Spectrum Sharing Scenarios and Resulting Technical Requirements for 5G Systems

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***Abstract*—Cellular networks today are designed for and operate in dedicated licensed spectrum. At the same time there are other spectrum usage authorization models for wireless communication, such as unlicensed spectrum or, as widely discussed currently but not yet implemented in practice, various forms of licensed shared spectrum. Hence, cellular technology as of today can only operate in a subset of the spectrum that is in principle available. Hence, a future wireless system may benefit from the ability to access also spectrum opportunities other than dedicated licensed spectrum. It is therefore important to identify which additional ways of authorizing spectrum usage are deemed to become relevant in the future and to analyze the resulting technical requirements. The implications of sharing spectrum between different technologies are analyzed in this paper, both from efficiency and technology neutrality perspective. Different known sharing techniques are outlined and their applicability to the relevant range of future spectrum regulatory regimes is discussed. Based on an assumed range of relevant (according to the views of the authors) future spectrum sharing scenarios, a toolbox of certain spectrum sharing techniques is proposed as the basis for the design of spectrum sharing related functionality in future mobile broadband systems.**

***Index Terms*— 5G mobile communication, Licensed shared spectrum, Radio spectrum management, Spectrum sharing**

I. Introduction

SIGNIFICANTLY more spectrum and much wider bandwidths than what is available today will be needed in order to realize the performance targets of future mobile broadband (MBB) systems [1], [2]. The extremely wide bandwidths considered, several 100 MHz up to a few GHz, imply that the spectrum will be difficult to find in the lower frequency ranges. In addition, it is expected that in the future, spectrum will - at least in some cases - be made available under horizontal and/or vertical spectrum sharing regimes. It is not clear today which of the many different proposed spectrum sharing options will become relevant in practice.

Even if the relevance of spectrum sharing is expected to increase, dedicated licensed spectrum access that provides reliability and investment certainty for cellular MBB systems is expected to remain the baseline approach for mobile broadband. Network components using shared spectrum are expected to play a complementary role (cf. Wi-Fi offloading). The focus in the remainder of this paper is on these complementary approaches.

The objectives of this paper is to (i) identify the range of spectrum sharing scenarios that are deemed relevant for future MBB systems and (ii) to outline the range of technical enablers that could be used to address these scenarios. This is done by mapping technical enablers to regulatory frameworks and vice versa, so that the consequences of a MBB system supporting, or not supporting, a certain functionality can be understood.

It is possible that a given scenario requires, or can receive benefits from, more than one technical solution; e.g., one solution may be required to enable vertical sharing, whereas another may be beneficial for horizontal spectrum sharing[1].

This paper only considers somewhat advanced scenarios and enablers for spectrum sharing, in which sophisticated approaches as well as technical measures beyond the state-of-the-art would be necessary to avoid harmful interference. The trivial case of static geographical sharing based on manually engineered frequency re-use distance obtained from simple worst-case link budget calculations is out of scope.

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[1] Vertical sharing is sharing between systems of different priority, e.g. protection of incumbent users, and horizontal sharing is between systems of the same priority.

