum S1*: This is a dedicated band for the provisioning of PS services. Exclusive individual usage rights for this band are considered to be held by PS Operator 1 that fully or partly exploits S1 spectrum in the PSN 1 infrastructure deployed in the incident area.
- *Spectrum S2*: Like spectrum S1, this is a dedicated band for the provisioning of PS services. Exclusive individual rights of use over S2 are held by PS Operator 2 that fully or partly exploits it in the PSN 2 infrastructure.
- *Spectrum S3*: This is a band also dedicated to the provisioning of PS services whose exclusive individual usage rights are held by PS Operator 3 that uses them to run PSN 3. However, unlike PSN 1 and PSN 2, it is considered that the PSN 3 infrastructure does not have coverage in the incident area.
- *Spectrum S4*: This is a band used to provide services other than PS services (e.g., commercial cellular services, TV broadcasting, military communications, among others). A non-PS operator, denoted as Operator 4, is assumed to have exclusive individual rights of use over S4. The spectrum is used by Network 4 communications facilities run by Operator 4.
- *Spectrum S5*: Like S4, this is a band used to provide non-PS services. Exclusive individual usage rights of this spectrum are considered to be held by another non-PS operator, denoted as Operator 5. In this case, it is assumed that this operator does not have any communication facilities using spectrum S5 in the incident area.
- *Spectrum S6*: This band represents a portion of the spectrum that is set to be used by multiple authorized users that do not hold exclusive individual rights of use (e.g., license-exempt band).

It is worth noting that under a classical regulation and communications technologies, spectrum usage for PS communications in the incident scenario depicted in Figure 1 would be limited to spectrum S1, S2, and S6. Furthermore, the usage of S1 and S2 would be strictly coupled to PSN 1 and PSN 2 infrastructures, respectively, without any flexibility to reallocate it as needed across both networks. In contrast, the next section elaborates possible spectrum sharing models aimed at improving spectrum availability and flexibility of use for PPDR in the incident scenario, thus enhancing the capacity available for PS communications.

Spectrum Sharing Models for PPDR Communications

Based on the analysis of the incident scenario described in the previous section, five spectrum sharing models that intended to bring additional capacity for PPDR

TABLE 1 Principles and applicability of "dynamic transfer of exclusive rights of use" sharing model.

Spectrum Sharing Model: Dynamic Transfer of Exclusive Rights of Use	
Sharing principles	Spectrum rights of use are temporarily transferred from the licensee to other users by means of leasing mechanisms. Prioritization and preemption principles can be put in place in the leasing models.
Applicability	Spectrum bands where access authorization relies on holding exclusive spectrum rights of use (i.e., S1–S5 bands).
Illustrative examples	A PPDR user is the licensee, and leasing is restricted to PPDR applications. For example, since S3 is not used in the incident area, PS Operator 3 could temporary transfer S3 usage rights to either PS Operator 1 or PS Operator 2.
	A non-PPDR user is the licensee, and leasing for PPDR use is permitted. For example, let's consider that S5 usage rights are held by military users. PPDR users involved in the incident response or in a major planned event (e.g., Olympics Games) could request military users to lease part of this spectrum for PPDR use. The lease could be interrupted, and spectrum rights are transferred back to military users if needed.
	A PPDR user is the licensee of the band, and leasing for non-PPDR use is permitted. For example, when there is no emergency situation and part of S1 is not used for PPDR routine tasks, spectrum usage rights could be leased to Operator 4 for commercial services delivery through Network 4 (e.g., rural Internet wireless access). This leasing can also be interruptible under strict guarantees when required by PS Operator 1.

TABLE 2 Principles and applicability of "secondary access sharing" models.

