Mobile Networks and Applications (2020) 25:1749–1764
https://doi.org/10.1007/s11036-020-01564-w

Survey on Wireless Networks Coexistence: Resource Sharing in the 5G Era

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Abstract

The next generation of mobile-enabled wireless networks, known as 5G networks, is announced to be deployed by 2020. In the 5G framework, access technologies are one of the main features that would allow users to seamlessly connect to the Internet using any of the available technologies. These technologies are going to coexist in the same physical environment. This coexistence has the advantage of offering the user multiple options for establishing communications. On the other hand, existing and upcoming wireless standards have not given this coexistence enough attention. In this paper, we survey existing communication protocols, techniques and mechanisms, as well as features of the 5G communication standards that allow technology to cope well with coexistence. We focus on access layer solutions that can be used in unlicensed frequency bands. We also argue that resource sharing should be extended not only to manage the available spectrum but also the available physical systems. We argue in this paper that resource sharing mechanisms would have a positive impact on the 5G infrastructure for better spectrum efficiency.

Keywords Networks coexistence · Spectrum efficiency · Resource sharing · Connected cities · 5G

1 Introduction

Academies, industries, and standardization bodies are working around the world to build and meet the vision of 5G networks [1]. They all agree to the fact that 5G has to be a heterogeneous networking environment [2, 3] with the integration of licensed and unlicensed technologies [4, 5]. Indeed, this will ensure that technologies can profit from the use of any available bandwidth in the area of deployment.

The main vision of 5G is to enable a global wireless connectivity by bringing together all network actors and elements (e.g. people, things, cities, applications and data) by 2020 and beyond. Hence, the convergence and the coexistence of networks in a globally harmonised communication network environment is as *necessary* as it is *inevitable*.

(i) A necessity: because network convergence could be a solution for optimization aspects needed in the global 5G concept, such as throughput, latency, coverage and load balancing. In this perspective, the industrial consortium WBA (Wireless Broadband Alliance) reviewed in [5] candidate technologies and made some standardization proposals on currently ongoing standardization efforts [6]. Networks convergence is already used in Internet Exchange Points (IXP), where many Internet Service Providers (ISP) share the same routing and switching infrastructures for cost efficiency. Therefore, one can also imagine resource sharing applied to 5G network infrastructures in dense urban environment, for the sake of spectrum and resource efficiency in addition to cost benefits.

(ii) Coexistence of networks is inevitable: global deployment of Internet of Things (IoT) networks together with Cooperative Intelligent Transport Systems (C-ITS) network infrastructures is a clear example of heterogeneous technologies that will coexist in connected cities and urban areas. In such smart cities, IoT and C-ITS access networks, usually use the limited number of unlicensed frequency bands in addition to

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> their licensed bands. In [7], Contreras-Castillo et al. propose a comprehension framework of the applications of heterogeneous networking environment of connected vehicles and discuss some challenges (such as the selection of the appropriate networks for disseminating information) in the concept of Internet of Vehicles (IoV) in general.
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> In more general terms, we call resource sharing, a scenario of deployment and management of heterogeneous applications and networking technologies for the sake of a global efficiency of resource use. Resources can be network nodes, access interfaces (and their respective standard access technologies), or spectrum (which is the main focus of this paper). Figure 1 summarizes the definition of our concept of resource sharing.

Access technologies operating on unlicensed bands in smart cities environment are typically IEEE *802.15.4*, *LoRaWAN*, *Sigfox* and *IEEE 802.11ah* which trade speed for range and power consumption for IoT networks, and the other *IEEE 802.11* series such as *802.11ac*, *802.11ax* and *802.11ay* which, according to the future connectivity paper of Wi-Fi Alliance will also play an important role in the 5G scenario (of Enhanced Mobile Broadband) requiring high data rates in a wide coverage area [8]. By using unlicensed bands, these access technologies already share the available frequency spectrum.

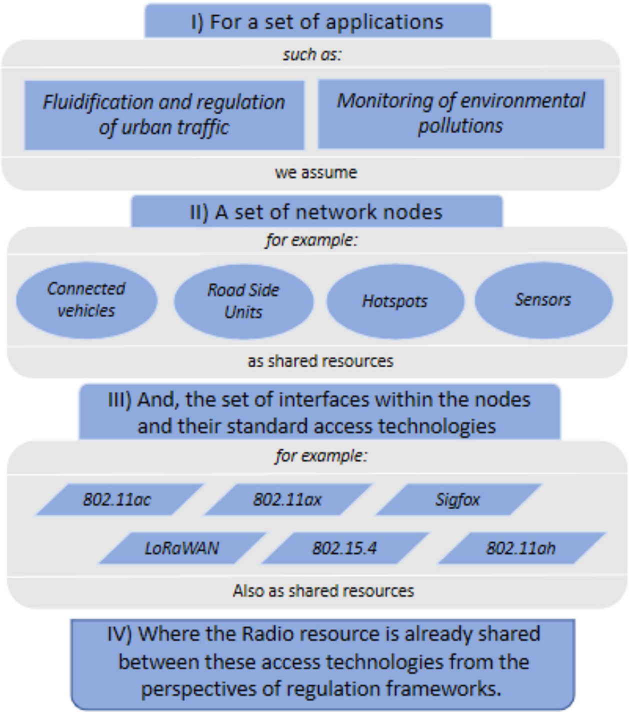

Fig. 1 A definition of our concept of resource sharing: in the context of smart city network infrastructures and applications

Globally, Spectrum Efficiency (SE) issue in 5G can be seen as a consequence of this inevitable trend of networks to coexist and caused by the physical limitations of resources. Allocations of this scarce resource are getting increasingly difficult, and unlicensed bands are getting increasingly crowded. In the era of 5G networks, from the industrialists point of view, allocation of radio spectrum needs a global scale synchronisation to make 5G a reality [9, 10].

Furthermore, proposals for sharing computing resources in vehicular networks are emerging in the literature in order to reduce the latency in vehicular applications through a cooperation between the connected vehicles and their surrounding resources (e.g. RSUs and Cloud resources) [11]. The main challenges of these proposals towards a universal framework are the discovery and dynamic exploitation of resources.

Cognitive Radio (CR) technologies are studied in the literature to deal with the SE problem. Cognitive Radio systems can be defined as a set of mechanisms related to sensing, interaction, and adaptation with and to the surrounding radio frequency environment as described in [12–15]. A system implementing resource sharing, aiming to optimize the usage of radio resource, must decide which technology alternatives it has to use to transmit application data (this is called *spectrum decision*). This decision should be based on the availability of radio resource at the transmission attempt (*spectrum sensing*). And finally, the system should be able to coordinate concurrent nodes to access the radio resource (*spectrum sharing*). These decisions are closely related to CR mechanisms.

