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Enabling generic wireless coexistence through technology-agnostic dynamic spectrum access

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Abstract Every year that passes, new standardized and proprietary wireless communication technologies are introduced in the market that seeks to find its place within the already highly congested spectrum. Regulation bodies all around the globe are struggling to keep up with the continuously increasing demand for new bands to offer to specific technologies, some of them requiring by design an exclusive frequency band in order to operate efficiently. Even wireless bands offered for public or scientific usage like the ISM bands are becoming the natural habitat of multiple wireless technologies that seek to use or "abuse" them in order to provide even more bandwidth to their offered applications. Wireless research teams targeting heterogeneous wireless communication coexistence are developing techniques for enabling one-to-one coexistence between various wireless technologies. Can such an exhaustive approach be the solution for N wireless technologies that wish to operate in the same band? We believe that a one-to-one approach is inefficient and cannot lead to a generic coexistence paradigm, applicable to every existing or new wireless communication technology that will arise in the future. Can another approach provide a more generic solution in terms of frequency reuse and coexistence compared to the one-dimensional frequency separation approach commonly used in commercial deployments today. Can such a generic approach provide a simple and easily adoptable coexistence model for existing technologies? In this paper we present a new generic medium sharing model that solves the huge coexistence problems observed today in a simple and efficient way. Our approach is technology-agnostic and compatible with all existing wireless communication technologies and also has the capability to support emerging ones with minimum overhead.

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1 Introduction

It is estimated that around 2020, there will be hundred of billion of heterogeneous devices that would rely on heterogeneous wireless networks [1–3]. Such significant increase in the number of devices that are dependent on wireless communication and the use of diverse wireless technologies will result in an explosive growth in traffic demands via wireless access services [4, 5]. In addition, with constant technological advances, new wireless technologies are being developed and are in demand for satisfactory radio spectrum resources.

The Cisco 'Visual Networking Index 2017' report shows that Wi-Fi and mobile traffic are both growing faster than fixed traffic (traffic generated from devices connected to the network through Ethernet). It is projected that fixed traffic is going to fall from 52% of total IP traffic in 2015 to 33% by 2020. Wi-Fi traffic from both mobile devices and Wi-Fi only devices together will increase to 49% of total IP traffic by 2020, from 42% in 2015 [6]. This is illustrated in Fig. 1. Because of increased number of wireless technologies and increased wireless traffic, regulation committees are struggling to keep up with the continuously increasing demand for additional available spectrum.

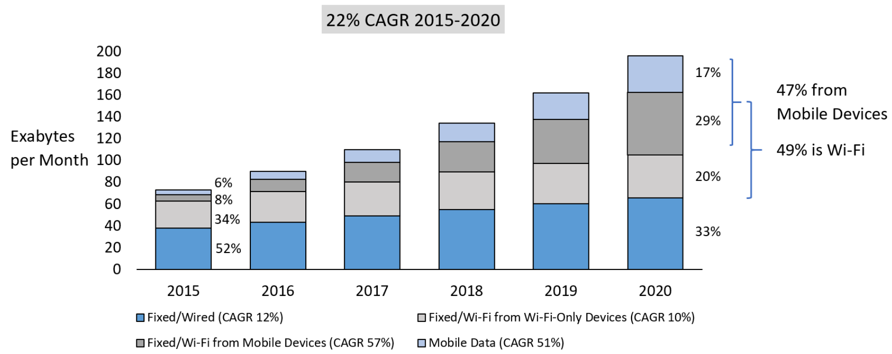

Fig. 1 Cisco 'Visual Networking Index 2017' report [6]

Radio spectrum is becoming a scarce resource. The main problem is not actual shortage of available radio spectrum, but inefficient use of the spectrum (under-utilization). Spectrum is mainly being allocated to licensees that are not always using it to its fullest temporal and spatial potential. In addition, the spectrum usage is concentrated on certain portions of the spectrum while a significant amount of the spectrum remains unutilized. By analyzing utilization of the radio spectrum, vast temporal and geographic variations in the usage of allocated spectrum are being recorded. A report from the Federal Communications Commissions (FCC) Spectrum Policy Task Force shows that at different periods of day and across different geographical areas, utilization is ranging from 15% to 85% in the bands below 3 GHz. In the frequency range above 3 GHz the bands are even more poorly utilized [7]. This inefficiency arises from the inflexibility of the regulatory and licensing process but also from the monolithic design and implementation of wireless technologies, aiming to support operation only within a limited fixed frequency band. Regulatory and licensing process typically assigns the complete rights to access a frequency band to a primary user. This approach makes it extremely difficult to recycle these bands once they are allocated, even if they stay unused for a long period of time in certain geographic locations. Issues with low spectrum utilization are best shown in the Fig. 2 [8]. Spectrum utilization measurements are conducted in an urban area during the mid-day in 0-6 GHz frequency band. In the spectrum below 3 GHz we can see an utilization of roughly 30% and spectrum in interval of 3-6 GHz is utilized only around 0.5%. Because radio spectrum has high economic value and spectrum usage efficiency is of huge importance, it is clear that wasting this important resource must be avoided.

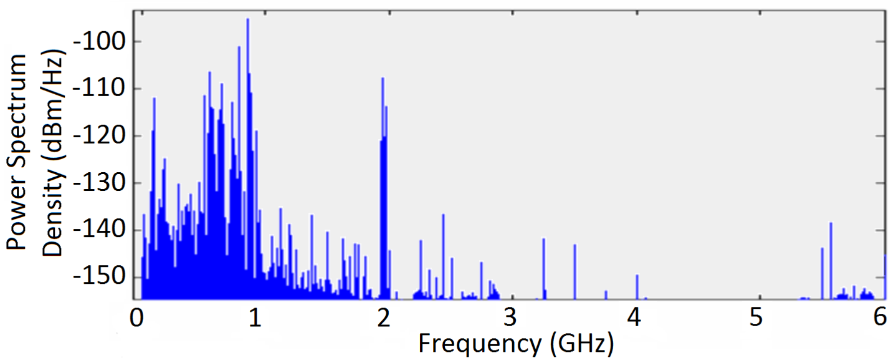

Fig. 2 Measurement of spectrum utilization in downtown Berkeley [8]

Two main models of spectrum usage are dominant today (Table 1). Those are licensed access and unlicensed shared access. In licensed access model, frequency bands are assigned to single user where regulatory committees are guarantying interference free usage of the assigned bands. The assignment of a frequency band to a user and the issue of the associated license, gives the selected user the authority for transmitting in that frequency (the assigned frequency) and the bandwidth of emission (the assigned frequency band) for stated purposes using stated emission parameters [9].

Unlicensed shared access model is license-free model, where users of the unlicensed spectrum need to adhere to regional regulation like power limits and possible duty cycle. In unlicensed radio spectrum, resource planning is not possible and satisfying bandwidth allocation requirements cannot be guaranteed. Unlicensed bands are becoming the natural habitat of multiple wireless technologies, thus wireless networks operating in spatially overlap-

Table 1 Spectrum usage models

	Model	Description	Deployment	Technologies
TODAY	Licensed access	Exclusive assignment of frequency band	Single mobile operator	Traditional cellular networks (e.g. GSM, UMTS, LTE, 5G)
TODAY	Unlicensed shared access	License-free operation according to regional regulation	Many providers	Uncoordinated operation of many technologies (short range: IEEE802.11, IEEE802.15.4, Bluetooth, MulteFire,..., long range: LoRa, SigFox, Dash, IEEE802.11ah...)
UPCOMING	Licensed spectrum sharing	Frequency band assigned to multiple providers based on sharing rules (location, spectrum)	Authorized provider (micro-operators) + mobile operators	Private LTE/5G networks (e.g. CBRS) Directive from FCC (US) : SAS Directive from RSC (EC) : LSA
UPCOMING	Licensed assisted access (LAA)	Use of unlicensed band(s) in addition to licensed band to boost performance	Mobile operator + unlicensed network providers	Coexistence of cellular + unlicensed technologies (e.g. LTE-LAA)
UPCOMING	Sharing in application-specific bands	Frequency band assigned to specific applications	Multiple providers	DSRC 5.9 GHz for ITS: IEEE802.11p + LTE V2X
UPCOMING	Dynamic spectrum access (DSA)	Unlicensed users use temporarily unused licensed band(s)	Authorized provider + unlicensed network providers	IEEE 802.11, IEEE 802.15.4, IEEE 802.22, WiMAX

ping domains can experience significant mutual interference and performance degradation. To reduce effects of mutual interference, using Listen Before Talk (LBT) schemes is proposed, but not all technologies in unlicensed spectrum are using LBT schemes, so the fairness between technologies is not possible. Even if using LBT becomes a requirement for all technologies residing in unlicensed spectrum, the acquired time slice duration varies per technology, so the fair distribution of unlicensed spectrum would still not be achieved.