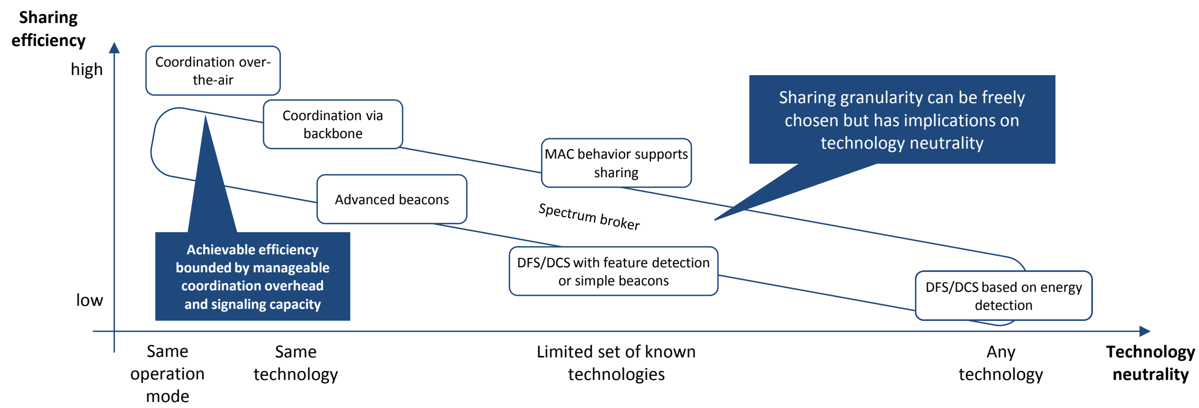

Fig. 1. Relation between the level of technology neutrality in a regulatory framework and the achievable efficiency of horizontal spectrum sharing enablers.

II. Horizontal Sharing Between Different Technologies

A central aspect in a horizontal spectrum sharing scenario is what type of radio systems that share the spectrum, see Fig. 1. To obtain the highest sharing efficiency sophisticated technical enablers implemented in all coexisting systems are required. This is likely to happen only if all systems apply the same or at least very similar radio access technology or implement the same standard. On the other hand, if sharing is expected or required to work across very different technologies, the achievable efficiency and granularity of the sharing is limited.

The problem that arises from this trade-off is that different regulatory objectives are contradictory in this regard. Regulators on the one hand are obliged to foster efficient use of spectrum, which would call for limiting the set of technologies that are used in a band, since in this case spectrum sharing would be most efficient. On the other hand it has been an objective of regulation in the recent past to be technology-neutral in a sense that regulatory frameworks should not allow only one or a limited set of technologies to operate in any given frequency range. This implies less efficient sharing or a higher risk of interference, which in turn devaluates such spectrum and is thus an obstacle towards networks investments.

Three options for sharing between different technologies can be distinguished: Only one technology, a limited set of technologies, and any technology taking part in the sharing.

The case of only one technology, i.e., all coexisting systems use the same radio access technology, implies that spectrum sharing functionality can be completely integrated in the transmission scheme and that solutions can be implemented that rely on a certain behavior on both ends of a sharing relationship. The systems are thus able to coordinate their usage on a very high granularity and can adapt their parameters for maximum spectrum efficiency and minimal interference risk. There is however a conflict with the technology neutrality principle and limitations to certain technologies by means of regulation can be detrimental in the long run[2].

In the second case, spectrum sharing occurs between a few well-defined technologies. This situation may be the result of regulatory rules that allow only a set of certain, to at least some extent compatible, technologies in the band. A system that accesses the shared spectrum has knowledge of the set of systems it may have to share spectrum with and one may select which sharing methodologies to support accordingly. In this scenario certain spectrum sharing functionality could be assumed to be part of the design of all systems belonging to the same family. The resulting sharing efficiency and granularity is expected to be lower than in the "only one technology" situation since the enablers will likely not be as integrated in the system design. This case however brings the possibility for the regulators to specify simple coexistence schemes on a detailed level which have to be included in the system design of the involved standards. A coexistence beacon concept (see Sec. III.A) is one example of such an approach. This implies that new technologies developed at a later stage would only be admitted if they can demonstrate compatibility with the already existing technologies.

In the final case, regulators allow any technology that fulfills the operating conditions of the bands. The operating conditions for the band are typically rather lightweight. They could also concern high level sharing methodologies, e.g. in the form of requirements of

[2] One such example is the GSM Directive, which designated the 900 MHz band in Europe for GSM systems only. This turned out to be a significant barrier in opening the 900 MHz band for UMTS or LTE.

database access for vertical and/or horizontal sharing or MAC behavior. This type of regulatory framework implies that the sharing parties cannot in advance be certain of what technologies they will need to share with. The set of systems to share with can vary quickly over time and/or space. New systems may also appear in the band in the future. Since the systems sharing the band may react in different and unpredictable manners the set of universal sharing methodologies, i.e. methodologies that are applicable for any combination of technologies, is limited to contain only rather basic methodologies. In this case an operator's flexibility to select or change technology is the highest, but the supported spectrum sharing granularity and efficiency is the lowest.