Software Defined Networking (SDN) is a key technology in 5G networks for flexible and agile service delivery in the core network of mobile operators [16]. It can be an alternative solution to implement resource and spectrum sharing. In fact, there are several architectures for IoV (and IoT in general) based on SDN [17, 18], which mainly manage the network resources on a centralized controller. SDNs are out of the scope of this paper, here we mainly concentrate on distributed solutions and techniques that can be applied for SE and resource sharing aims.

This paper aims to present current efforts in both the literature and the standardization bodies on incorporating coexistence techniques for spectrum sharing in the 5G era. Also, we propose an extension to the spectrum sharing that goes to the physical system sharing by mutualization communication nodes to serve multiple applications and services. We will discuss CR mechanisms that can benefit the coexistence of heterogeneous technologies and concentrate on resource sharing methods proposed in the literature and supported in some of the standardized solutions.

The remainder of the paper is structured as follow: In Section 2, we review literature proposals related to wireless resource sharing where the various approaches are summarized in Table 1. In Section 3, we identify and discuss coexistence features included in the standards that will be used in the 5G era. We suggest in Section 4 several open issues for allowing heterogeneous networking technologies to efficiently coexist in smart city environments, and finally conclude the paper in Section 5.

2 Wireless resource sharing in the literature

In this section, we provide a quick overview of the existing techniques proposed in the literature for wireless resource sharing with a special focus on access layer techniques. We start the section with a brief introduction to CR operations and how they benefit spectrum sharing, then we describe how MAC protocols can include features that allow them the better use the available spectrum, and we end this section with an overview of protocols that switch between different MAC protocols in order to better adapt to the surrounding environment.

2.1 Cognitive Radio systems

A Cognitive Radio system can be defined as a radio system that can sense and interact with its surrounding environment in order to adapt its behaviour [19]. Thus, in a scenario of deployment and management of heterogeneous networking technologies and applications such as defined in Fig. 1, the underlying system has to deal with the common aspects of CR system stages, where each stage of the system has its own set of design challenges [12].

2.1.1 Spectrum sensing

It is the stage where the system builds its map (frequency and time matrix) describing spectrum access opportunities. There are several frameworks for sensing aspects in cognitive wireless networks [13, 15]. For example, energy is a critical resource for sensors and IoT networks, and thus, systems built on energy efficient algorithms (physical layer functionalities) such as energy detector [20, 21] and Waveform-based [22] sensing would be more suited to share resources of sensor networks.

2.1.2 Spectrum decision and mobility

After sensing the spectrum, it can happen that the system has many opportunities. The goal of this stage is to choose the appropriate network interfaces and technologies to be used for transmission, and keep track of another best opportunity compared to the one in use. There are several proposals in the literature about decision algorithms in heterogeneous networks [23, 24]. Overall, the common

Table 1 Related works of wireless resource sharing and their main approach

Proposal	Mainly shared entities / resources	Targeted optimization	Approach
Farago et al. [29]	MAC protocols	Improve overall performance of a broadcast channel in varying network conditions.	Automatic combination of MAC protocols in a per-frame MAC protocol based on computational learning theory and machine learning techniques.
Doerr et al. [30]	MAC protocols, Access devices	Implementation of MAC protocol adaption agility in varying network conditions.	Override of commodity 802.11 network cards in order to have control over frame creation mechanism and the timing elements.
Cordeiro and Challapali [28]	Licensed and unlicensed spectrum	Increase overall throughput and links robustness.	Based on synchronized time-slot and multi-channel MAC protocols.
Lien et al. [26]	Licensed spectrum	Maximize overall usage of spectrum.	Opportunistic spectrum access by Secondary Users in an environment of Primary Users.
Kim et al. [31]	MAC protocols	Increase throughput and reduce communication latency.	A centralized framework architecture that can dynamically change a MAC protocol based on some QoS constraints of supported applications.
Qiao et al. [32]	MAC protocols	Model of predicting adapted MAC protocol in varying network conditions.	Training of machine learning algorithms with Network Parametric Features and Network Statistics Features.
Feng et al. [11]	CPUs (Central Processing Units), multiple communication channels	Reduce application latency.	Application of Mobile Edge Computing paradigm in vehicular networks in order to reduce the latency of intensive in-vehicle applications.

design challenges are to take into account the QoS constraints of the supported applications and physical specificities of the spectrum opportunities.

2.1.3 Spectrum sharing

This stage relates to coordination between possible concurrent candidates to exploit the spectrum opportunities. This stage of sharing must solve almost all classical problems of MAC sub-layer, such as protocol overhead and the design of a synchronization channel. In an environment sharing several access technologies for more resource efficiency, the underlying system has to deal with coordination and synchronization. We will discuss some proposals in the literature that deal with these aspects in Section 2.3.

2.2 MAC protocols in cognitive radio environment

In a general concept of resource sharing, the proposals of MAC protocols in CR environment can be globally seen as techniques to mutualize radio resource at the MAC sub-layer between two categories of network users: Primary Users (PUs) who have priority to access to a given spectrum portion, and Secondary Users (PUs) who have lower priority than the PUs; most of the proposals are designed for opportunistic spectrum access by SUs in an environment of PUs.

There are various MAC proposals in the literature related to CR theory [12, 14, 25]. Nevertheless, the standardization efforts in cognitive MAC protocols remains particularly challenging: the common proposals target specific scenarios. In addition, most proposals are not backward compatible with standardized protocols such as the Distributed Coordination Function (DCF) of IEEE 802.11.

In the following paragraphs, we will discuss the mode of operation of two representative proposals.

CSMA in cognitive radio networks A CSMA/CA based MAC protocol is proposed by [26] to enable the coexistence of a network of PUs and a network of SUs, but with possible interference between them. The network of SUs called Cognitive Radio Network (CRN) and the network of PUs called Primary System (PS) are infra-structured networks, where PUs and SUs are associated to their respective Base Stations (BS). There are only data transmissions from subscribers to BSs. Each BS defines and adapts the modulation and coding scheme of its subscribers during the handshake procedure of data transmission. Under the following assumption: all interferences caused by RTS (Request to Send) and CTS (Clear to Send) packets can be mitigated by a strong forward error correction code, the medium access scheme is as follow:

PUs contend with CSMA/CA with RTS/CTS handshake to transmit their data after the waiting period τ_p. To transmit their data, SUs wait for period τ_s, where $\tau_s >> \tau_p$, and also use CSMA/CA with RTS/CTS handshake, with two modifications: (i) if the channel is occupied by PUs after τ_s, a SU still sends its RTS packet. (ii) If a RTS packet is received by its BS, the BS computes the feasible transmission power and rate and reply in consequence with a CTS if the transmission is feasible without causing data loss for PUs.