To reduce negative impact from competing heterogeneous technologies, there is need for coexistence schemes. Many coexistence schemes are implemented until today, but with constantly increasing number of technologies in unlicensed radio spectrum, there is also an increased need for developing new and improved coexistence schemes mainly between pairs of specific mainstream wireless technologies. Significant standardization effort/overhead is needed for two technologies to coexist. Number of coexistence solutions needed for N technologies is calculated based on Eq. 1. With the constant technological advancements and increasing number of technologies, those requirements would be impossible to handle in the near future.

$$\binom{N}{k} = \frac{N!}{k!(N-k)!}, k = 2 \Longrightarrow \binom{N}{2} = \frac{N(N-1)}{2} \tag{1}$$

To solve the impeding problems observed today in the wireless community worldwide, an alternative approach is needed. We propose an approach that provide a more generic solution in frequency band reusability and coexistence of heterogeneous wireless technologies. In our approach, instead of typical frequency division of radio spectrum, we divide radio spectrum both in frequency and time. Those basic units of radio spectrum, we shall call them spectrum slices from now on, are dynamically allocated to the users based on the users demands. The proposed model would increase utilization of the spectrum and reduce interference in the license-free parts of the spectrum. In addition, it offers compatibility towards all existing wireless technologies and is able to effortlessly support any emerging wireless technology with minimum overhead. This would allow multiple heterogeneous wireless networks to coexist in radio spectrum with no or minimum knowledge of other present technologies. It replaces the one-dimensional frequency separation approach that is most commonly used today in commercial applications as well as all MAC related efforts to provide coexistence through MAC techniques like LBT etc., while providing a simple and easily adoptable coexistence model for existing technologies.

In the remainder of this paper we present the following: We give first in Section 2 a short review of the related work until today. In Section 3, we present the proposed general architecture. Section 4 includes description of system functionality with description of protocols used for achieving reliable spectrum sharing. Section 4 is divided in two proposals for centralized and decentralized models. Analysis of costs and benefits of the proposed spectrum sharing model is presented in Section 5. Finally, this work is concluded in Section 6.

2 Related work

A lot of research effort is towards implementing coexistence schemes for heterogeneous wireless technologies in unlicensed radio spectrum. Researchers are especially focused on the most used technologies in unlicensed radio spectrum, such as LTE and Wi-Fi. Two main approaches for improving LTE technology are LAA [10,11] and LTE-U [12]. LAA and LTE-U propose use of unlicensed bands in addition to licensed bands to boost the performance of the wireless LTE networks while trying to support coexistence with other technologies using unlicensed spectrum, especially focusing on coexistence with Wi-Fi technology.

Because of increasing demands for additional radio spectrum resources, new spectrum usage models are emerging lately, as is shown in Table 1. A lot of significance is being put on concepts of using radio spectrum in other ways than statically allocated spectrum [13–17]. Main idea is in dynamic allocation of spectrum to radio services instead of a fixed allocation as it takes place today. Most work is being conducted in fields of Licensed Shared Access (LSA) and Dynamic Spectrum Access (DSA). In LSA, frequency bands (shareable spectrum bands) are assigned to multiple users based on specific sharing rules. LSA represents a regulatory approach to allow any incumbent to share its licensed spectrum with prospective users in accordance with a sharing framework, predefined by the national regulatory authority (NRA)

[18,19]. DSA is the concept of allowing secondary users (unlicensed devices) to use spectrum unused by primary users (licensed devices). Secondary users utilize parts of the spectrum that belongs to primary users based on the agreements and constraints imposed by primary users so that primary users will not be affected in any negative way. The main goal of DSA is to create flexibility in the spectrum usage so that unlicensed users could have access to the parts of radio spectrum temporarily unused by licensed users and this technique is expected to increase spectrum utilization [20]. Aim of the DSA is to manage the radio spectrum by sharing it among different wireless networks over space and time to increase overall spectrum efficiency [21,22]. A lot of work is done on different DSA frameworks to optimize utilization of primary users unutilized bands. LSA and DSA approaches are imposing several research challenges. Research challenges are emerging because of broad range of radio spectrum and because of diversity of Quality of Service (QoS) requirements of heterogeneous wireless networks. In addition, increased valorisation and enhanced control of spectrum usage by Regulatory Committees needs to be established. At the same time, these approaches do not guarantee satisfying QoS requirements of secondary users, because primary users are prioritized in these concepts.

Architecture in DSA networks for sharing of the spectrum can be centralized and distributed. Centralized spectrum sharing is discussed in [23,24], while distributed spectrum sharing is discussed in [25–28]. In [29], an entity named global spectrum controller (GSC) carries out coordinated spectrum sharing related tasks. It stores spectrum resource availability information and ensures that shared spectrum system operates in conformance with the licensing regime. Spectrum Manager in [30] is responsible for spectrum fragmentation and allocation of fragments to base stations. Fragments are extracted from subcarrier grid; shared spectrum is dynamically fragmented and allocated to the operators for "in-band" sharing. Both [29] and [30] are based on subcarriers as a minimum fragment of spectrum used for dynamic allocation; we do not consider that to be a sufficient approach of spectrum fragmentation for our proposal. In addition, sharing spectrum in [29] and [30] is solely focused on network operator level, while our approach is more flexible and is offering to any type of deployed wireless network to be part of the architecture and enter the spectrum, without prioritizing larger networks. Dynamic Spectrum Access Protocol (DSAP) is centralized protocol that enables lease-based dynamic spectrum access through a coordinating central entity and allows efficient resource-sharing and utilization in wireless environments. DSAP is designed to provide spectrum leases to wireless devices in a limited geographic region at small timescales and focuses solely on unlicensed band, thus not solving problems of under-utilization in licensed bands, nor addressing spectrum management on a global scale. DSAP uses a database (RadioMap) for storing important radio spectrum information and provides dynamic allocation of radio spectrum to network nodes [31], which is similar to our proposal but for specific regions of the spectrum. Dynamic intelligent management of spectrum for ubiquitous mobile-access network (DIMSUMnet) is a centralized mechanism based on spectrum brokering that manages large portions of the spectrum and assigns its portions to individual domains or users. DIMSUMnet implements statistically multiplexed coordinated access to spectrum in the Coordinated Access Band (CAB). The concept of CAB is a contiguous chunk of spectrum reserved by regulating authorities and it is used for controlled dynamic access [32]. DIMSUMnet uses a centralized, regional network level brokering mechanism that aims to significantly improve spectrum utilization while reducing the complexity and the agility requirements of the deployed system [33]. DIMSUMnet is only focused on dynamic spectrum access in CAB bands that are part of the radio spectrum and reserved in advance for purposes of dynamic spectrum access. In the DIMSUMnet proposal, clients decide what application service to select only once they receive reserved spectrum information. In a second part of their proposal, clients can participate in a leasing process and request spectrum access themselves. This induces high complexity in case of large scale deployments in the leasing process.

