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NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey

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Abstract

Today's wireless networks are characterized by a fixed spectrum assignment policy. However, a large portion of the assigned spectrum is used sporadically and geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with a high variance in time. The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. This new networking paradigm is referred to as NeXt Generation (xG) Networks as well as Dynamic Spectrum Access (DSA) and cognitive radio networks. The term xG networks is used throughout the paper. The novel functionalities and current research challenges of the xG networks are explained in detail. More specifically, a brief overview of the cognitive radio technology is provided and the xG network architecture is introduced. Moreover, the xG network functions such as spectrum management, spectrum mobility and spectrum sharing are explained in detail. The influence of these functions on the performance of the upper layer protocols such as routing and transport are investigated and open research issues in these areas are also outlined. Finally, the cross-layer design challenges in xG networks are discussed.

Keywords: Next generation networks; Dynamic spectrum access networks; Cognitive radio networks; Spectrum sensing; Spectrum management; Spectrum mobility; Spectrum sharing

1. Introduction

Today's wireless networks are regulated by a fixed spectrum assignment policy, i.e. the spectrum is regulated by governmental agencies and is assigned to license holders or services on a long term basis for large geographical regions. In addition, a large portion of the assigned spectrum is used sporadically as illustrated in Fig. 1, where the signal strength distribution over a large portion of the wireless spectrum is shown. The spectrum usage is concentrated on certain portions of the spectrum while a significant amount of the spectrum remains unutilized. According to Federal Communications

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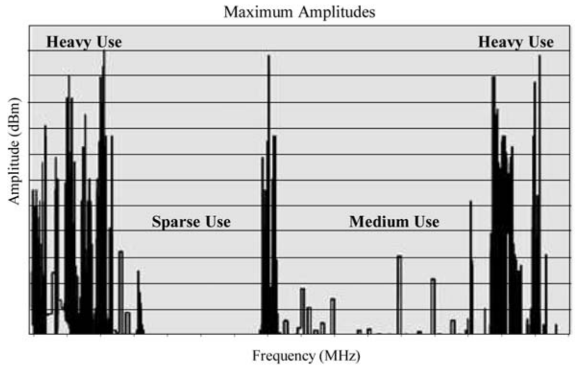

Fig. 1. Spectrum utilization.

Commission (FCC) [20], temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85%. Although the fixed spectrum assignment policy generally served well in the past, there is a dramatic increase in the access to the limited spectrum for mobile services in the recent years. This increase is straining the effectiveness of the traditional spectrum policies.

The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically [3]. Dynamic spectrum access is proposed to solve these current spectrum inefficiency problems. DARPAs approach on Dynamic Spectrum Access network, the so-called NeXt Generation (xG) program aims to implement the policy based intelligent radios known as cognitive radios [67,68].

NeXt Generation (xG) communication networks, also known as Dynamic Spectrum Access Networks (DSANs) as well as cognitive radio networks, will provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques. The inefficient usage of the existing spectrum can be improved through opportunistic access to the licensed bands without interfering with the existing users. xG networks, however, impose several research challenges due to the broad range of available spectrum as well as diverse Quality-of-Service (QoS) requirements of applications. These heterogeneities must be captured and handled dynamically as mobile terminals roam between wireless architectures and along the available spectrum pool.

The key enabling technology of xG networks is the cognitive radio. Cognitive radio techniques provide the capability to use or share the spectrum in an opportunistic manner. Dynamic spectrum access techniques allow the cognitive radio to operate in the *best available channel*. More specifically, the cognitive radio technology will enable the users to (1) determine which portions of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (*spectrum sensing*), (2) select the best available channel (*spectrum management*), (3) coordinate access to this channel with other users (*spectrum sharing*), and (4) vacate the channel when a licensed user is detected (*spectrum mobility*).

Once a cognitive radio supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum. Hence, new functionalities are required in an xG network to support this adaptivity. In summary, the main functions for cognitive radios in xG networks can be summarized as follows:

- *Spectrum sensing*: Detecting unused spectrum and sharing the spectrum without harmful interference with other users.
- *Spectrum management*: Capturing the best available spectrum to meet user communication requirements.
- *Spectrum mobility*: Maintaining seamless communication requirements during the transition to better spectrum.
- *Spectrum sharing*: Providing the fair spectrum scheduling method among coexisting xG users.