With this model of access scheme and the strong assumption of ignoring interference caused by all RTS/CTS packets, interferences can still occur to frames received by the PS BS during data transmission of the SUs [14].

The optimization scenario of this proposal can be implemented as a use case of IEEE 802.11e [27], if the two BSs are implemented as a single Hybrid Coordinator (HC), and SUs and PUs networks are implemented into two distinct traffic node classes functioning in Enhanced Distributed Channel Access (EDCA) mode associated to the HC.

Cognitive-MAC for multi-channel wireless networks Cognitive-MAC (C-MAC) [28] proposal is based on synchronized time-slot and multi-channel MAC protocols, it aims to increase the overall throughput of the links and the robustness to spectrum changes.

Implemented in a completely distributed manner, the following features are supported by C-MAC.

- *Inter-channel coordination:* there is no need for a dedicated common coordination channel. Each channel available is a potential one for coordination, called Rendezvous Channel (RC). It is dynamically selected and can change over time.
- *Distributed beaconing:* there is no need for a central device for beaconing, each device is expected to transmit and/or receive a beacon on the RC.
- *Load balancing:* using the RC, each network node shares its channel occupation information, and the channel selection algorithm at each node takes this into account for load balancing.
- *Coexistence:* in C-MAC framework every channel has two consecutive periods: Beacon Period (BP) and Data Transfer Period (DTP). During the DTP of each channel, there are quiet periods scheduled to sense the PUs.

The RC is initiated as follow. Upon power up, a node starts by scanning all the channels to search for already initiated RC. If no RC is found, the node initiates one itself. Thus, it may have more than one RC in the network at a given time due to the distributed nature of the network.

The symmetric functioning of C-MAC could be summarized as follow. (i) During the association to the network, a node starts by a search of the RC to know which node is located on which channel by analyzing the beacons received. (ii) Then, the node selects a channel, and contends to get a permanent slot chosen among the first two slots of the BP of the channel (these two first slots are reserved for this purpose). (iii) If the node does not select the RC (probably for the sake of load balancing), it still periodically visits the RC to get resynchronized and for multicast or broadcast diffusion.

One of the drawbacks of C-MAC is that all beacons of network nodes must fit within the BPs of a superframe, which could limit the scaling factor of the proposal.

2.3 Toward architectures for MAC protocols orchestration

In general, MAC protocols are designed to optimize specific network scenario conditions. What we call architecture for MAC protocols orchestration are the literature proposals trying to build a system that can dynamically choose a specific MAC protocol suited to specific network conditions. Thus, these architectures can be seen as proposals which mutualize several MAC protocols between the nodes of a network. Even if each proposal has its own definition of network condition, there are some common assumptions: (i) a network node may have several MAC protocols, (ii) each MAC protocol is more suited for a specific network condition, (iii) and, the network condition can change over time.

In the following paragraphs we will discuss the mode of operation of some of these proposals.

Meta-MAC protocols Inspired by the computational learning theory and machine learning techniques, Farago et al. [29] are among the first to propose a framework to coordinate a broadcast channel with an automatic selection of MAC protocols. In their framework, there is no need for any coordination or message exchanges. A network node decides locally to transmit a frame or not during a slot. The node is assumed to have perfect “feedback” about its previous transmission decision at the end of each slot. The feedback is a binary variable which tells the node whether or not its previous decision was “correct” or “incorrect”. Each node relies on its feedback to locally update a trust coefficient for each of its MAC protocols. These coefficients are initiated at system startup and decrease for a MAC protocol when decisions are incorrect.

According to our knowledge, there is no implementation of this theoretical framework, apart from an attempt by Doerr et al. [30].

MAC protocol service Kim et al. [31] made a proof of concept of a centralized framework architecture that can dynamically change a MAC protocol, the change is based on some QoS constraints of the supported applications in the network. In their framework, the central node has three software components. (i) An *Analyzer* which periodically gets QoS information of running applications (e.g. latency bound and Packet Error Rate) and system information (e.g. channel state information and number of connected devices). (ii) A *Protocol Engine* which gathers information from the *analyzer* to set the parameter values of a Linear Optimization Problem (this LOP is built and used offline), and solves the LOP in order to select the optimal MAC protocol. (iii) A *Protocol Realizer* which parses protocol reconfiguration information received from the *Protocol Engine*. Then, it reconfigures the protocol stack of the central node, and through a dedicated channel, forwards reconfiguration information to the *Protocol Realizer* deployed on other network nodes, which in turn reconfigure their protocol stacks.

A practical use case of this framework is a connected home where the central node of the architecture could be a smartphone controlling sensors and actuators.

MAC protocol selection based on machine learning With fewer concerns on real deployment requirements, authors in Qiao et al. [32] reported a framework of prediction of a suited MAC protocol (e.g. competitive or non-competitive) given network load circonstances with machine learning techniques. The proposed prediction model is based on a support vector machine training algorithm (Sequential Minimal Optimization) trained with data set collected through extensive simulations by varying Network Parametric Features such as the number of nodes, data rate, inter-arrival time and packet length, and the associated Network Statistics Features such as average load and throughput.

A practical use case of this model can be an infrastructure network, where the central node has full and real-time knowledge of the network conditions and ideal wireless channels.

In this perspective towards MAC protocol orchestration architectures, there has been plenty of work on software-based implementation of the MAC layer in the paradigm of Software Defined Radios using typically Field-Programmable Gate Arrays (FPGAs) Circuits [33–35]. These implementations offer flexibility compared to hardware-specific implementations. The main argument in favor of adopting hardware-based approaches instead of FPGAs has long been the fact that software-based implementations fail to achieve timing requirements, resulting in poor performance [36, 37].

3 Coexistence efforts in standardized technologies in the 5G era

The revolutionary side in 5G is that of a framework that encompasses and integrates all access technologies. Recent standards of wireless access technologies toward the 5G vision integrate more coexistence features, either between nodes using the same technology or nodes using different technologies. In this section, we will go through the coexistence features of the main standardized solution to be operating in the 5G era. In Section 3.1 we will identify coexistence features embedded in some IEEE 802.11 (Wi-Fi) amendments and discuss their usage under some scenarios of connected cities. In Section 3.2 we will describe some coexistence aspects of Wi-Fi and LTE in unlicensed bands. We will summarize in Section 3.3 some interference issues and adapted solutions for short-range technologies in coexistence scenarios. Then, in Section 3.4 we provide an overview of standardization efforts of 3GPP and IETF toward Radio Access Network convergence and discuss some requirements of these standards under scenarios of the 5G urban environment. We end Section 3 with a summary table (Table 2) of the main features included in the latest wireless standards.