Beside above-mentioned centralized DSA networks, using a database to store information about available spectrum in white-space (under-utilized TV bands) for DSA is proposed by many researchers [34, 35]. Temporally unused parts of the spectrum are referred to as spectrum hole or white space. Existence of accurate spectrum database to provide spectrum maps at different locations is proposed in [36]. Proposed architecture is using common control channel (CCC) for nodes to connect to the database and exchange control messages. The concept of using repository for storing spectrum related information can also be find in LSA [37].

It was noticed that current division of spectrum resources only in frequency domain is not optimal and that much efficient usage of spectrum would be achieved if spectrum is divided in more axis than one. Therefore, dividing spectrum in non-overlapping orthogonal channels, where channel division can follow format of TDMA, FDMA, CDMA or a combination of them is proposed [38–40]. In [41] radio access model is reduced from frequency division-based sharing among operators to a time-division duplex (TDD) system and each operator is allocated a certain number of slots in superframe. The Dynamic Radio for IP Services in Vehicular Environments (DRiVE) project [42] is another approach to the problem of dynamic spectrum allocation that uses CCC and is focused on heterogeneous networks. It proposes use of contiguous radio spectrum instead of fixed radio bands. The extension of DRiVE project is Spectrum Efficient Uni- and Multicast Over Dynamic Radio Networks in Vehicular Environments (OverDRiVE) project [43] that enhances the proposed contiguous division of spectrum to fragmented radio spectrum. In our proposal, we adopt and enhance approach presented in OverDRiVe project, while other proposals are not offering enough spectrum granularity to find them eligible as a starting point.

In our proposed decentralized proposal, a long distance wireless technology is destined to play the role of the control channel. In addition, in centralized proposal, connection of networks entry points (gateways, access points, base stations) to central entity can be a wireless connection, if no wired infrastructure is available. For successful exchange of the control packets using a wireless medium, part of the spectrum (control time-frequency slice) is used. Many spectrum sharing solutions, assume above mentioned CCC for spectrum sharing [31, 44, 45]. Similar approach is proposed in [46], where small amount of spectrum is allocated for control messages and called Common Spectrum Coordination Channel. Above-mentioned papers are reserving whole frequency bands for control messages, while in our proposal we only need a spectrum slice, so just a part of a frequency band, for successful exchange of control messages, while the rest can be used for leasing purposes.

It is noted by the research community that for dynamic allocation of the spectrum, current OSI stack model is often not sufficient. Part of our proposal is a enhanced OSI stack model with an additional sublayer for dynamical spectrum allocation. Research on the need for additional layers in case of dynamic spectrum allocation has been carried out earlier and Dynamic bandwidth allocation (DBA) sublayer has been proposed [15], while in [47] both legacy stack and modified stack are used. Based on the specifics of every proposal, every proposed model of OSI stack offers different stack modifications and functionalities. We claim that our enhanced OSI stack model offers improved functionalities with minimum modifications on the preexisting layer models.

3 Architecture of proposed radio spectrum sharing model

In this chapter the architecture of the proposed radio spectrum sharing model is presented and light is shed on the sub-modules of the architecture and their role and functionality towards the defined goal of dynamic spectrum sharing.

3.1 Division of radio spectrum in frequency-time slices

Licensed and unlicensed radio spectrum is currently divided in frequency bands/channels that are the fundamental units of spectrum usage. These channels are generated as non-overlapping and usually some guard space (Minimum Frequency Separation) is reserved in between them [48]. Licensed spectrum bands are assigned to primary users (license holders), while technologies in unlicensed spectrum try to coexist with other technologies present there. This leaves us with underutilized licensed frequency bands and huge interference probability in unlicensed frequency bands. To achieve more granularity out of available spectrum we adopt and enhance the approach proposed in OverDRiVE project [43] where radio spectrum is divided in fragments. Instead of solely frequency division of radio spectrum, we use typical Time Division Multiple Access (TDMA) approach and divide frequency bands in time, so the fundamental units of radio spectrum in our proposal are frequency-time slices/slots. Typical frequency division of the radio spectrum and more granular division of radio spectrum on frequency-time slices is shown in the 3. Each frequency-time slice can be used to facilitate an unknown communication technology for the duration of the slice. This approach is completely agnostic

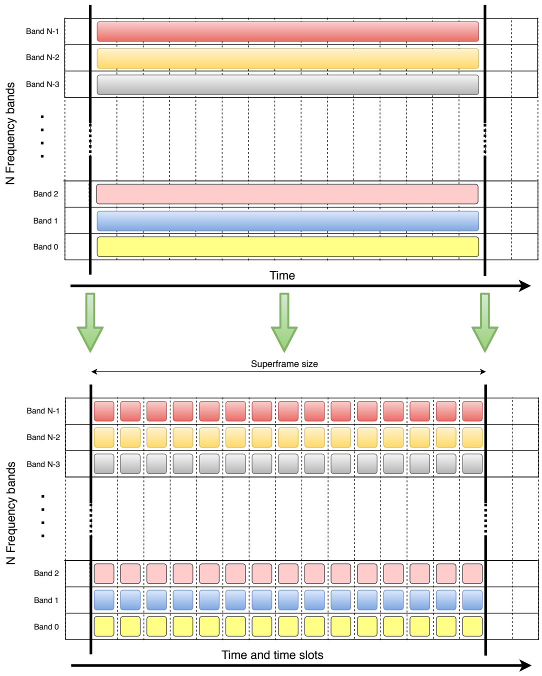

Fig. 3 Transformation from frequency division to frequency-time division of radio spectrum

and there is no need for any kind of compatibility between technologies. During the slice duration, heterogeneous wireless technologies are allowed to use any medium access protocol without fear of negative effects caused by other technologies. In addition, any type of channel coding/modulation scheme and physical layer signaling is acceptable.

This approach allows Regulatory Committees to assign to any heterogeneous wireless network appropriate number of slices depending on networks requirements. It also mitigates under-utilization and interference issues that are occurring today. Time duration of slices can be determined based on theoretical knowledge or experimental results for present technologies and updated when new wireless technologies emerge on the market. Additionally, time duration of slices can vary from frequency to frequency band, based on expected technologies and medium access protocols employed in each frequency band.

3.2 MAC Spectrum Management Layer

As a part of the proposed medium sharing architecture, we propose an upgrade to the current OSI model, an addition of one more layer that is responsible for providing time and frequency accessibility of radio spectrum to the link layer. In proposed OSI model, Medium Access Control (MAC) Spectrum Management Layer exists in parallel with legacy MAC layer, as shown in Fig. 4.

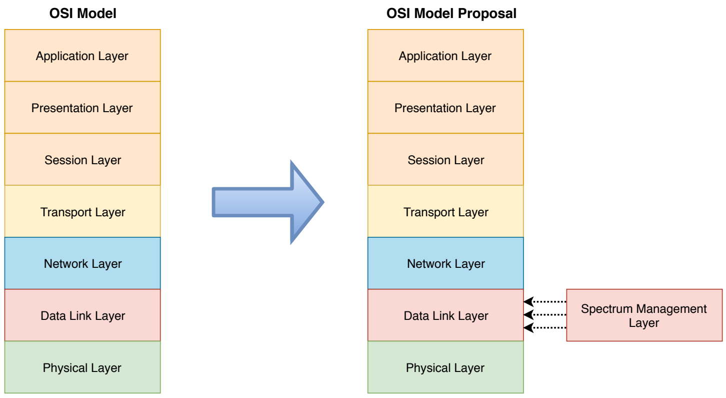

Fig. 4 Proposed OSI model with MAC Spectrum Management Layer

In remainder of the paper we shall refer to this layer as a Spectrum Management Layer (SML). For every managed network, SML is going to keep information about allocated time-frequency slices in local storage space. The information needed is central frequency and bandwidth, slice start and end time as well as possible periodicity information of the slice. SML of every node is communicating with networks entry point to obtain information about the allocated/deallocated spectrum slices for that network. The MAC layer is informed about slice allocations by the SML. If the managed network is assigned with slices that are going to be shared with other managed networks, this information is also provided to SML. Now, the SML can notify MAC layer what additional features should be enabled to achieve coexistence or cooperation with other existing managed networks. The proposed OSI model improves conventional layer architecture and it is a core of our dynamic spectrum sharing proposal.