These functionalities of xG networks enable spectrum-aware communication protocols. However, the dynamic use of the spectrum causes adverse effects on the performance of conventional communication protocols, which were developed considering a fixed frequency band for communication. So far, networking in xG networks is an unexplored topic. In this paper, we also capture the intrinsic challenges for networking in xG networks and lay out guidelines for further research in this area. More specifically, we overview the recent proposals for spectrum sharing and routing in xG networks as well as the challenges for transport protocols. Moreover, the effect of cross-layer design is addressed for communication in xG networks.

The xG network communication components and their interactions are illustrated in Fig. 2. It is evident from the significant number of interactions that the xG network functionalities necessitate a cross-layer design approach. More specifically, spec-

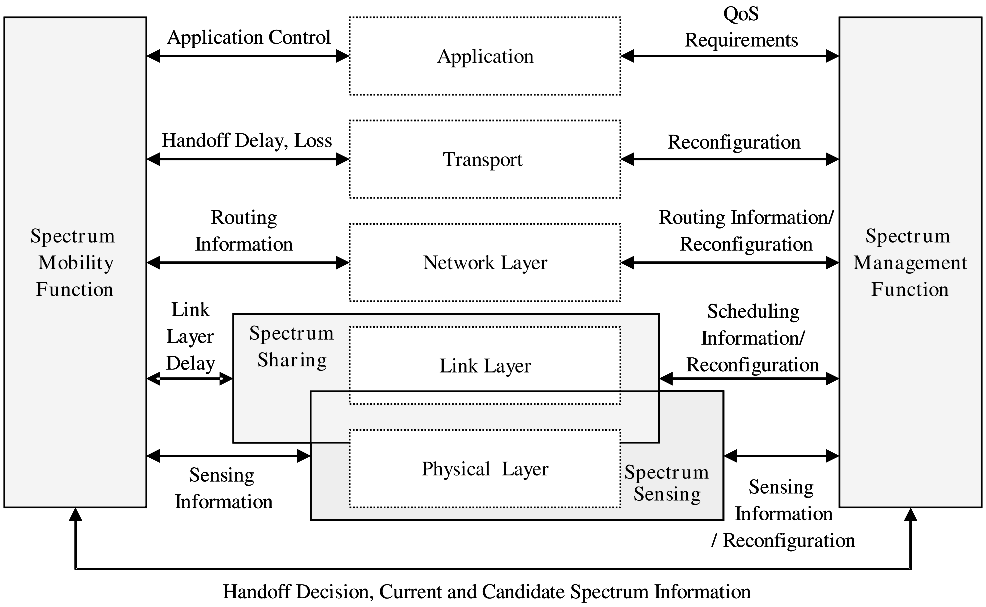

Fig. 2. xG network communication functionalities.

trum sensing and spectrum sharing cooperate with each other to enhance spectrum efficiency. In spectrum management and spectrum mobility functions, application, transport, routing, medium access and physical layer functionalities are carried out in a cooperative way, considering the dynamic nature of the underlying spectrum.

This paper presents a definition, functions and current research challenges of the xG networks. In Section 2, we provide a brief overview of the cognitive radio technology. The xG network architectures on licensed band and on unlicensed band are presented in Section 3. In Section 4, we explain the existing work and challenges in spectrum sensing. Then, we describe the xG network functionalities: spectrum management, spectrum mobility and spectrum sharing in Sections 5, 6, and 7, respectively. In Section 8, we investigate how xG features influence the performance of the upper layer protocols, i.e., routing and transport. Finally, we explain how xG functions can be implemented in a cross-layer approach in Section 9 and conclude the paper in Section 10.

2. Cognitive radio

Cognitive radio technology is the key technology that enables an xG network to use spectrum in a dynamic manner. The term, cognitive radio, can formally be defined as follows [20]:

A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.

From this definition, two main characteristics of the cognitive radio can be defined [27,58]:

- *Cognitive capability*: Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency band of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.
- *Reconfigurability*: The cognitive capability provides spectrum awareness whereas reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design [34].

The cognitive radio concept was first introduced in [45,46], where the main focus was on the radio knowledge representation language (RKRL) and how the cognitive radio can enhance the flexibility of personal wireless services. The cognitive radio is regarded as a small part of the physical world to use and provide information from environment.

The ultimate objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurability as described before. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Fig. 3. The cognitive radio enables the usage of temporally unused spectrum, which is referred to as *spectrum hole* or *white space* [27]. If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference as shown in Fig. 3.