3.1 In IEEE 802.11 (Wi-Fi) coexistence

Wi-Fi is one of the most popular unlicensed access technologies in the environment of connected cities such as C-ITS infrastructures, airports or stadiums. Recent versions of Wi-Fi such as 802.11ac (2013) and 802.11ax (2020) integrate more features to optimize coexistence scenarios between nodes of 802.11 standards.

Furthermore, IEEE adapts in the 802.11ah (2016) standard their Wi-Fi technology to the emerging market of the IoT in the context of 5G. Beside 802.15.4 (2003-2011), 802.11ah could be an alternative for sensor networks in the environment of connected cities.

802.11ac (Wi-Fi) 802.11ac is a more flexible form of 802.11n (Wi-Fi 4, 2009). An 802.11ac Access Point (AP) offers a dynamic throughput of up to 6.9 Gbps to a client under ideal conditions [38, 39]. The main factors of this dynamic throughput mechanism is to take account of:

- *The client capacity:* such as the version of 802.11 (a, n or ac) that the client implements, and the number of antennas it can use for spatial streams (multiplexing).

Table 2 Standards towards 5G and their main coexistence efficiency features

Standard	Features of efficient coexistence	Status
802.11ac (Wi-Fi 5)	Introduces per-frame channel and bandwidth selection through the enhancement of the RTS/CTS mechanism in order to negotiate maximum bandwidth in a transmission attempt.	Approved by IEEE (2013).
802.11ax (Wi-Fi 6)	Introduces access based on OFDMA scheduling in the contention based access framework (DCF) to reduce access latency in crowed environments, and extensions to RTS/CTS procedure for a safe coexistence with older users. Introduces also adaptive carrier sensing threshold, transmit power and the basic service set coloring to improve spatial reuse for dense WLAN deployments.	Draft IEEE standard currently being approved.
License Assisted Access (LAA)	Intended to offload cellular traffic through unlicensed bands in 5GHz and do listen-before-talk access mechanism to coexist with other unlicensed technologies in the same band (e.g. Wi-Fi).	Under study for 3GPP release 16 for access centric integration of licensed and unlicensed technologies.
Multi-Path TCP	Aggregates multiple flows of access networks in a single TCP session for a global efficiency in terms of throughput and load balancing.	Approved by the IETF in RFC 6824.
Multi-Path QUIC protocol	Like Multi-Path TCP, it is intended to aggregate multiple flows of access networks, but for applications using UDP.	Draft standard at the IETF [71].
Multi-Access Management Service framework	Specifies framework for aggregating several network interfaces at both ends of a service over an IP network that is not tied to a specific protocol of the IETF like Multi-Path-TCP or Multi-Path-QUIC.	Draft standard at the IETF [72].
5G New Radio: Multi-RATs framework	Introduces a User Equipment (UE) model which has to simultaneously operate on other frequency bands than those of the usual LTE for 5G use cases (e.g. V2X communications). In the current state of this framework the EU (e.g. a vehicle) is assumed to be able to select the best RAT based on either pre-configured information, QoS related constraints or its surrounding connection possibilities (e.g. connected vehicles, RSUs/hotspots or base stations).	Will be included as part of 3GPP release 16.

- *The number of available channels:* in the vicinity of the AP and of the client at the time of the transmission attempts.

From the MAC sub-layer perspectives, in 802.11ac, available throughput is increased thanks to:

- *The frame aggregation* mechanism introduced in 802.11n, is mandatory between exchanges of 802.11ac nodes. One of the rationales to this is to achieve more throughput by reducing protocol overhead due to headers of small data frames.
- The concept of *per-frame channel and bandwidth selection*. This is achieved through the enhancement of the RTS/CTS mechanism in order to negotiate maximum bandwidth. This mechanism is called *RTS/CTS with bandwidth indication*.

802.11ac is fully compatible with all previous 802.11 versions operating in the 5 GHz frequency band, such as 802.11a (Wi-Fi 2, 1999) and 802.11n. This backward compatibility means, for example, that an 802.11ac AP must be able to associate 802.11$a|n|ac$ clients. And 802.11$a|n$ compliant nodes should be able to update their *Virtual Carrier Sensing Data* (the data which 802.11 compliant nodes rely on to know whether a channel is idle or not) from the activities of 802.11ac compliant nodes in their vicinity.

802.11ac backward compatibility is ensured by the use of the same preamble and header format as those in use since 802.11a PLCP (Physical Layer Convergence Procedure Protocol) Protocol Data Unit (PPDU), for control frames such as RTS/CTS.

In order to illustrate the channel negotiation mechanism through the RTS/CTS with bandwidth indication of 802.11ac, and its backward compatibility, we present the following scenario: an 802.11ac *node-1* wants to transmit a frame to another 802.11ac *node-2* with potentially 802.11$a|n|ac$ nodes in their vicinity.

(i) In the Clear Channel Assessment (CCA) stage, according to the standard, node-1 performs the following steps:

  - Node-1 first tests the availability of a first 20 MHz channel, let's call this channel *ch-A*;
  - If *ch-A* is available, node-1 then checks the availability of another 20 MHz channel adjacent to *ch-A*, let's call this channel *ch-B*;
  - Node-1 continues the process to double its transmission bandwidth each time, up to 160MHz (the maximum bandwidth authorized in the standard).

  Suppose at the end of its CCA, node-1 has successfully tested the availability of a 80 MHz bandwidth, thus four 20 MHz adjacent channels (let's call them *ch-A*, *ch-B*, *ch-C* and *ch-D*).

(ii) Node-1 sends the same RTS frame in 802.11a PPDU format, on four channels to node-2. From this point on, two cases of interest are to be identified, illustrated in Fig. 2.

(iii-a) No interference case (Fig. 2-a): node-2 receives the four RTS frames and responds with four CTS frames corresponding to the four channels. As a result, this would give node-1 the opportunity to send data across the resulting 80 MHz channel.

(iii-b) Interference case (Fig. 2-b), node-2 receives only two RTS frames (two channels are occupied) and responds with the corresponding two CTS frames. As a result, this would give node-1 the opportunity to transmit on only a 40 MHz wide channel.