Legacy MAC layer for every technology should only exploit transmission opportunities in slices that are approved for that technology. It also needs to take into account duration of the slice, so that transmission attempts will not go out of slice bounds. By carefully designed interface of SML, this can be achieved with the minimal modifications of existing legacy MAC layers. For this to be feasible, SMLs interface needs to present requirements in a transparent way to all existing legacy MAC layers.

SML is imposing constraints on legacy MAC layer in form of Application programming interface (API) primitives as shown in Fig. 5. SML is sending Block_at and Unblock_at calls in a way that is transparent to any existing legacy MAC layer. Block and unblock calls are sent with at least millisecond precision, taking into account the overall accuracy of the chosen synchronization mechanism across the architecture. In addition to blocking/unblocking calls, another API primitive interfacing to legacy MACs is information about central frequency and allowed bandwidth. In case that spectrum slice is shared with another managed network, another API primitive is used to inform legacy

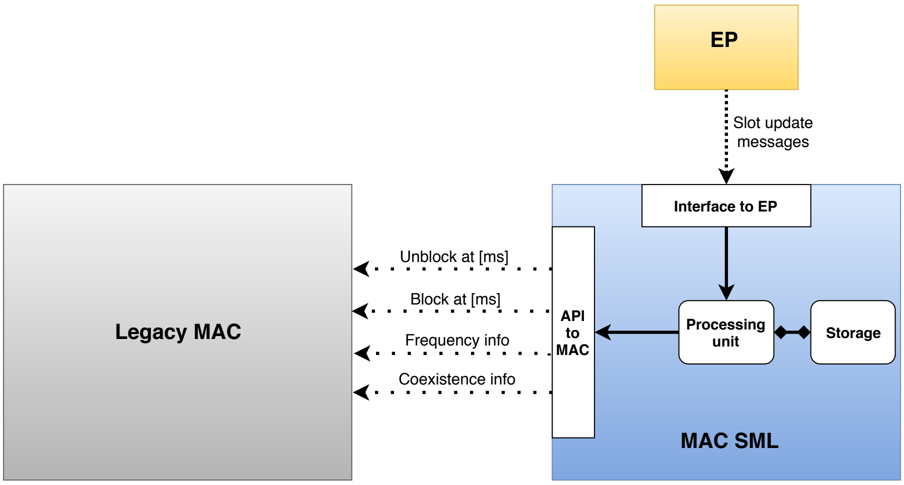

Fig. 5 Application programming interface from SML to MAC layer

MAC layer about which technology is already present in the slice, so that legacy MAC can enable existing coexistence scheme during that slice. Slices where coexistence with other managed networks is needed would be proposed only as a last resort measure (heavily inhabited unlicensed bands for example) and only when central entity (CE) has information that legacy MAC has implementation of coexistence schemes that are prerequisite for successful coexistence in the same slice. Required updates of legacy MACs to comply with SMLs API interface are minimal. Any legacy MAC needs only to exploit received calls to schedule execution of already implemented MAC algorithms during reserved time slices. An additional new functionality is the possibility of runtime enabling of coexistence schemes, if slices are shared. Block_at and unblock_at calls are sent adequate time in advance, so that legacy MAC is in time to process received calls, do the scheduling and perform MACs algorithm inside the bounds of an active spectrum slice. Based on the mentioned technology requirements sent from network's entry point to CE, duration of slice bounded by blocking/unblocking calls is sufficient for legacy MAC protocol to perform typical MAC operations without the risks of exceeding the imposed time limits.

3.3 Regulation committees central entities

Regulation committees (RCs) today play mostly the role of the rule maker but most of the times they lack the mechanisms to enforce spectrum access based on the defined spectrum slices. In our proposal, RCs take up the active role of spectrum sharing policy makers in runtime. All radio spectrum manipulation (radio spectrum slices allocation and deallocation) is controlled by regulation committees central entities (CEs) that are responsible for controlling and maximizing spectrum utilization. These CEs are fixed infrastructure components that are connected through wireless/wired connections to all managed deployed networks and are responsible for the direct control of allocation of available radio spectrum resources. They represent the main part of the regulation system and are responsible for exchanging the necessary control messages with the deployed managed networks whose spectrum access will be regulated. Loss of control messages should be minimal, therefore a wired connection to the deployed networks would be the preferred option. However, if wireless connection is the chosen or only available option, part of the radio spectrum for communication of CEs to other parts of the system should be allocated (control radio slices) to be used only for that purpose. As today spectrum is regulated on national, regional and worldwide level, CEs should equally negotiate usage of radio spectrum slices on those levels. CEs should mainly control spectrum usage on national level, but they should also be coordinated at higher levels, so that no interference and usage of the same slices in neighboring state border regions occur. National CEs are connected to regional CEs and share information about spectrum usage via those regional CEs. The focus is especially on sharing information about spectrum usage in border regions of the countries. Main task of the national CEs is providing slices to different wireless networks/providers/vendors dynamically, while mitigating the interference and enabling efficient utilization and reuse of the spectrum. In the remainder of the paper, heterogeneous wireless networks managed by CEs shall be called managed networks. The overall behavior of CEs enables enforcement of national and regional regulatory spectrum allocation policies while retaining flexibility on spectrum allocation.

Every national CE is keeping a location-time-frequency database (repository) and should update its database with the data received from national CEs of neighboring countries and regions. CEs also contains information on spectrum resources (time-frequency slices) availability in accordance to each countrys specific regulatory framework. It keeps information about geographical features of the heterogeneous managed networks (spatial location represented with latitude, longitude, altitude), frequency-time slices assigned to different networks, spectrum regulations and policies. Once the duration of a slice reservation expires, CEs database is updated and the related request to free the slice is sent to the related networks entry point. In the database, CE stores specific information about heterogeneous managed networks that are using parts of the spectrum, as wireless technology used, medium access protocol used, modulation schemes etc. This way, CE is able to assign same slices to different managed networks in case that spectrum is fully utilized and it has information that two or multiple managed networks can successfully cooperate or coexist. As new wireless technologies emerge constantly, before any upcoming technology enters the market, it should provide RCs and CEs with enough information on its possibilities of coexistence or cooperation with existing technologies. Provided information enables CEs to reuse parts of the spectrum if deemed necessary in certain conditions. However, this approach can be used only as a last resort. Every new technology that enters the market and provides necessary information to CEs, is then assigned with a unique technology ID (identification number) and managed networks based on that technology are able to participate in the future in dynamic radio spectrum allocation process.

CE is responsible for communicating with networks entry points for purposes of allocation/deallocation of frequency-time slices. It calculates slices to allocate/deallocate based on the proposed algorithm, described in Section 4. As an input, CE takes managed networks entry points requests, extracts necessary data from the requests and access the available information in the CEs database. CE is also responsible for updating its database when an allocation/deallocation procedure is finalized and it should periodically exchange radio spectrum information with other CEs in its vicinity. CEs will therefore become the active instrument that will allow regulation authorities to monitor managed networks and to ensure that managed networks operate in conformance within existing regulatory framework.

3.4 Managed networks entry points

The link between CEs and managed networks is the access point (AP), base station (BS) or gateway (GW) of any managed network. The entry point (EP) of the managed network (AP, BS, or GW) is responsible for introduction of a new managed network to the radio spectrum and for maintenance of the network. It keeps track of the network requirements and forwards these requirements to the related CE for dynamic adjustment of the allocated spectrum to this network. In addition, it is responsible for handling any request it might receive from the CE to keep the network in compliance with the regulatory framework. In case of local area heterogeneous networks, EPs communicate directly to other EPs in the area and keep a local database with information on spectrum usage in that area. On the global level, any change in the allowed spectrum access of the network is first forwarded to the EP by the CE, which then forward the information to all the nodes in the network. For our dynamic spectrum sharing proposal, time synchronization of all the network components is assumed. If the nodes in the network do not have any means for global time synchronization, EP is obliged to synchronize all the nodes in the network to global time. Information about global time can be obtained using any standardized method (GPS, NTP etc.) as long as the slices minimum duration is not in the range of the synchronization accuracy of the employed method.