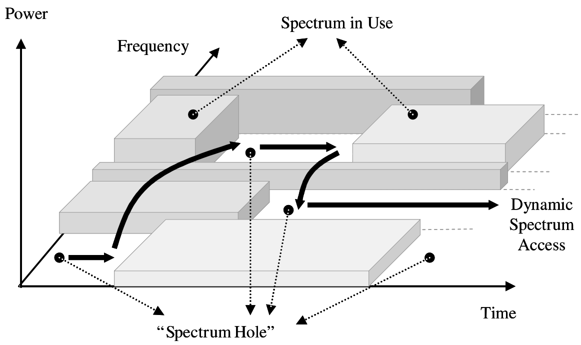

Fig. 3. Spectrum hole concept.

In the following subsections, we describe the physical architecture, cognitive functions and reconfigurability capabilities of the cognitive radio technology.

2.1. Physical architecture of the cognitive radio

A generic architecture of a cognitive radio transceiver is shown in Fig. 4(a) [34]. The main components of a cognitive radio transceiver are the radio front-end and the baseband processing unit. Each component can be reconfigured via a control bus

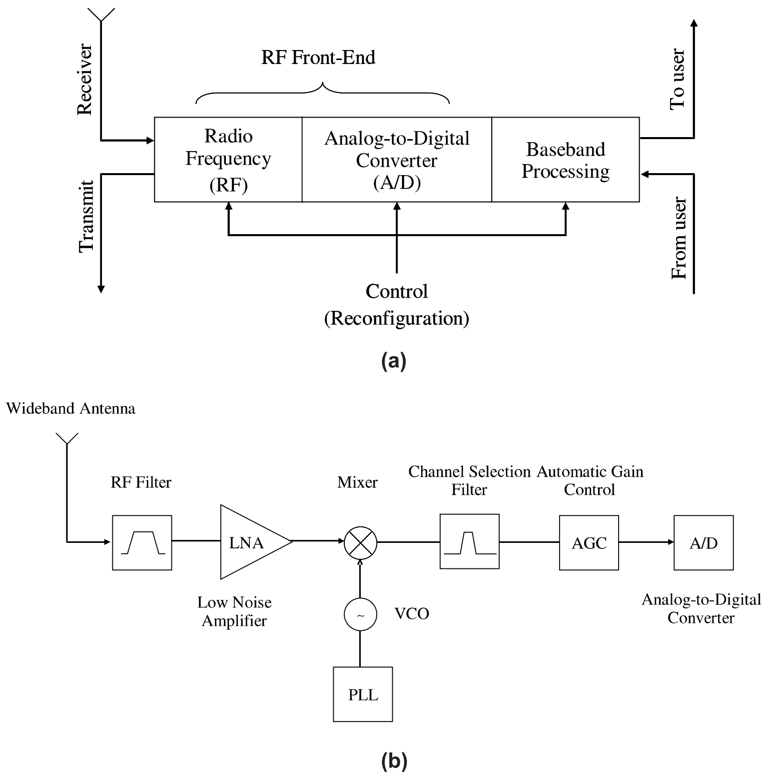

Fig. 4. Physical architecture of the cognitive radio [12,34]: (a) Cognitive radio transceiver and (b) wideband RF/analog front-end architecture.

to adapt to the time-varying RF environment. In the RF front-end, the received signal is amplified, mixed and A/D converted. In the baseband processing unit, the signal is modulated/demodulated and encoded/decoded. The baseband processing unit of a cognitive radio is essentially similar to existing transceivers. However, the novelty of the cognitive radio is the RF front-end. Hence, next, we focus on the RF front-end of the cognitive radios.

The novel characteristic of cognitive radio transceiver is a wideband sensing capability of the RF front-end. This function is mainly related to RF hardware technologies such as wideband antenna, power amplifier, and adaptive filter. RF hardware for the cognitive radio should be capable of tuning to any part of a large range of frequency spectrum. Also such spectrum sensing enables real-time measurements of spectrum information from radio environment. Generally, a wideband front-end architecture for the cognitive radio has the following structure as shown in Fig. 4(b) [12]. The components of a cognitive radio RF front-end are as follows:

- *RF filter*: The RF filter selects the desired band by bandpass filtering the received RF signal.
- *Low noise amplifier (LNA)*: The LNA amplifies the desired signal while simultaneously minimizing noise component.
- *Mixer*: In the mixer, the received signal is mixed with locally generated RF frequency and converted to the baseband or the intermediate frequency (IF).
- *Voltage-controlled oscillator (VCO)*: The VCO generates a signal at a specific frequency for a given voltage to mix with the incoming signal. This procedure converts the incoming signal to baseband or an intermediate frequency.
- *Phase locked loop (PLL)*: The PLL ensures that a signal is locked on a specific frequency and can also be used to generate precise frequencies with fine resolution.
- *Channel selection filter*: The channel selection filter is used to select the desired channel and to reject the adjacent channels. There are two types of channel selection filters [52]. The *direct conversion receiver* uses a low-pass filter for the channel selection. On the other hand, the *superheterodyne receiver* adopts a bandpass filter.
- *Automatic gain control (AGC)*: The AGC maintains the gain or output power level of an amplifier constant over a wide range of input signal levels.