Spectrum Sharing Model: Secondary Access Based on Coordination Mechanisms	
Sharing principles	Other users (denoted as secondary users) than the licensee can get access to the spectrum provided that the licensee (denoted as the primary user) is not impacted by harmful interference. A primary–secondary coordination mechanism is used to allow the primary user to have some control on the secondary access (e.g., dynamically decide whether secondary access is allowed or not).
Applicability	Spectrum bands where there is a (primary) owner of spectrum rights of use (i.e., S1–S5 bands).
Illustrative examples	Secondary access is allowed to PPDR users in non-PPDR bands. For example, Operator 4 in charge of a cellular network can unleash part of spectrum S4 in the incident area and advertise it through a beacon signal sent via Network 4. Unleashed S4 spectrum could then be exploited by PPDR users.
	Secondary access is allowed in PPDR bands. For example, PS Operator 2 may advertise that part of S2 is not used under routine operation and make this spectrum available for secondary access. Secondary users can be restricted to PPDR applications or be open to non-PS services (e.g., commercial Operator 4 may benefit). Whenever PSN 2 requires the entire S2 band again (e.g., crisis response), PSN 2 infrastructure stops advertising the availability of this spectrum for secondary access.
Spectrum Sharing Model: Secondary Access Based on Coexistence Mechanisms	
Sharing principles	In this case, there is no primary–secondary coordination mechanisms and primary users have no control over secondary access (i.e., primary and secondary users coexist without explicit interactions).
Applicability	Spectrum bands where there is a (primary) owner of spectrum rights of use (i.e., S1–S5 bands).
Illustrative examples	Secondary access is allowed in PPDR bands, although restricted to PPDR applications. For example, communication devices, such as IAN equipment, brought in the incident area by PPDR agencies served by PS Operator 1 and PS Operator 2 could detect (by sensing or geolocation database) the unused S3 spectrum and exploit it.
	Secondary access is allowed to PPDR users in non-PPDR bands. For example, monitoring stations for the environment could detect that part of S4 (e.g., used to run a commercial PMN network) and/or S5 (e.g., exploited by military users) is not being utilized and use it for enhancing ad hoc connectivity of the monitoring system.

communications have been identified. Tables 1–3 provide a description of the key principles behind each identified model and discuss its applicability by means of illustrative examples that can be directly mapped to the incident scenario depicted in Figure 1. It is worth noting here that the proposed taxonomy intends to provide a comprehensive view of the problem, thus embedding both the perspective of spectrum sharing models raised by Peha [8] and the spectrum access (management) models raised by Buddhikot [9].

The model presented in Table 1 and the two models in Table 2 are to be applied over licensed bands (e.g., S1–S5 in Figure 1) to allow 1) PPDR users to grab more spectrum when needed from bands primarily devoted to support non-PPDR applications and 2) part of the spectrum devoted to primarily support PPDR applications to be exploited for other purposes when not needed for PPDR. On the other hand, the two models in Table 3 are to be applied in bands managed under a collective use of spectrum model [7] where no exclusive rights of use exist. These types of bands could provide a valuable additional capacity for PPDR users to deploy temporary communications facilities (e.g., IANs, point-to-point links, and so on).

TABLE 3 Principles and applicability of "Collective use of spectrum" sharing models.

Spectrum Sharing Model: Collective Use of Spectrum Based on Coordination Mechanisms	
Sharing principles	A number of users are authorized to use the band as a result of either a general authorization regime (e.g., license-exempt band with no limitations in the number of users) or a light-licensing regime (i.e., users are to be registered within the spectrum regulatory authority that might place limits on the number of authorizations). Coordination among authorized users/devices is required through a common management protocol to cope with mutual interference.
Applicability	This model can be applied to S6 spectrum.
Illustrative examples	S6 could be a band managed under a light-licensing regime and restricted to PPDR applications. Hence, all registered and explicitly authorized PPDR agencies might use S6 to set up fast deployable equipment (e.g., wireless access points and point-to-point links). The coordination of channel assignment is carried out through a common protocol supported by all authorized devices. The development of such a common protocol is facilitated by the restriction of this band to PPDR applications.
Spectrum Sharing Model: Collective Use of Spectrum Based on Coexistence Mechanisms	
Sharing principles	In this case, no common management protocol is defined among authorized devices. Instead, coping with mutual interference is mainly pursued through the compliance of devices to the specific regulator-imposed rules (i.e., spectrum etiquettes).
Applicability	This model can be applied to manage S6 spectrum.
Illustrative examples	S6 can be a general-purpose license-exempt band such as the 2.4 or 5 GHz industrial, scientific and medical (ISM) bands. The use of this band can bring additional capacity in the incident area for local area communications, although no preferential access or coordination mechanisms will be available for PPDR users to control the interference from any other legitimate user of the band (e.g., personal devices or private/public wireless access networks).