3.5 Minimum duration of spectrum slices

EP of every managed network has a knowledge of wireless technology and MAC protocols used by the devices in the network. All existing legacy MAC protocols have specific requirements on time interval needed to reach its goals.

Timing requirements are most important for procedures of packet transmission and reception. To avoid being assigned with spectrum slices of insufficient time duration, where basic MAC operations will not fit, an important parameter to provide to the CE when requesting new spectrum slices is the minimum acceptable duration of the slice; we shall refer to it as slice base duration. Requested slice base duration for any MAC protocol should not exceed predefined national value, otherwise CE will discard the request and notify EP that allocation request failed, with provided reason for failure.

As an example of feasible slice base duration, in typical Carrier-sense multiple access/channel assessment (CSMA/CA) MAC protocol, slice base duration can be calculated based on time needed to complete one packet transmission. In the calculated time, the time duration of typical basic procedures or critical defined times of CSMA is included like duration of Interframe Spaces (SIFS and DIFS), Clear Channel Assessment (CCA) needed time, transmission period for maximum valid data packet size and acknowledgment transmission period. In case of CSMA/CA protocols with included Request to Send (RTS) and Clear to Send (CTS) messages, time for transmission of these messages is included as well. In the case of a typical TDMA MAC protocol, the slice base duration should be at least the size of TDMA superframe or a multiple of TDMA supeframe size, so that one or multiple superframes can fit into one allocated spectrum slice.

4 Proposed radio spectrum sharing models and protocols

4.1 Centralized model proposal

In the proposed centralized model, regulation committees CEs handle requests and approve the usage of frequency-time slices. CEs have full information on spectrum utilization stored in their database/repository following the history of approved requests of spectrum usage in their area of control. To communicate with CEs and exchange messages for allocation and deallocation of radio spectrum, every EP must have a wired/wireless connection to the CE. The proposed architecture for a centralized dynamic sharing model is presented in Fig. 6. In case of employing a wireless connection between EPs and CEs, part of the radio spectrum should be reserved (control radio slices) for exchange of control messages. In addition to communication between EPs and CEs, the control radio slices are also used for communication between different CEs forming a control channel between the parts of the architecture. Managed networks are not permitted to use the control radio slices in order to avoid interference but also avoid high data traffic to impact the reliability of the control traffic.

For efficient utilization of the spectrum, CEs need to know the location and spatial distribution of the managed networks that require to access the medium. For that to be possible, localization is needed for EPs, either through using Global Positioning System (GPS) or other standardized methods. Based

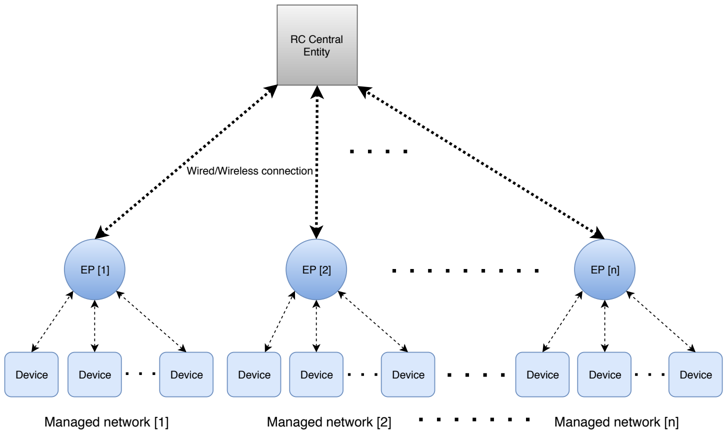

Fig. 6 Centralized model architecture

on their requests, managed networks are allowed access to adequate number of frequency-time slices. To avoid collision with other managed networks in the area where multiple networks reside, time synchronization for EPs is needed through additional hardware like GPS, by using established network based techniques like Network Time Protocol (NTP) or any other acceptable method that can provide at least millisecond level accuracy. Besides time synchronization in the EPs level, in order to follow the established rules of transmitting inside the assigned slices, every client node also needs to follow the global time. For the time synchronization of the network nodes, the same approach can be used as for the EPs, or the EPs can adopt also the role of synchronization master of their internal network nodes based on any related protocol. If that is not feasible, additional hardware to provide synchronization of the network nodes can be deployed like GPS receiver. To avoid extreme costs of user equipment devices, GPS can be employed in the EP level for worldwide synchronization of all EPs, while network protocols like PTP or NTP can be used to synchronize the client devices to the local EP.

Slice negotiation and allocation for all heterogeneous managed networks is initiated by networks EP based on specific requirements (data rate, user demands, QoS etc.). EPs are performing continuous control of the requested Quality of Service (QoS). When QoS requirements changes in a way that the currently assigned spectrum is insufficient or part of the spectrum becomes unused, EPs initiate appropriate action. Spectrum usage is paid per number of slices used outside free bands, which as a result reduces unutilized radio spectrum, as no spectrum user is willing to pay for more spectrum than needed to satisfy its demands. To reduce costs of using the spectrum, if the bandwidth requirements are reduced, EPs can send remove requests and deallocate part of the used spectrum. Main purpose of centralized model of dynamic spectrum sharing for licensed spectrum is efficient utilization of spectrum usage but also a result of reduced cost for the users can be present. For the unlicensed spectrum, with proposed sharing model, better utilization is also achieved, while collisions between heterogeneous managed networks is avoided where needed and coexistence of compatible networks is also exploited. All this is achieved while at the same time the authorized networks (spectrum slices holders) are being served the necessary spectrum in order to be able to provide a certain QoS to their users.

When a new managed network wants to enter the spectrum, its EP follows the specified procedure and exchanges request and response messages with the related CE. The proposed procedures are explained later in this section. Once the networks EP acquire information of radio spectrum available for it to use, EP communicate to all network nodes employing the proposed SML of the OSI model, forwarding all the necessary information. EPs of managed networks are responsible for carrying out successful transfer of slices information messages to internal nodes, using any approach that is most preferred by the managed network specific technology characteristics. It is assumed that every EP of a managed network can have direct or multi-hop communication with all internal nodes of their network. After reception of slices information messages, network nodes can operate using the spectrum slices that are allocated for that managed network, regardless of the existence of other managed networks in its vicinity. An example of spectrum sharing between heterogeneous managed networks in the same vicinity is shown in Fig. 7. Every change in the usage of radio spectrum initiated by EP or CE are forwarded to the SML of every node and being enforced on all nodes.

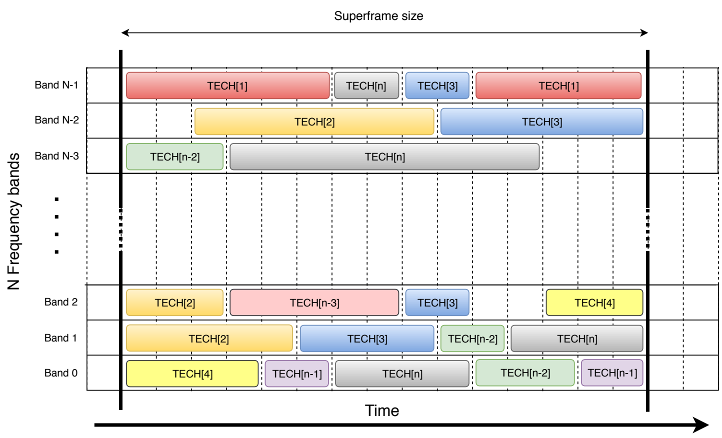

Fig. 7 Centralized model spectrum allocation

CEs can be set up on the national, regional, continental or global level. All the lower CEs (national level) are synchronized and aligned in a global network of CEs controlled by higher level CEs (regional, continental level). This enables exchange of the information between CEs, avoidance of the spectrum interference in the border areas that are controlled by national entities and better spectrum utilization. Any prioritization or precedence needed to be given to specific networks like military or public safety networks should be implemented within the CEs, embedded in the decision making process of accepting or denying spectrum requests from all managed networks. The network priority parameter should be taken into account in the spectrum allocation procedure in order to make sure that the higher priority networks are never starved of spectrum resources.