III. Spectrum Sharing Techniques

The technical capabilities needed to enable MBB systems to share spectrum can be broadly categorized in distributed solutions and centralized solutions. In a distributed solution the systems coordinate among each other on equal basis. In a centralized solution each system coordinates separately with a central entity and the systems do not directly interact with each other.

A. Distributed spectrum sharing techniques

Distributed solutions have the advantage that coordination can be more efficient since it can take place in a local context. In principle it is possible to only coordinate those transmissions that actually create interference between systems. Solutions for distributed coordination can be fully integrated into standards and can thus be defined so that they operate without the need for commercial agreements between operators or equipment owners, cf. the situation for Wi-Fi systems.

In a *peer-to-peer coexistence protocol* the coordination of horizontal spectrum sharing happens through explicit exchange of messages directly between the sharing systems via some well-defined interface. The protocol defines the behavior of the nodes when receiving certain messages or when certain events take place. An example of such a protocol is given in [3].

In *coexistence beacon* based solutions the systems regularly transmit commonly understood signals that indicate presence and potentially additional information, e.g., activity factor and when they will transmit. Other systems can use this information in order to adapt their spectrum access behavior to provide fair spectrum sharing. Coexistence beacons are a possible solution for both, horizontal and vertical sharing scenarios. An example of a coexistence beacon implementation is the 802.22.1 standard [4].

In *MAC behavior* based schemes the MAC protocol is designed to enable horizontal spectrum sharing. Examples are the request to send / clear to send (RTS/CTS) functionality employed in IEEE 802.11 WLAN systems and the frequency hopping used in Bluetooth. A *Wi-Fi coexistence mode* is a particular example of how a MAC behavior of a non-contention-based system may be adapted to allow for smooth horizontal coexistence with Wi-Fi systems: the MAC protocol may leave silent periods during which Wi-Fi systems are able to operate. In this mode the MAC behavior may alternatively use a listen-before-talk approach that allows Wi-Fi systems to gain channel access, or some other suitable sharing implementation.

Spectrum sensing and dynamic frequency/channel selection (DFS/DCS) are solutions in which systems dynamically select their operating frequency range based on measurement results. The measurements can e.g. be energy detection, or feature detection. Feature detection can be used to detect the abovementioned coexistence beacons. DFS/DCS is typically not considered a very reliable method (due to the so-called "hidden node problem") which may make it unattractive as sole means for protecting a primary user[3] in vertical sharing. In horizontal sharing scenarios DFS/DCS can have a supporting role to e.g. identify those channels that have least other users present so that sharing overhead is minimized.

B. Centralized spectrum sharing techniques

Centralized solutions are expected to be useful for sharing on somewhat longer time scales, i.e. the granularity of spectrum sharing would be on a higher level than the actual radio resource allocation granularity within each system. The limitation that coordination is done on a comparably slow time scale implies that a typical solution is conservative and likely to separate users on orthogonal resources without complete information on whether they would actually interfere or not. The benefits are in terms of reliability, predictability and control. If monetary transactions are involved in spectrum sharing, centralized approaches are likely preferable.

An example of a centralized sharing technique is the *geo-location database (GLDB)* approach in which a system queries a database to acquire information on what resources are available at a specific location [5]. This is typically the required vertical sharing solution for access to locally unused TV bands [6].

Another example is the *spectrum broker* approach where horizontally sharing systems negotiate with a central resource management entity to obtain short term grants to use spectrum resources on an exclusive basis

[3] A primary user is a user in a system that operates in a band in which no other system has higher access priority.