During CCA, the channel sensing algorithm in 802.11ac is based on two methods of 802.11: *energy detection* and *signal detection*, which are respectively in the category of Energy detector [20] and Waveform-based sensing [21]. 802.11ac keeps the same CCA sensitivity rules as 802.11n for 20 MHz and 40 MHz channels [38]. But, with one additional rule: every time the channel bandwidth doubles, the required signal threshold also doubles. In other words, in a transmission attempt, from a channel of 40 MHz bandwidth, the requirement of link quality level grows proportionally to the required bandwidth. Hence, 802.11ac compliant devices would less often be able to use wider channels in a crowded urban environment where many hotspots would be deployed.

802.11ax (Wi-Fi 6) The access scheme of 802.11ac (Wi-Fi 5) is based on pure contention within a spatial stream. Hence, in the context of crowded stadium or busy airport with hundreds of end users attempting to access the internet at the same time, the system loses efficiency and performance. 802.11ax draft standard currently being approved by IEEE is built on the strengths of 802.11ac while adding a new level of flexibility and scalability to be more suited to crowded environments [40]. This is achieved through (i) an introduction of frequency multiplexing based access (similar to that of LTE/cellular) within the fundamental contention based access framework of 802.11 (DCF) to reduce access latency, and therefore (ii) extensions to RTS/CTS procedures for multi-user to help avoid collisions with users using older single-user mode for a safe coexistence.

Instead of enhancing overall performances and services, the densification of massive basic service set (BSS) deployment degrades overall performances due to limited spectrum and co-channel interference. That's why one of the main goals of 802.11ax is to address this densification

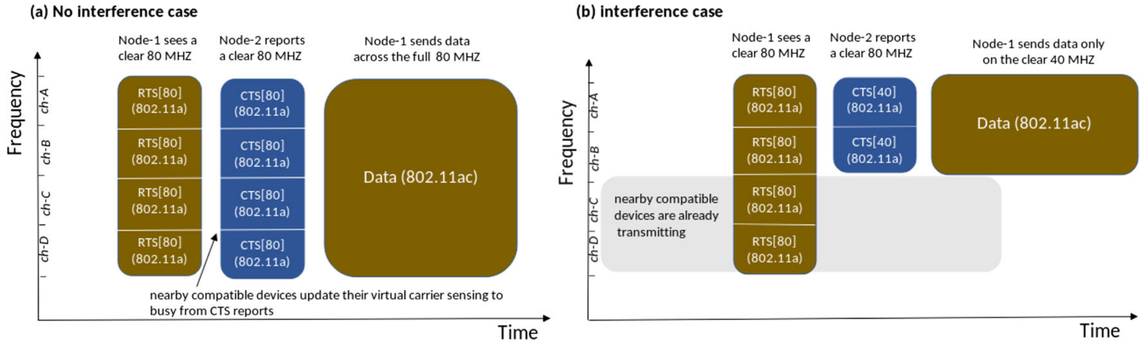

Fig. 2 RTS/CTS with bandwidth indication use scenario in 802.11ac

problem by improving Spatial Reuse (SR) to maximize parallel transmissions. A challenge of a proper SR mechanism is adjusting the Carrier Sensing Threshold (CST) of stations (STA) during their medium access procedures because, reducing this threshold reduces SR, whereas an increase results in more collisions [41]. In the current 802.11ax standard three main mechanisms are adapted to improve SR: i) the adaptive CST level, ii) the adaptive transmit power (ATP) level, and iii) the BSS coloring [42]. The main idea is to combine these mechanisms as follows. When an STA receives a packet that does not belong to its BSS (a packet with a different color), instead of applying a fixed CST for medium access, it applies a more aggressive threshold with an inversely proportional transmit power to address fairness problem with neighbor BBS.

802.11ax includes a new feature called Target Wake Time (TWT) which conserves bandwidth and battery power through scheduling of short windows of engagement. It is intended to assist resource constrained IoT devices to reduce their energy consumption.

Unlike 802.11ac which operates over 5 GHz only, 802.11ax operates on frequency bands between 1 and 7.125 GHz, and uses a preamble header that ensures compatibility with legacy IEEE 802.11 devices [42]. Thus, 802.11ax access points such as those of *Cisco Catalyst 9100* which have also support IoT specific protocols (e.g. Zigbee and Bluetooth) are typically the nodes for the mutualization of legacy and already deployed access resources with new infrastructures of connected cities operating on unlicensed frequency bands [43].

802.11ah (Wi-Fi haLow) The IEEE 802.11ah Task Group ratified a standard which operates in the unlicensed frequency band below 1 GHz [44]. Unlike the classical 802.11 series such as 802.11$ac|ax$, 802.11ah trades speed to optimize range and power consumption, hence making it more suited in IoT networks for resource constrained devices such as sensors [45]. 802.11ah is better than the 802.15.4 in terms of association time, throughput, delay, and coverage range based on a study published in [46]. According to the Wi-Fi Alliance, 802.11ah is an alternative to the 3GPP (3rd Generation Partnership Project) specifications for the IoT market in the context of 5G [47].

3.2 Coexistence of Wi-Fi and LTE in unlicensed bands

The growing demand of mobile traffic and the scarcity of licence radio bands are the main motivation of the mobile industry to design access technologies which operate on unlicensed bands, in particular, the bands in 5GHz [48].

License Assisted Access (LAA) led by 3GPP (introduced in release 13) is intended to offload cellular traffic through the Unlicensed National Information Infrastructure bands in 5GHz, the band in which 802.11 operates. Both LAA and 802.11 do a listen-before-talk access mechanism as mandated by the regulatory framework (e.g. in Europe), but this does not guarantee successful coexistence because the two standards have different physical and MAC layers [49].

LTE unlicensed (LTE-U) promoted by LTE-Forum prescribes Carrier Sense Adaptive Transmission (CSAT) as an alternative to LAA for offloading cellular traffic in regions (e.g. USA and China) where regulations do not mandate the listen-before-talk mechanism [50]. LTE-U adapts a duty cycle mechanism by extending LTE carrier aggregation from licensed to unlicensed bands, which, unlike LAA, is a relatively simple mechanism that does not require changes to the LTE air interface protocol [51]. Results of a study from Google in [52] show that in many circumstances this approach is aggressive to a coexisting Wi-Fi network due mainly to the fact that an LTE-U transmission can start while another one from the Wi-Fi network is already in progress. Other results indicate that if the LTE-U duty cycle is fixed to 50% and the load of Wi-Fi network increases, a better overall throughput is obtained compared to another coexisting Wi-Fi network [53].