4.2 Radio spectrum slices negotiation protocol (centralized model)

When a new managed network enters the spectrum, first step is to allocate part of the spectrum based on QoS requirements. If the requirements for the spectrum increase over time, networks EP can request more slices of spectrum from the CE following the same procedure as in its initial entry phase. In addition, if there is a reduction in required spectrum, EP can ask from CE to deallocate some of the slices previously allocated. If there is a necessity to move time-frequency slices used by the network from one frequency band to another, slice move procedure can be initiated. CE initiates procedures only when it is needed to move or remove a network slice in order to decrease interference or because a more prioritized request has occurred in the vicinity of the managed network and there is no more spectrum to be offered. Its purpose is to keep the system stable, to reduce interference and increase number of unused spectrum slices that can later be assigned to other upcoming technologies. So, there are 4 main primitives that comprise the protocol for centralized spectrum sharing and are described in more details in the following subsection.

1. Slice allocation
2. Slice deallocation
3. Slice move
4. Housekeeping (heartbeat)

There are 4 message types used for successful negotiation of slices between network EPs and national CEs:

1. Request messages
2. Response messages
3. Heartbeat messages
4. Slice update messages

Request messages are sent from network EP to CEs. They are used whenever a managed network needs more spectrum slices to satisfy user demands or some of the slices are not needed, so deallocating them would reduce costs induced by RCs. Allocation, deallocation and move protocols are initiated by corresponding Request messages. Response messages from CEs to EPs are sent in case of both possible outcomes: successful execution of protocol primitive or failure. Response failure messages are classified on response failure type A and type B messages. Response failure type A messages are response messages from CE to the EP in case of request messages not satisfying protocol requirements, for example request message not including all information needed for CE to do the computation and generate proper response. Response failure type B messages are exchanged when CE calculates that request from the EP is not feasible (requesting too much spectrum share, not enough free spectrum slices available in database, network technology not coexistent with any other technology already using spectrum etc.). Response success messages are sent to EPs from CEs if negotiation is successful and network is approved to allocate additional spectrum, remove part of currently allocated spectrum or reallocate its current slices to other part of radio spectrum. Slice update messages are used to update SML of every node in the managed network with newly allocated/deallocated slices. Heartbeat messages are part of housekeeping protocol and are responsible for keeping the system stable and error-free.

1. **Slice allocation procedure:** In the Request allocate message, the network's EP needs to provide its unique technology identification number to the CE, in order for the CE to fetch additional information about the specific technology features from its database, like MAC protocols supported by the technology, possibility of coexistence with other technologies etc. EP also needs to include spectrum requirements based on its user needs and QoS requirements. Request allocate message should contain required bandwidth, duty cycle, slice base duration and location information of the network. In the CE side, the location information can be used to build a spatial map of wireless coverage in order to then proceed into the most appropriate spectrum slice allocation, minimizing interference to co-locating networks. Location of the EP is acquired by GPS or can even be fixed, set during deployment if the EP cannot move. Information about expected duration of access to approved slices should be in the Request allocate message as well. CE gathers necessary information from CE's database (free spectrum slices, technology information based on received unique ID etc.) and calculates the minimum number of frequency-time slices that can satisfy requirements received in Request allocate message. CE then updates the local database and notify EP about calculation results via Response allocate message. Response allocate message carries information about spectrum slices that are now allocated to the managed network. In case that in one or more of these slices, the newly deployed managed network would coexist with other networks, additional information about coexisting networks technology is also provided.
2. **Slice deallocation procedure:** Request deallocate message carries information about network requesting removal of a subset of its slices and its new bandwidth and duty cycle requirements. CE will do the recalculation and find number of slices that can safely be deallocated, to keep up with new requirements of the managed network. CE is going to deallocate those slices from the database and notify EPs via Response deallocate message to do the same.

Slice allocation and slice deallocation protocols are presented in Fig. 8.

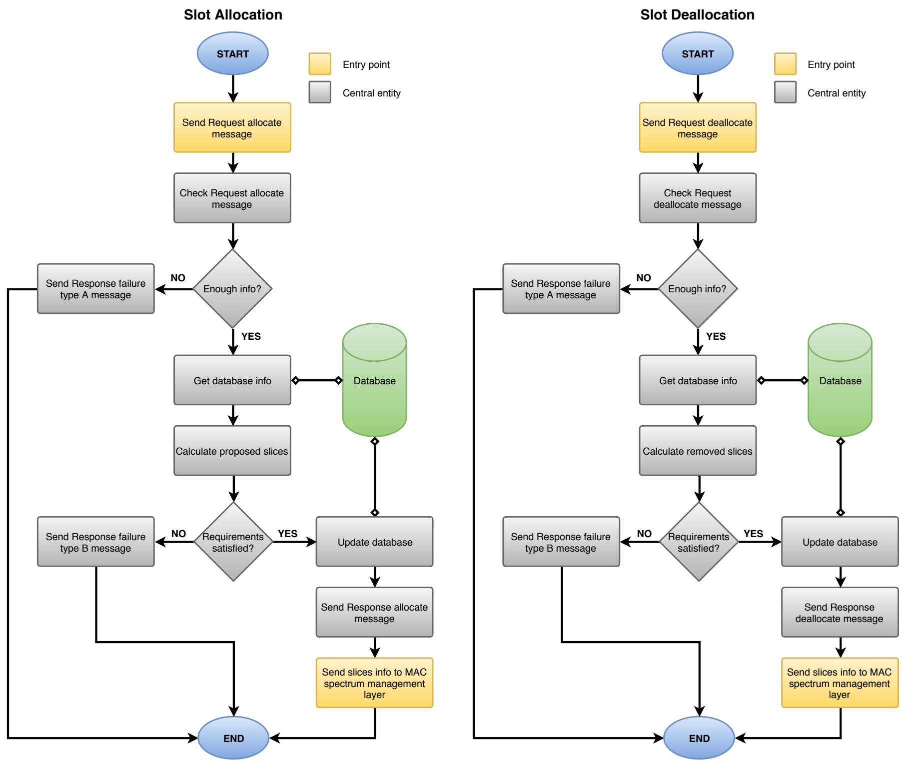

Fig. 8 Centralized model allocation and deallocation protocols

3. **Slice move procedure:** Move procedure is similar as the two procedures mentioned above. CE receives Request move message and it deallocates part of the allocated frequency-time slices. Then CE responds to EP with list of slices that should be deallocated and list of the slices that should be used in their place from now on by EPs managed network.

In case of the failure of any of the above procedures, CE keeps its database intact and notifies EP about the issues encountered. Based on the response, EP can send another request to the CE that would bypass issues that occurred in the previously sent request. Once the EP successfully negotiate slice allocation/deallocation, next step is to inform SML about changes in spectrum usage. This is done by sending Slice update messages (Slice allocation and Slice deallocation messages). Slice allocation message contains list of slices that EP acquired, while Slice deallocation message contains list of removed slices. Slices are represented as frequency-time pairs and with reserved duration of the slice. According to that information, SML updates local list of slices that can be used for transmission/reception. If there are slices where coexistence with other technologies should be in place, the local list of the slices contains additional information, so that the related coexistence schemes can be enabled in MAC layer of the internal network nodes.