[7]. This grant sets the frame for the system internal radio resource management. The spectrum broker can in some cases, e.g., if there is additional vertical sharing with a higher priority user, be seen as an extension of the geo-location database.

Both the GLDB and the spectrum broker approach may additionally assist horizontal sharing between unlicensed systems, although this would typically not be required from the regulator.

IV. Spectrum Sharing Modes and Scenarios

Components in a future multi-RAT multi-carrier MBB system can be envisaged at a given time in a given frequency band to operate in one of the three different modes of spectrum sharing: Primary user mode, unlicensed mode, and licensed shared mode. These modes relate to the regulatory framework of the band which impacts what technologies can be present and hence which sharing enablers are suitable.

A. Primary user mode

From the viewpoint of MBB systems, in a primary user mode the only relevant spectrum sharing scenario[4] is horizontal sharing with other primary systems. There may in principle be secondary systems present, but the primary system need not take the operation of those into consideration. The most relevant primary user mode sharing scenarios are the mutual renting and limited spectrum pool scenarios.

In the *mutual renting* scenario the spectrum resources in a band are subdivided into several blocks and each block is licensed to one operator. Operators mutually allow other operators to "rent" parts of their licensed resources. An operator can rent resources from multiple other operators simultaneously. The actual "owner" of a resource has always strict priority in accessing its licensed part of the spectrum, including the possibility of preemption at any time. This approach could be applied to bands that have initially been used in a dedicated licensed way where there is a need to increase peak data rate beyond what is possible within one licensed block.

The *limited spectrum pool* scenario allows an operator to obtain an authorization, usually a license, to use up to the whole band on a shared basis with a limited number of other known authorized users. This setup does not provide guarantee for instantaneous access to a minimum amount of spectrum, but it is envisioned that mutual agreements between licensees are such that the long term share of an individual operator has a predictable minimum value. This is similar to the sharing situation in unlicensed bands but it is a priori known how many authorizations a regulator will give out and what the rules for the band will be, hence providing the necessary certainty for investments into large networks.

Concerning technical enablers for the primary user mode a spectrum broker or a peer-to-peer messaging protocol over the backhaul seem to give the largest flexibility, since it could address both the mutual renting and the limited spectrum pool scenario. The spectrum broker approach is likely limited in the supported granularity of the sharing, i.e. the solution might be less than optimally efficient. The different enablers may also be combined to give additional benefits that may be exploited by a system in a particular sharing scenario. For example, coexistence beacons can be part of a coordination protocol, e.g. when they serve the purpose of claiming resources or estimating path loss between coordinating nodes.

If coexistence is limited to systems of the same kind, or optimal performance is only required for those situations, an alternative to the previous solutions are over-the-air peer-to-peer coexistence messaging protocols. The advantage of over-the-air coordination compared to a backhaul-based solution could be a faster coordination leading to overall higher efficiency. This solution could be combined with a DCS/DFS or beacon approach for coexistence with known or unknown other systems in bands where the (set of) allowed technologies is not known.

B. Unlicensed mode

In an unlicensed mode an MBB system has to share spectrum with other unlicensed systems while, in special cases, ensuring the protection of primary users of the band. Depending on the nature of the primary system and the regulatory environment, different technical enablers can be required for these scenarios.

For horizontal sharing in an unlicensed band a system must be prepared for coexistence with any other technology that may be present in the band. Non-system specific sharing methods will thus be needed for robustness. For this case de-centralized solutions for coexistence are preferred. Over-the-air signaling may work for sharing within the same technology, but the limitation to a single coexistence situation may make it less preferred. The most realistic solutions are probably coexistence beacons, MAC behavior for coexistence (e.g. for Wi-Fi coexistence), and spectrum sensing with DFS/DCS.

Vertical sharing functionality may also be required for a system operating in unlicensed mode if a primary user exists in the band. Typically, there will be strict requirements to not cause harmful interference to the

[4] Note that systems operating in primary user mode are expected to often operate in dedicated licensed spectrum, and that shared spectrum access in primary user mode will be limited to special situations in certain frequency bands.