LTE-V2X mode 4 (introduced in 3GPP release 14) operates on the bands for Intelligent Transportation System in 5.9GHz, the band in which 802.11p also operates on. LTE-V2X (vehicle to everything) mode 4 and 802.11p have relatively the same performance for vehicular ad-hoc communications [54]. The inherent coexistence issues of these two access technologies are also due to their different design of physical and MAC layers [55].

3.3 Coexistence of some short-range technologies used in IoT networks

ZigBee ZigBee is a popular technology for implementing low cost and low power wireless control networks with high deployment flexibility. It adapts IEEE 802.15.4 PHY and MAC layers in the 2.4 GHz ISM band and is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) algorithm for channel access. In the literature coexistence and interference issues have been widely studied both on analytical and practical approaches in IEEE 802.15.4 [56–58]. Most of the studies have been concentrated on IEEE 802.11 transmitters since Wi-Fi and ZigBee are widely deployed in common areas such as residential and office environments. Overall it is shown that ZigBee performance (in terms of access delay and energy consumption) is impacted by an increase of Wi-Fi duty cycle or power level, especially when operating in IEEE 802.11b. To mitigate these performance degradation issues of coexisting ZigBee networks, widely adapted solutions are the frequency agility consisting in scanning, evaluating and avoiding noisy channels [59].

Bluetooth Bluetooth is also a popular technology for short-range communicating and low-power operating IoT devices deployed in a star topology, where the central node is the coordinator of channel access with a frequency and time division multiple access based method [60]. It operates in the 2.4 GHz ISM band and adapts a frequency-hopping spread spectrum technique on the physical layer. To mitigate interference issues with coexisting networks in the same band, both Bluetooth Special Interest Group and IEEE 802.15.2 Coexistence Task Group prescribe solutions that rely on interference detection and estimation such as adaptive frequency hopping techniques[61–64].

RFID Radio Frequency IDentification (RFID) technologies are used in networking of our daily life objects for applications such as checking identities, managing the supply chain, and replacing barcodes. The most popular ones are those that are not equipped with a source of energy (called passive RFID tags), instead, the energy needed to operate them is supplied by the RFID reader during the tag reading process [65]. Since multiple RFID tags may be within the reading range of RFID reader, multiple access problem is inherent to avoid collision of signals from multiple tags. Most anti-collision algorithms for RFID rely on perfect environment, and the challenge is to design procedure that is suitable for practical applications and takes into account various environmental effects [66]. Common RFID technologies operate on unlicensed bands ranging from Low Frequencies to Ultra High Frequencies. The influence of other technologies on some of them was studied in the literature. For instance, it is shown that the performance of CEN Dedicated Short Range Communication On Board Unit (used for road tolling applications) is negatively affected by ITS-G5 transmission in the 5.9 GHz band [67].

3.4 Convergence of radio access networks

The international standardization organization 3GPP ratified in release 15 some base components of 3GPP systems toward the 5G vision, such as the 5G New Radio (5G-NR) and the 5G Core Network. Since this release, the 5G-NR introduces the framework of Multi-RATs (Radio Access Technologies) for a User Equipment (UE) which has to simultaneously operate on more frequency bands than those of the usual LTE to address new 5G use cases such as V2X communication scenarios. In the current state of the framework [68], a UE (e.g. a connected vehicle) is assumed to be able to select the best RAT for transmission based on either pre-configured information, QoS related constraints or its surrounding connection possibilities (e.g. other vehicles, RSUs or base stations). However, the issues related to the dynamic discovery of these access resources by an EU remain open according to our knowledge.

The next standard from 3GPP (Release 16) also deals with the integration of unlicensed technologies into the 5G Core Network (5G-CN). The 5G-CN is designed with the implementation of the flat IP theory (an all IP network) [2]. Thus, besides the access centric interactions such as LAA, some serious candidates for integrating unlicensed technologies (such as Wi-Fi) to 3GPP based systems (licensed technologies) are based on Internet Engineering Task Force (IETF) standards.

The IETF ratified standards for convergence of IP based networks. The purpose of these technologies is to manage and optimize resource usage in the scenario where a network node may have many interfaces to get to the service of an IP network. Globally, these technologies could be seen as a class of tools that enable to mutualize radio resources between wireless access technologies, but only for IP based networks. In what follows, we will discuss some specificities of these technologies and their deployment requirements in relation to the network infrastructures of connected cities.

Multi-Path TCP The Multi-Path Transmission Control Protocol (MP-TCP) has been standardized by the IETF in RFC 6824. Unlike traditional TCP, Multipath TCP can use multiple flows in a single TCP session for the sake of more resource efficiency in terms of throughput and load balancing. For example, when a device is connected simultaneously to a Wi-Fi and a cellular network, MP-TCP can dynamically dispatch application traffic over these two interfaces in a way that is transparent to the application and the underlying networks.

From a deployment perspective, MP-TCP keeps the same Application Programming Interface (API) as traditional TCP, which enables legacy applications to work with MP-TCP without any modifications of the code. But, both endpoints of a MP-TCP session should implement the protocol. IP technologies are usually implemented in the kernel space of Operating Systems (OSs), hence, for practical use of MP-TCP, the OSs of both endpoints should be upgraded. There exists a Linux kernel implementation of MP-TCP, but it is still far from being widely deployed on the Internet [5]. Thus, MP-TCP cannot be an option for example to implement the mutualization of a legacy sensor network which is difficult to access in an urban environment, and new infrastructures of a connected city, even if the supported applications by the underlying system need TCP constraints.

Furthermore, there are draft standards of IETF trying to mitigate the deployment problem of MP-TCP by using proxy servers [69].

Multi-Path QUIC protocol The purpose of Quick UDP Internet Connection (QUIC) draft standard is to reduce the latency of client-server applications based on TCP/Transport Layer Security (TLS)/Hypertext Transfer Protocol (HTTP) protocol stack, by using UDP (User Datagram Protocol) instead of TCP [70]. The Multi-Path version of QUIC (MP-QUIC) [71] aims at aggregating several UDP links for a more efficient use of resources while maintaining seamless interface handover to the application layer.

By being developed above the conventional UDP APIs, Multi-Path QUIC reduces the deployment constraints experienced by MP-TCP for sharing network interfaces in general. In a resource sharing context, Multi-Path QUIC can be used to mutualize radio interfaces when the applications use HTTP and if the network nodes support TLS constraints such as data integrity checks.

Multi-access management service framework The Multi-Access Management Service (MAMS) framework is a draft standard which also aims at aggregating several network interfaces at both ends of a service over an IP network [71].