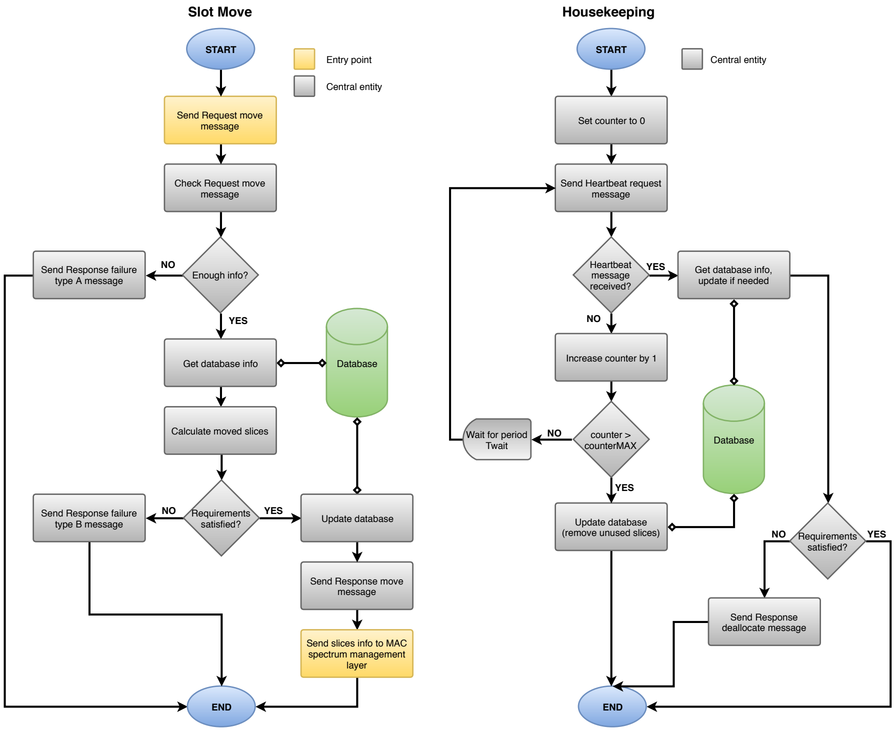

Fig. 9 Centralized model move and housekeeping protocols

4. **Housekeeping (heartbeat) procedure:** For housekeeping of the whole system, CEs periodically send probe messages (Heartbeat request messages) to every EP that they have stored in the database. After receiving probe message, EP answers with Heartbeat message that contains spectrum usage information in form of used frequency-time slices. On the reception of Heartbeat message, CEs are aware that network previously approved with part of the spectrum is still active and can compare information from heartbeat message with the information stored in CEs database. If data from the heartbeat message and database differs, so that message contains reduced or in any way altered number of slices, CE deallocate slices that are not part of the heartbeat message and is going to reuse them for other purposes. If heartbeat message contains information of slice usage that are not stored as used by that network, CE sends Response deallocate message with slices that needs to be released by the network. With the initiation of periodic housekeeping protocol, besides checking for inactive networks, CEs check if any systematic errors occurred during the process of slice allocation/deallocation and take care that those issues are fixed promptly. In case of unanswered Heartbeat request message after $Twait$ delay period is passed, CE sends another probe message and this procedure continues until $counterMax$ value is exceeded. Then, CE con-

cludes that probed managed network is not active anymore in the radio spectrum and that it has vacated the spectrum without sending Request deallocate message. CE can safely deallocate slices previously used by that network from database and assign them to other networks that request part of the spectrum in the future. Values for $Twait$ and $counterMax$ can be determined per network deployment type (static long term deployment or opportunistic short term local deployments), based on experimental results and can differ between different technologies types.

Slice move protocol and housekeeping procedure are presented in Fig. 9.

4.3 Decentralized model proposal

For dynamic spectrum sharing of unlicensed bands in case of local area networks, we propose a decentralized spectrum sharing model that can operate in the absence of a CE. Because there can be no reachable CEs to control usage of the spectrum and no possibilities to charge for the licensed spectrum used in local area networks, this model is only focused on utilization and interference avoidance within unlicensed spectrum. Because heterogeneous wireless networks present in remote areas are not managed by CEs, instead of managed networks, we shall refer to them as a self-managed networks.

For successful negotiation of the available unlicensed spectrum in local area networks, EPs should assume the responsibility of exchanging information on spectrum usage. For that to be possible, all EPs of the local networks need to have integrated a common long-range wireless technology besides the primary wireless technology used for data transmission. The architecture of a decentralized dynamic spectrum sharing model is presented in Fig. 10.

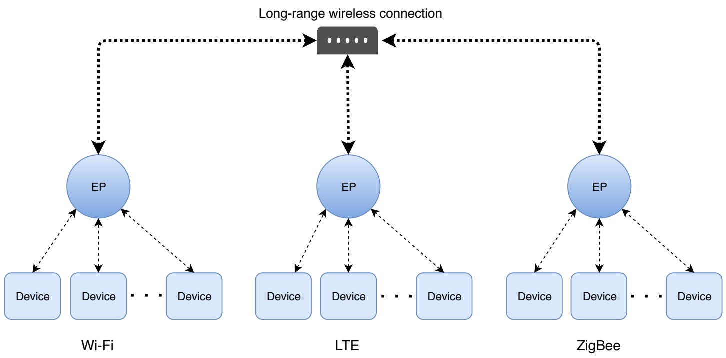

Fig. 10 Decentralized model architecture

For communication between the EPs in a local area, a single time-frequency slice (control radio slice) in the unlicensed radio spectrum is reserved and not available to local self-managed networks for data transmission. If an EP of a local self-managed network does not have integrated long range wireless technology, another possibility for entering a local area is to integrate a local Artificial Intelligence (AI) module and radio spectrum sensing capabilities. Sensing capabilities are used to inform AI module about the state of the spectrum. Based on the sensing information, the AI module can chose radio spectrum slices where no transmission activities are recorded for some predefined period of time. Distributed approach for accessing radio spectrum that relies on spectrum sensing capabilities is heavily researched and present in form of Cognitive Radios (CR) [49–51]. Example of coexistence of three most common wireless technologies LTE, Wi-Fi and ZigBee in unlicensed radio spectrum is shown in Fig. 11. Such an approach can be employed to offer a complete solution for decentralized spectrum access while minimizing possible interference between competing networks on the spectrum slice level.

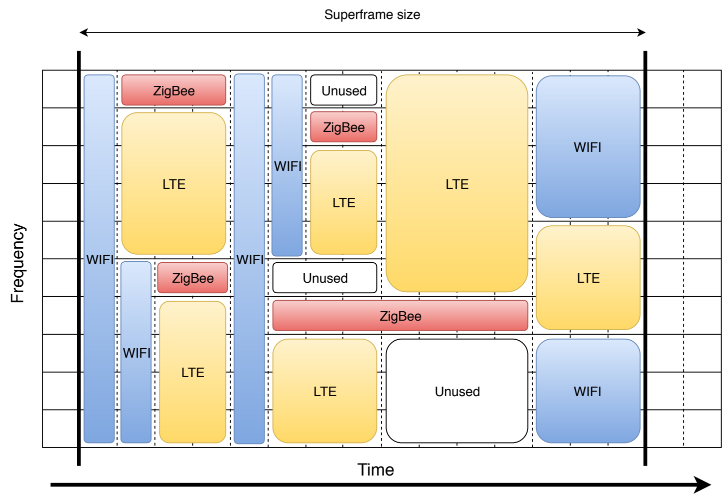

Fig. 11 Decentralized model spectrum allocation

One of the main issues with increased demands for unlicensed bands is that if a new network is trying to establish itself in a local area where many other networks are residing, it might occur that not enough free slices are available. In that case EP can chose slices that are used by the networks with technologies that can coexist with its own wireless technology. It is important that this approach does not drastically reduce performance of the other networks already using spectrum slices. In any case, even if two self-managed networks use wireless technologies that are perfectly cooperative with each other, same slices should be used by different self-managed networks only as a last resort.