Deployment of Spectrum Sharing Models

The feasibility of each sharing model for PPDR communications primarily depends on the type of users involved in the sharing framework. At the European level, sharing spectrum resources among commercial, military, and PS domains is under consideration in regulatory and standardization bodies such as the European Conference of Postal and Telecommunications Administrations [4] and the European Telecommunications Standards Institute (ETSI) [10]. The adoption of a given sharing model may require changes to the organizational structures and relationships among commercial, PS, and military entities. In some cases, these changes are just an extension of existing agreements (e.g., joint procedures for disaster management between military and PS in large natural disasters). In other cases, new agreements (e.g., service level agreements) must be put in place. Moreover, the amount of changes required in the existing infrastructures managed by these different communities is another important aspect to consider. Any proposed sharing model should minimize or not require changes to the existing infrastructures.

Furthermore, from a PPDR operational point of view, the deployment of sharing models is also contingent upon the type of applications and services being provided. In this context, PPDR communication services are usually distinguished between mission-critical (mandatory) and non-mission-critical (optional) applications. Mission-critical applications have specific technical requirements in terms of quality of service (QoS), time to set up the call, and provision of functions (e.g., group call and broadcast) [6]. On the other hand, non-mission-critical applications, such as data distribution without time constraints, can be based on a best effort communication model to a certain extent. While some debate is still ongoing about the mission-critical level of emerging data-oriented applications demanded by PPDR, the current opinion by PS officers is that voice and

TABLE 4 Suitability considerations on "Dynamic transfer of exclusive rights of use" sharing model.

Spectrum Sharing Model: Dynamic Transfer of Exclusive Rights of Use
This model is already regulated in many countries [11]. Current spectrum transfer procedures can take some days, which is suitable for long-planned events (e.g., G20 summit or Olympic games). Operation at lower time scales needs further regulatory and technical developments.
Feasible model, even for mission-critical PPDR applications as full protection, is guaranteed through spectrum usage rights. Its realization needs cognitive or (at least) tunable radios that can be configured to operate in different spectral bands.
Initial deployment could be restricted to spectrum transfers among PPDR users, including the possibility to create spectrum pools contributed by multiple licensees for mutual use [12]. Extension to other governmental and/or commercial marketplace users could be addressed in a subsequent stage.
Newly allocated bands could be explicitly designated by regulatory authority for spectrum sharing through dynamic transfer of rights of use. Assignment of spectrum usage rights could be managed through a centralized mechanism in the form of spectrum coordination server or spectrum broker.

TABLE 5 Suitability considerations on ''Secondary access'' sharing models.

Spectrum Sharing Model: Secondary Access (Coexistence and Coordination Models)
Solutions for PPDR spectrum sharing may benefit from proposals and achievements within the TV white space domain, based currently on the usage of a geolocation database [13], [14].
If PPDR is primary use, it is a feasible model even for mission-critical PPDR applications. Indeed, secondary access to (primary) PPDR spectrum is not precluded by ETSI in [10] under a strict preemptive regime to ensure the performance of PPDR communications. Using PPDR spectrum for commercial use with preferential access given to PPDR in case of emergencies was also considered by Federal Communications Commission in an intent to promote the deployment of a joint-use network employing both PS and commercial spectrum (i.e., D block) [15].
If PPDR is secondary use, it can provide an opportunistic additional capacity to alleviate congestion problems for mission-critical applications as well as facilitate the deployment of non-mission-critical applications. PPDR secondary access to (primary) military spectrum is a possible approach, considering that military organizations possess considerable regions of spectrum that may not be used in the location of the incident. A three-level sharing scheme, where military is the primary user, PPDR is a second-tier primary user, and commercial networks are the secondary users is discussed in [10].
Coordination models can offer more QoS guarantees at the cost of added complexity. Coordination can be addressed at communications system level (e.g., beacon signals broadcasted by PPDR networks to enable/disable secondary access) or at organizational and procedural levels (e.g., extension of existing procedures for coordinated disaster management in the case of military-PPDR spectrum sharing).
Coexistence models are necessary in cases where coordination fails or is not possible (e.g., geolocation databases not reachable). CR technology is particularly relevant in these cases.