Globally, MAMS separates control plane and user plane, in order to dynamical use any of the existing IETF protocols like MP-TCP or MP-QUIC for link aggregation. The cost of this flexibility is that MAMS supported device should implement locally additional software components (client proxies) which are backed by some management services. Thus, it is difficult to imagine the implementation of MAMS components within a resource constrained device such as a small sensor, which usually has only the necessary resources to run its base applications. MAMS assumes permanent interactions between client proxies and the management backend services. This could be an additional source of interference to the already crowded environment of dense wireless network infrastructures of connected cities.

4 Opportunities and open issues

In this section, we focus on open issues related to coexistence of heterogeneous networks in the 5G era. We present several mechanisms and concepts for enhancement based on a typical coexistence example.

4.1 Coexistence of heterogeneous networks and 5G communications

Typical requirements of 5G infrastructures are i) high data rates across a wide coverage area (known as eMBB for enhanced Mobile BroadBand), ii) strict requirements of low communication latency (known as URLLC for Ultra-Reliable Low Latency Communications), and iii) support for dense IoT deployments known as massive Machine Type Communication (mMTC). To meet such diverse communication needs, 5G involves diversified technologies and several of them are expected to operate on unlicensed bands especially for scenarios of mMTC. For successful coexistence of these technologies on these bands, the following issues are of particular challenge.

4.1.1 Fairness of spectrum sharing

This issue relates to ensuring unbiased spectrum sharing between coexisting technologies on a common deployment site. Information exchange and coordination between the underlying networks are unlikely to be possible which makes it more challenging to achieve fairness [73].

4.1.2 QoS guarantees in access

Access to unlicensed bands in a multi-user environment should typically be based on contention. This results in a heterogeneous network environment in additional access delays, an increase of packet loss rates and of energy consumption on devices. Guaranteeing QoS on unlicensed bands to answer 5G use cases requirements with ultra low latencies for high density deployments remains very challenging [57].

4.1.3 beamforming and millimeter-wave

millimeter-wave transmission requires adaptive beamforming and spatial multiplexing to overcome the high path loss, as well as other losses due to rain and gas absorption [74, 75]. Beamforming can also be considered as a means to overcome coexistence issues by exploiting spatial reuse. However, one of the major challenges in the development of millimeter-wave technologies is the lack of appropriate channel models for a variety of indoor and outdoor communication scenarios [76].

4.1.4 Standardization

Multiple projects have been working on frameworks for coexistence and coverage of heterogeneous access networks [77, 78]. Yet a technology-neutral framework for efficient and harmonious coexistence would still be required for overwhelmingly diversified technologies in the 5G era.

4.2 Mechanisms to improve resource efficiency in coexistence scenarios

In order to efficiently allow heterogeneous networking technologies to coexist in connected city environments through resource sharing, we consider the following scenario. A roundabout with a Road Side Unit (RSU) broadcasting the states of the traffic lights and a connected vehicle approaching this roundabout which retrieves through a dedicate network interface, the states of traffic lights in order to pass with the optimal speed. A gas station is situated near this roundabout with a wireless sensor network deployed for monitoring the station infrastructure and a public hotspot deployed for visitors. The wireless sensor network produces useful information for near-by cars about the availability of each type of fuel, the prices and the average time spent at the station. The sensor network can be seen as a set of resources that can serve the C-ITS network and provide additional and needed information for near-by or interested vehicles. Thus, in a resource sharing context, the sensor network and the C-ITS platform can agree on network elements to be shared such as data, channels, and relay nodes. The extended scenario is depicted in Fig. 3. *Scenario a* in figure 3 represents a hotspot A that acts as a gateway for different types of network devices. In this scenario, suppose that: the sensors use 802.15.4 technology to exchange with the hotspot, the RSUs use 802.11ah technology to exchange with the hotspot, and the mobile users implement various 802.11 standards (e.g. $n|ac|ax$). Thus, in this use case the impact of network access offloading through the Mutualized Hotspot A (MH-A) having multiple access technologies on the performance of application profiles of the network is a main investigation.

A deployment of supplementary local management components within the MH-A may serve for example: (i) to reduce interference between these heterogeneous networks, (ii) and better control and globally guarantee the QoS constraints of the applications form these different networks. Hence, this may lead to a more global efficient coexistence and usage of the resources. A proposal aiming to optimize such resource sharing approach has to deal with the following issues:

1) the MH-A should be able to maintain an up to date table indicating technology capabilities of nodes. 2) The MH-A should be able to associate dynamically a cost for each access technology, for example, this cost can be related to the data rate or the packet loss associated with each technology at the transmission time. And, 3) the MH-A should also be able at a given time to detect the access technologies that could cause harmful interference to each other.

In order to maintain the table indicating the access technology capabilities of neighbouring nodes, the MH-A could build and rely on the communication statistics of its associated devices. When the QoS constraints are defined as a simple requirement of throughput levels, the MN could rely on the different data rates of the standards (Modulation and Coding Schemes) to associate dynamically a cost to the access technologies.

A more general use case of a resource sharing approach would be the mutualisation of the three hotspots (A, B and C) of the Fig. 3 by all the nodes in the vicinity (e.g. connected vehicles, surrounding sensors and mobile users). Thus, this deployment scenario implementing a resource sharing approach may allow to increase the connectivity of the network nodes and to avoid harmful interference between the devices through common radio management techniques between the hotspots [79]. This may lead to a more efficient coexistence and usage of the network access resources. However, the following issues remain open:

1) *A universal framework:* the question is to know the scenarios (e.g. expected node density, coverage needs) in which to add more such mutualized hotspots or to add mobility to some of them. For example, for the vehicles in figure 3 *Scenario b*, when leaving the coverage of the (fixed) access point B and before reaching the coverage of the (mobile) access point C, delay-sensitive applications on these vehicles (such as a critical control application for monitoring/controlling automated vehicles) may fail to meet their QoS requirements due to lack of coverage. A proposal for such a framework should, therefore, take into account the usual strict requirements of reliability and latency of communication scenarios.