In this architecture, a wideband signal is received through the RF front-end, sampled by the high speed analog-to-digital (A/D) converter, and measurements are performed for the detection of the licensed user signal. However, there exist some limitations on developing the cognitive radio front-end. The wideband RF antenna receives signals from various transmitters operating at different power levels, bandwidths, and locations. As a result, the RF front-end should have the capability to detect a weak signal in a large dynamic range. However, this capability requires a multi-GHz speed A/D converter with high resolution, which might be infeasible [12,13].

The requirement of a multi-GHz speed A/D converter necessitates the dynamic range of the signal to be reduced before A/D conversion. This reduction can be achieved by filtering strong signals. Since strong signals can be located anywhere in the wide spectrum range, tunable notch filters are required for the reduction [12]. Another approach is to use multiple antennas such that signal filtering is performed in the spatial domain rather than in the frequency domain. Multiple antennas can receive signals selectively using beamforming techniques [13].

As explained previously, the key challenge of the physical architecture of the cognitive radio is an accurate detection of weak signals of licensed users over a wide spectrum range. Hence, the implementation of RF wideband front-end and A/D converter are critical issues in xG networks.

2.2. Cognitive capability

The cognitive capability of a cognitive radio enables real time interaction with its environment to determine appropriate communication parameters and adapt to the dynamic radio environment. The tasks required for adaptive operation in open spectrum are shown in Fig. 5 [27,46,58], which is referred to as the *cognitive cycle*. In this section, we provide an overview of the three main steps of the cognitive cycle: *spectrum sensing*, *spectrum analysis*, and *spectrum decision*. The details and the related work of these functions are described in Sections 4 and 5.

The steps of the cognitive cycle as shown in Fig. 5 are as follows:

1. *Spectrum sensing*: A cognitive radio monitors the available spectrum bands, captures their information, and then detects the spectrum holes.

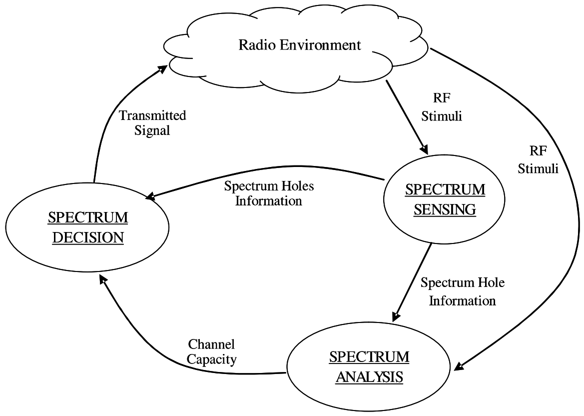

Fig. 5. Cognitive cycle.

2. *Spectrum analysis*: The characteristics of the spectrum holes that are detected through spectrum sensing are estimated.
3. *Spectrum decision*: A cognitive radio determines the data rate, the transmission mode, and the bandwidth of the transmission. Then, the appropriate spectrum band is chosen according to the spectrum characteristics and user requirements.

Once the operating spectrum band is determined, the communication can be performed over this spectrum band. However, since the radio environment changes over time and space, the cognitive radio should keep track of the changes of the radio environment. If the current spectrum band in use becomes unavailable, the *spectrum mobility* function that will be explained in Section 6, is performed to provide a seamless transmission. Any environmental change during the transmission such as primary user appearance, user movement, or traffic variation can trigger this adjustment.