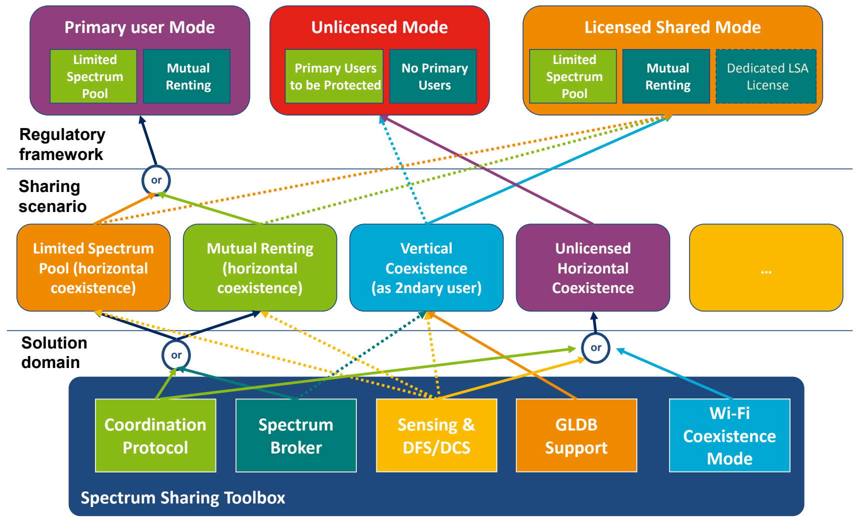

Fig. 2. The spectrum sharing toolbox. Solid arrows illustrate "required" relations (e.g., needed tools or scenarios which are necessary parts of a regulatory framework) whereas dotted arrows illustrate "optional" or "possible" relations.

primary user. The regulator will likely mandate their protection by a particular sharing technique, likely a centralized geo-location database solution or a DFS/DCS scheme.

C. *Licensed shared access (LSA) mode*

In an LSA mode a licensee has the right to access spectrum that is unused by an incumbent user at certain locations and/or times. This vertical sharing is based on well-defined conditions which are parts of a sharing license.

In initial regulatory frameworks, e.g., the LSA concept currently being developed in CEPT working group FM53, the licenses are expected to be long term and exclusive, such that no horizontal sharing would be required. As the concept evolves, the LSA concept may in the longer term be combined with horizontal sharing so that the issued licenses could be non-exclusive and require several licensees to coexist and e.g. share a common spectrum pool. In such scenarios, which is what is considered herein, there is a need for efficient horizontal sharing solutions.

Centralized spectrum sharing solutions will likely be preferred to coordinate the coexistence with the incumbent system. The appropriate solutions to enable horizontal sharing between licensees are similar to those applicable in the primary user mode. Reusing the centralized framework for enabling horizontal coexistence is straightforward and hence GLDB and spectrum broker approaches are possible. Peer-to-peer sharing and coexistence beacon solutions are also envisioned to be applicable to the horizontal sharing, but they would then be somewhat separated from the vertical sharing mechanism.

V. THE SPECTRUM SHARING TOOLBOX

Based on the considerations in the previous sections a number of spectrum sharing "tools" have been identified that will enable a future MBB system to operate in the range of potentially relevant spectrum sharing scenarios. Sometimes one particular tool can enable a certain scenario alone, in some other cases a combination of tools may be required. For the latter there may be multiple options that can enable a given scenario.

It needs to be emphasized that in particular situations only a sub-set of these tools may have to be implemented in a given product or product variant, since it may be designed to address only a subset of the spectrum scenarios. But from a conceptual point of view a MBB system needs to support them all in order to achieve the objective of being able to operate under the full range of different future spectrum authorization models.