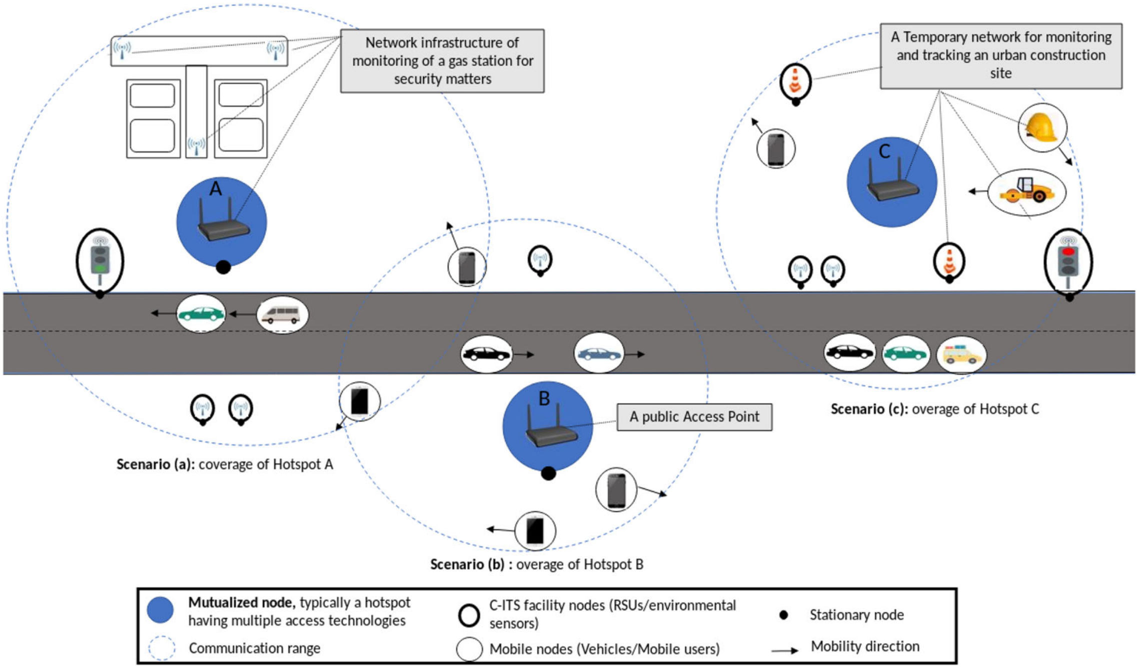

Fig. 3 Network deployment scenario implementing a resource sharing approach in a typical dense urban environment, where the resources of several hotspots having multi-access technologies are pooled by other nodes in the vicinity such as connected vehicles, surrounding sensors or mobile users

2) *Appropriate technologies:* the question is to know the appropriate technologies to deploy within the mutualized hotspots in order to get a maximum of the global efficiency of the access resources. For example, without dedicated access technologies, the temporally deployed hotspot C (in figure 3 *Scenario c*) may not be able to serve as gateway to the surrounding environmental sensors that would be deployed for C-ITS facilities.
3) *Coordination and centralization:* in order to have an optimal mutualisation strategy there must be a kind of coordination between the nodes and especially those that have mutualisation abilities and intelligence such as the hotspots in our example. This coordination may not always be possible due to different owners and access providers of these hotspots.
4) *Preconfigured sharing strategies:* having a classification of application profiles will help answering the QoS of each application according to its priority. Having a complete list of application profiles is almost impossible to achieve but one can imagine categories of applications and universal classification of these categories. This can be compared to the effort made in Class of Service types of 802.11e for example. Extending this to multiple technologies remains a challenge and an open issue.
5) *Availability:* in order to achieve mutualisation, there must be resources available to be shared. Hence, owners of resources should adhere to this concept in order for this concept to be feasible. This can be encouraged by governments and financial bodies by supporting providers and solutions that are open for sharing.
6) *Security:* confidentiality, authentication and integrity of data should be guaranteed from end to end in the process of resource sharing. Thus, rethinking security protocols in such a way to allow negotiation of security elements between heterogeneous nodes and standards would be the next step towards harmonizing security mechanisms.
7) *Efficiency evaluation and experimentations:* in the typical vehicle to everything networking environment of Fig. 3, performance evaluation of the protocols is usually made through computer simulations because of the cost and the difficulty of putting in place large scale field tests. To the best of our knowledge, there is no simulation platform that models and brings together the access technologies expected under the 5G umbrella. Nevertheless, a full stack network simulation module for OMNEST and OMNeT++ having protocol models for IEEE 802.11$a|n|g|p|ac$ and IEEE 802.15.4 is adding to its Framework a model to consider partial interferences of overlapping radio channels for more

realistic simulation of spectral coexistence of wireless access technologies [80–83].

5 Conclusions

Wireless technology is one of the important assets of the 5G paradigm. Internet of Things, Intelligent Transport Systems, Smart Cities, Smart Buildings, in addition to smart phones, laptops, tablets, etc. rely on wireless communications to connect to the Internet and exchange information with the rest of the communicating entities. The overwhelming number of connected nodes using wireless technology is rapidly increasing and getting closer to the 50 billion nodes threshold announced by Cisco back in 2011 for 2020 [84].

This tendency is overloading the communication channels in the available bandwidth used by the different types of technologies part of the 5G. For licensed frequency bands, operators have the hand for managing the access strategies. When it comes to unlicensed frequency bands, communication protocols should be designed in such a way to take into consideration the existence of other nearby nodes using the same access technology or even different technologies using the same channels.

With the increasing need of guaranteeing connectivity everywhere, coexistence and coordination of heterogeneous wireless access networks in the 5G era becomes a necessity. Smart and connected cites are a great example of such a coexistence of heterogeneous wireless technologies where any connected device should be able to reach the Internet or other devices wherever and whenever it needs to. When it comes to operating on unlicensed bands, coexistence arises issues which are related to ensuring QoS guaranty in access and fair spectrum sharing. We discussed and presented mechanisms and techniques that could enhance the coexistence of such networks based on the concept of resource sharing. These resources are not only radio frequencies but also physical systems.

Existing protocols in the literature have already been proven efficient; we surveyed their methods and discussed their applicability to the 5G networks. We also analysed standardization efforts such as 3GPP, IEEE and IETF towards mutualisation and sharing in the 5G era. Most of the existing work deal with the issue of sharing and optimizing the use of the available spectrum without integrating the possibility of sharing physical systems.

We identified open issues related to the main concepts of resource sharing that could occupy the research community in the near future. Many challenges will arise when it comes to deal with requesting the use of a certain resource from the detection of the presence of this resource to the authorisation to use it. According to our knowledge, there are no current mechanisms that deal with these challenges that are directly related to legislation, cooperation between operators, information security, and evaluation of efficiency.

This paper constitutes an overview of existing techniques that would allow such a concept of resource sharing and mutualisation to be possible. We highlighted the possibilities that such a concept would open based on a simple example of multiple technologies coexisting in a Smart City environment. New mechanisms are being developed and gradually integrated into communication standards, the number of working groups and different standardization bodies might make the coexistence issue more or less complex depending on their level of collaboration.

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