narrowband data (now provided by PMR networks such as Terrestrial Trunked Radio) are clearly considered mission-critical services, whereas broadband applications are still considered non-mission-critical services [10].

The adoption of a sharing model is also dependent on the development of suitable technologies and regulatory frameworks. Different sharing models may require more or less complex modifications to existing standards and undertake different technical challenges. In some cases, the technical requirements for specific functions (e.g., spectrum sensing case of models built upon CR technologies) may be difficult to implement with the existing technological capabilities (e.g., computing/processing power). Furthermore, international, European, and national spectrum regulations must be modified to permit the deployment of some of the sharing models.

Based on the above-mentioned observations, Tables 4–6 synthesize, respectively, the discussion on the suitability of the identified spectrum sharing models considering organizational and operational aspects of involved users as well as relevant technical and regulatory initiatives that can contribute to pave the way toward their adoption.

Concluding Remarks

This article presents a comprehensive view of five possible spectra sharing models that can facilitate achieving enhanced capacity in emergency scenarios and enabling better PPDR communications. The ultimate goal of all the discussed models is twofold: 1) provide enough PPDR spectrum to satisfy stringent spectrum-demanding operational needs in major incidents and 2) avoid having a large assignation of PPDR spectrum (e.g., allocated to face spectrum demands in worst-case incident scenarios) lying unused when not required for routine PPDR tasks. Progressing toward the realization of these spectrum sharing models is believed to be essential to overcome the current spectrum deadlock faced by many spectrum regulatory authorities that are reluctant to allocate additional spectrum for PPDR exclusive use.

The taxonomy has been built upon a characterization of different types of spectrum that might be potentially used for emergency communications attending to the existence or not of spectrum individual's rights of use in spectrum bands, whether holder of spectrum rights are

TABLE 6 Suitability considerations on ''Collective use of spectrum'' sharing models.

Spectrum Sharing Model: Collective Use of Spectrum (Coexistence and Coordination Models)
Application-specific bands for PPDR communications are already available in the United States (4.9-GHz band) and in some European countries (broad band disaster relief band in the 5-GHz frequency range), especially to implement on-scene broadband wireless networks. Authorized users are responsible for interference prevention, mitigation, and resolution coordination among them. The use of the 4.9-GHz band is already supported by some PS equipment vendors.
They are suitable in bands devoted to support local area communications of multiple PPDR organizations.
A coordination approach (e.g., based on technologies such as IEEE 802.11y) could provide some degree of guaranteed QoS even for mission-critical PPDR applications.
Coexistence approaches (e.g., using existing general-purpose license-exempt bands such as ISM bands at 2.4 and 5 GHz) cannot offer QoS guarantees for mission-critical PPDR. However, as proven by the massive adoption of WiFi devices, the reality is that achieving some additional capacity with good perceived QoS in these bands is not rare. This fact can be even more evident in the utilization of those bands in nonresidential areas (e.g., crisis incident in rural areas).

PS or non-PS users and whether network infrastructures using available spectrum are in use in the affected area. Key principles behind each sharing model have been provided, and its applicability has been described through illustrative examples. In addition, a discussion on the suitability of the identified spectrum sharing models has been addressed considering organizational and operational aspects of potential sharing users (involving military, commercial, and PS users) as well as relevant technical and regulatory initiatives that can contribute to pave the way toward their adoption. The role that CR technology could play in the realization of different sharing models has been captured in this discussion.

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