In the same way with the centralized model proposal, EPs in decentralized model proposal that use long distance wireless for control messages exchange, need to have a method of obtaining global location and global time information. In addition, global time synchronization needs to be achieved on the node level, directly by nodes or by synchronization with EPs. If the AI and CR approach is used, EPs or nodes in the local network need to have sensing capabilities; time synchronization would improve interference mitigation, while localization in this case is not needed.

4.4 Radio spectrum slices negotiation protocol (decentralized model)

In the following subsection the decentralized procedure for allocation of spectrum slices in a local area is briefly described and presented in Fig. 12.

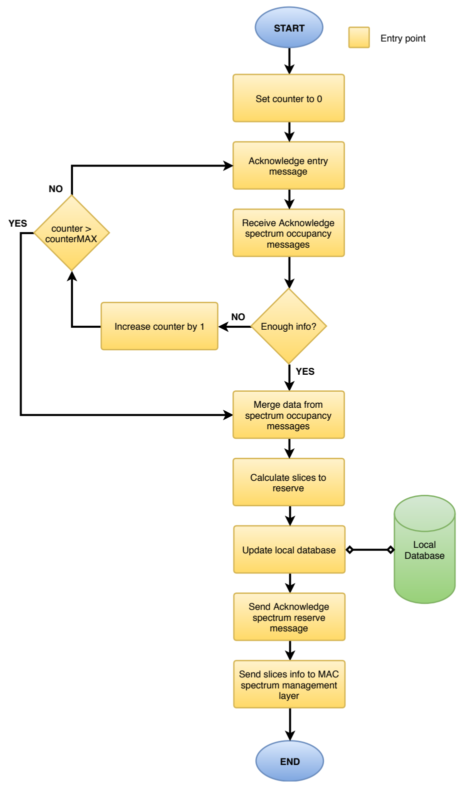

Fig. 12 Decentralized model protocol for accessing local area radio spectrum

For mutual coordination of self-managed networks in local area, Acknowledge messages are used with 5 different types of messages: entry, spectrum occupancy, spectrum reserve, presence and departure message type.

When new self-managed network wants to access the spectrum in a local area, its EP first sends an Acknowledge entry message. Other EPs in the local area upon reception of entry message respond with Acknowledge spectrum occupancy message containing data about used spectrum, spatial distribution of the network and additional data about wireless technology used by each network. If EP does not get any response from other EPs in the local area or the received information is not sufficient it retries sending an entry message. After maximum number of retries $counterMax$ is reached or after enough data about state of the unlicensed spectrum in local area is acquired, EP merges all information received and creates a table of used and unused spectrum slices. Then EP calculates number of slices needed in order to satisfy the networks requirements. It also chooses which time-frequency slices to allocate until sufficient number of slices is made available for use. Local database is updated with all slices allocated by other networks present in local area and slices allocated by that network itself. An Acknowledge reserve spectrum message is sent to all other EPs to acknowledge spectrum slices that the new network would use in the local area unlicensed spectrum. Other EPs update their local databases with newly allocated slices. Next step for the EP of the new network is to inform SMLs of all internal nodes in the network about slices to be used for the transmission/reception opportunities. If the local area is too congested with many other networks already present, slices where cooperation or coexistence with other technologies is expected can be allocated. All networks that are using slices where other networks reside, need to inform SMLs to enable coexistence schemes in MAC layer. SMLs receive the same Slice update messages as in centralized proposal and after that are able to inform MAC layers about valid slices to allow spectrum usage.

Local self-managed networks EPs should periodically send Acknowledge presence messages to inform other networks that their network is still active. If after some time one self-managed network appears IDLE, other EPs should update their local databases by removing slices previously used by IDLE self-managed network. Now, those slices can be reused in the future by existing self-managed networks or by any new self-managed network that attempts to enter local area. If a local self-managed network cease to exist, it should inform other local EPs about its intention to leave the local unlicensed spectrum by sending Acknowledge departure message. If that is not supported or fails, unused slices would be freed in any case by IDLE timeout for which no Acknowledge presence message is transmitted by local self-managed network.

5 Costs and benefits of proposed spectrum sharing model

Licensing regime used today, called command and control, allocates full non-overlapping frequency bands to licensees. Licensees are granted access to spectrum for long predefined periods, with limited rules and imposed requirements regarding the use of the assigned spectrum. This model of licensing regime is the main cause for spectrum scarcity and low spectrum utilization. Main benefit of the proposed spectrum sharing model is an increased efficiency in utilization of radio spectrum and better interference mitigation in unlicensed bands. By allocating smaller chunks of the spectrum and thus reducing initial costs, new technologies and new products will easier enter the market.

Reduced barriers for entering the market would allow better adjustment of wireless technologies to consumer trends and more innovation freedom in the field of telecommunications. Market demands would be the main driving force behind rational spectrum allocation and usage; more popular and dense deployed wireless technologies would be given more spectrum slices.

For the proposed sharing model, EPs need to be equipped with additional hardware for time synchronization, location acquisition and wireless control channel support. In addition, for the centralized model proposal, static infrastructure would need to be installed and coordinated on at least a country level. However, with constant technological advances, hardware components are becoming cheaper and thus more accessible. Extra costs of new infrastructure and required hardware to accomplish the goals of our spectrum-sharing framework would also be compensated by increased revenue from denser networks and higher efficiency use of the spectrum from all the new players that would be allowed to come in the market. New players would be able to easier deploy new advanced networks with low costs for accessing and using the spectrum. These reduced costs would come from the fact that every wireless network would only pay for the exact part of the radio spectrum that is needed to satisfy the demands and only for the time that it is active. Leasing of full frequency bands for long period of time and for high prices, which constitutes a high cost-wall for every new player, would be replaced with dynamic leasing of smaller chunks of the spectrum. This would enable smaller providers of wireless services to enter the licensed spectrum and thus to terminate monopoly present today in telecommunication services. As a result, users of the telecommunication services would be able to chose between a wider range of different options, which would push the providers of the wireless services to be more competitive in terms of reduced consumer prices and provided user services. The wireless providers offering best value for money, would attract more users and have better revenues. As a result, users would be offered enhanced services and QoS requirements. At the same time, increased revenues would give better financial conditions for providers to request for more slices in radio spectrum. This would allow the wireless technologies and wireless providers that provide the best user experience to be in better position to be granted bigger chunks of the priceless resource that is the radio spectrum, making it impossible for oligopolies to be formed in the wireless market of a country.

6 Conclusion

We have presented a generic, technology agnostic, dynamic spectrum sharing framework that, if adopted, can revolutionize the way spectrum is allocated, shared and payed for. It would offer the ability to all regional regulation committees to actually monitor and enforce spectrum usage policies in real time across their area of control, while enabling them to charge per accurate spectrum use of each spectrum user. All stakeholders of spectrum would still be able to lease in run time the spectrum they require at any given time, reducing costs since they would release spectrum when their traffic load is low. Coexistence problems between heterogeneous technologies would be defacto solved since there would be no chance of two incompatible technologies to share the same spectrum slice. Dynamic sharing of the same spectrum slice, based on MAC characteristics which is the most common approach today towards coexistence, would still be possible for compatible technologies if the need arises. The proposed framework will present no conflict with any future technology, as there are no requirements towards any emerging technology other than to be able to perform a single spectrum access procedure within a definitive period of time. It also supports the possibility for decentralized self-managed local network deployments, permitting the typical application scenario of local area network deployments, like a Wi-Fi network, with or without central control. Local deployments without central control support, can employ spectrum sensing and take intelligent decisions on spectrum usage to minimize local interference. Adopting the proposed framework would also allow the research community to turn its focus from defining and prototyping one-to-one coexistence solutions with huge costs in time and effort, releasing a big research potential, allowing to focus towards new wireless technologies, protocols and physical layers that would be a real breakthrough and actually bring the 5G+ era closer. To the knowledge of the authors, this is the first paper up to date proposing a generic, technology agnostic, dynamic spectrum sharing/leasing framework for all available regulated radio spectrum, not aiming in just subparts of the radio spectrum like the ISM bands and not focused or applicable only on specific existing technologies.

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