The sharing "tools" are collected into a toolbox and may be turned on to enable an encountered sharing situation. The proposed toolbox is illustrated in Fig. 2 and comprises:

- *Coordination protocol* – for efficient horizontal spectrum sharing between independent MBB deployments of the same type/technology,
- *Spectrum broker support* – a more technology-neutral centralized alternative for tightly coordinated sharing,
- Detect-and-avoid mechanisms such as *Dynamic Frequency Selection* or *Dynamic Channel Selection* – used either as a simple mechanism for low-granularity spectrum sharing or as an initial step of selecting the most favorable channel before other sharing techniques are applied within that channel,
- *Geo-location database support* – to enable scenarios

where this is mandated by the regulator for primary user protection, and

- *Wi-Fi coexistence mode* – to enable co-channel operation with Wi-Fi in unlicensed bands.

A. Tools to Enable Sharing in Primary User Mode

To address the primary user mode the coordination protocol and the spectrum broker are seen as the most promising tools. The former should enable the highest sharing efficiency and can benefit from the possibility to specify the behavior of the involved systems and a (default) sharing policy in detail. The latter will likely provide a lower supported sharing granularity and efficiency, due to the need to include some safety margins. On the other hand it would enable better control of the shared resource. Depending on the involved systems, their requirements and their deployment one tool would likely be preferable over the other, but it is not possible to safely conclude on this at this point.

In order to minimize the need for coordination, an automatic channel selection (sensing and DFS/DCS) mechanism would likely be involved as a first step in such scenarios, if applicable, in order to identify and select the best channel that causes the lowest sharing overhead.

B. Tools to Enable Sharing in Unlicensed Mode

For the unlicensed mode differentiation between techniques for horizontal and vertical sharing is needed.

For vertical sharing, detection and DCS/DFS as well as geo-location database (GLDB)-based approaches are suitable. The support of either of those will typically be a regulatory requirement. Extending a GLDB to function as a spectrum broker for horizontal sharing is an option.

For horizontal sharing in unlicensed bands a case-by-case combination of coordination protocol (for optimized coexistence with other MBB systems of the same type), Wi-Fi coexistence mode for sharing with Wi-Fi systems, and detection and DCS/DFS for avoidance of interference by unknown other systems is envisaged.

C. Tools to Enable Sharing in LSA Mode

The LSA mode inherently calls for some vertical sharing mechanism. GLDB support is the more likely option but a sensing and DCS/DFS based solution might be applicable in certain scenarios. The choice of the vertical sharing mechanism will likely be an external (regulatory) requirement.

In case of LSA being combined with horizontal sharing, the range of envisaged solutions includes all options discussed before for the primary user mode: coordination protocol possibly combined with detection and DCS/DFS, or alternatively spectrum broker. The latter would likely be combined with the anyway required GLDB for primary user protection, which may thus make it a preferred approach.

Spectrum sensing and DCS/DFS approaches as a sole measure for horizontal sharing seem to be in conflict with the expectation that LSA supports predictable QoS. A Wi-Fi coexistence mode seems unlikely since one would probably not mix very different technologies in an individual authorization context like LSA.

VI. Conclusions and Discussion

A spectrum sharing scenario is primarily characterized by the regulatory regime and the resulting requirements. In some cases one may meet regulatory requirements with different technical solutions, whereas in other cases a regulatory scenario may uniquely call for a certain technical solution. For example, for vertical sharing the need to effectively protect primary users typically leads to very specific regulatory requirements that normally allow only a certain technical solution. For horizontal sharing regulatory requirements tend to allow more freedom so that more than one option may be possible. Sometimes the solution for horizontal sharing will be subject to industry agreement or standardization; sometimes no agreement may be necessary at all.

Different technical solutions can be envisaged to enable a spectrum sharing scenario. Sometimes also a combination of different technical solutions can be required.

To allow a MBB system to support the full range of *relevant* future sharing scenarios, the spectrum sharing toolbox was introduced. It serves as the framework for enabling/activating sharing techniques on demand when a sharing situation is encountered.

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