2.3. Reconfigurability

Reconfigurability is the capability of adjusting operating parameters for the transmission on the fly without any modifications on the hardware components. This capability enables the cognitive radio to adapt easily to the dynamic radio environment. There are several reconfigurable parameters that can be incorporated into the cognitive radio [20] as explained below:

- *Operating frequency*: A cognitive radio is capable of changing the operating frequency. Based on the information about the radio environment, the most suitable operating frequency can be determined and the communication can be dynamically performed on this appropriate operating frequency.
- *Modulation*: A cognitive radio should reconfigure the modulation scheme adaptive to the user requirements and channel conditions. For example, in the case of delay sensitive applications, the data rate is more important than the error rate. Thus, the modulation scheme that enables the higher spectral efficiency should be selected. Conversely, the loss-sensitive applications focus on the error rate, which necessitate modulation schemes with low bit error rate.
- *Transmission power*: Transmission power can be reconfigured within the power constraints. Power control enables dynamic transmission power configuration within the permissible power limit. If higher power operation is not necessary, the cognitive radio reduces the transmitter power to a lower level to allow more users to share the spectrum and to decrease the interference.
- *Communication technology*: A cognitive radio can also be used to provide interoperability among different communication systems.

The transmission parameters of a cognitive radio can be reconfigured not only at the beginning of a transmission but also during the transmission. According to the spectrum characteristics, these parameters can be reconfigured such that the cognitive radio is switched to a different spectrum band, the transmitter and receiver parameters are reconfigured and the appropriate communication protocol parameters and modulation schemes are used.

3. The xG network architecture

Existing wireless network architectures employ heterogeneity in terms of both spectrum policies and communication technologies [3]. Moreover, some portion of the wireless spectrum is already licensed to different purposes while some bands remain unlicensed. For the development of communication protocols, a clear description of the xG network architecture is essential. In this section, the xG network architecture is presented such that all possible scenarios are considered.

The components of the xG network architecture, as shown in Fig. 6, can be classified in two groups as the *primary network* and the *xG network*. The basic

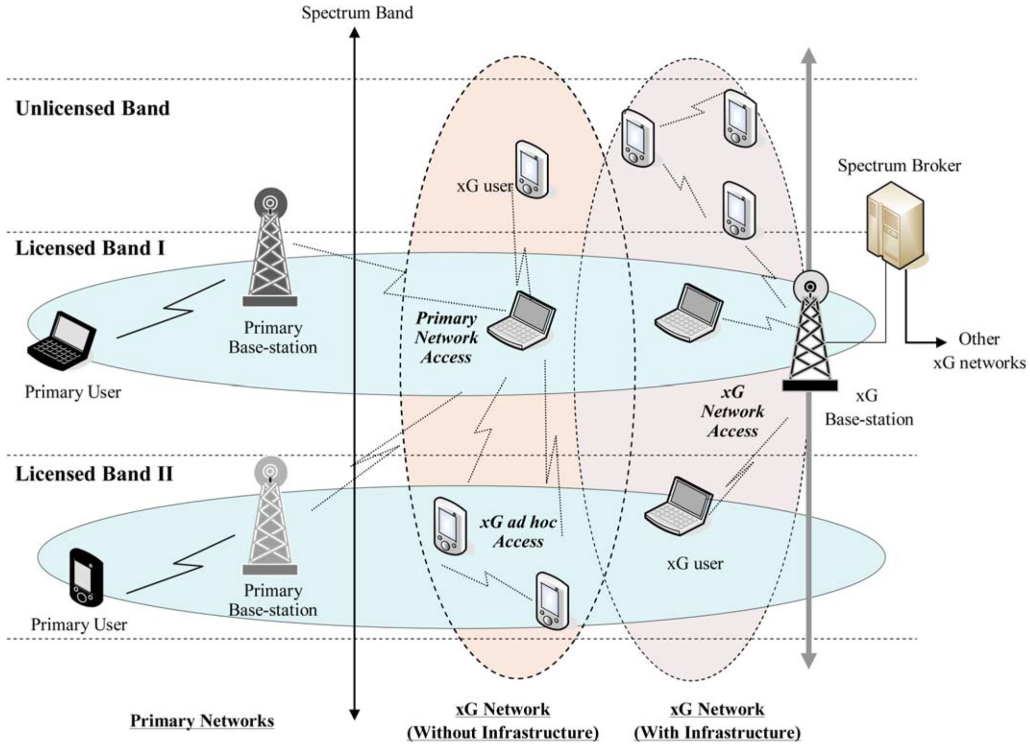

Fig. 6. xG network architecture.

elements of the primary and the xG network are defined as follows:

- *Primary network*: An existing network infrastructure is generally referred to as the primary network, which has an exclusive right to a certain spectrum band. Examples include the common cellular and TV broadcast networks. The components of the primary network are as follows:
  - *Primary user*: Primary user (or licensed user) has a license to operate in a certain spectrum band. This access can only be controlled by the primary base-station and should not be affected by the operations of any other unlicensed users. Primary users do not need any modification or additional functions for coexistence with xG base-stations and xG users.
  - *Primary base-station*: Primary base-station (or licensed base-station) is a fixed infrastructure network component which has a spectrum license such as base-station transceiver system (BTS) in a cellular system. In principle, the primary base-station does not have any xG capability for sharing spectrum with xG users. However, the primary base-station may be requested to have both legacy and xG protocols for the *primary network access* of xG users, which is explained below.
- *xG network*: xG network (or cognitive radio network, Dynamic Spectrum Access network, secondary network, unlicensed network) does not have license to operate in a desired band. Hence, the spectrum access is allowed only in an opportunistic manner. xG networks can be deployed both as an infrastructure network and an ad hoc network as shown in Fig. 6. The components of an xG network are as follows:
  - *xG user*: xG user (or unlicensed user, cognitive radio user, secondary user) has no spectrum license. Hence, additional functionalities are required to share the licensed spectrum band.
  - *xG base-station*: xG base-station (or unlicensed base-station, secondary base-station) is a fixed infrastructure component with xG capabilities. xG base-station provides single hop connection to xG users without spectrum access license. Through this connection, an xG user can access other networks.
  - *Spectrum broker*: Spectrum broker (or scheduling server) is a central network entity that plays a role in sharing the spectrum resources among different xG networks. Spectrum

broker can be connected to each network and can serve as a spectrum information manager to enable coexistence of multiple xG networks [10,32,70].

The reference xG network architecture is shown in Fig. 6, which consists of different types of networks: a primary network, an infrastructure based xG network, and an ad-hoc xG network. xG networks are operated under the mixed spectrum environment that consists of both licensed and unlicensed bands. Also, xG users can either communicate with each other in a multihop manner or access the base-station. Thus, in xG networks, there are three different access types as explained next:

- *xG network access*: xG users can access their own xG base-station both on licensed and unlicensed spectrum bands.
- *xG ad hoc access*: xG users can communicate with other xG users through ad hoc connection on both licensed and unlicensed spectrum bands.
- *Primary network access*: The xG users can also access the primary base-station through the licensed band.

According to the reference architecture shown in Fig. 6, various functionalities are required to support the heterogeneity in xG networks. In Section 3.1, we describe the xG network functions to support the heterogeneity of the network environment. Moreover, in Sections 3.2 and 3.3, we overview xG network applications and existing architectures.

3.1. xG network functions

As explained before, xG network can operate in both licensed and unlicensed bands. Hence, the functionalities required for xG networks vary according to whether the spectrum is licensed or unlicensed. Accordingly, in this section, we classify the xG network operations as *xG network on licensed band* and *xG network on unlicensed band*. The xG network functions are explained in the following sections according to this classification.

3.1.1. xG network on licensed band

As shown in Fig. 1, there exist temporally unused spectrum holes in the licensed spectrum band. Hence, xG networks can be deployed to exploit these spectrum holes through cognitive communication techniques. This architecture is depicted in

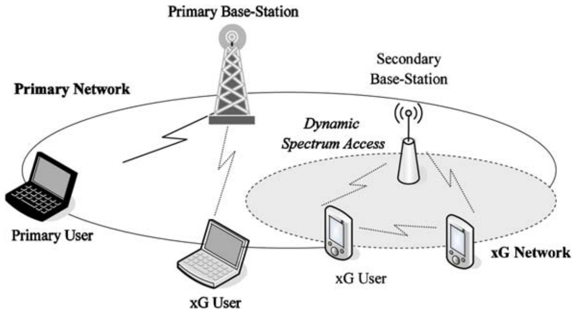

Fig. 7. xG network on licensed band.

Fig. 7, where the xG network coexists with the primary network at the same location and on the same spectrum band.

There are various challenges for xG networks on licensed band due to the existence of the primary users. Although the main purpose of the xG network is to determine the best available spectrum, xG functions in the licensed band are mainly aimed at the detection of the presence of primary users. The channel capacity of the spectrum holes depends on the interference at the nearby primary users. Thus, the interference avoidance with primary users is the most important issue in this architecture. Furthermore, if primary users appear in the spectrum band occupied by xG users, xG users should vacate the current spectrum band and move to the new available spectrum immediately, called *spectrum handoff*.

3.1.2. xG network on unlicensed band

Open spectrum policy that began in the industrial scientific and medical (ISM) band has caused an impressive variety of important technologies and innovative uses. However, due to the interference among multiple heterogeneous networks, the spectrum efficiency of ISM band is decreasing. Ultimately, the capacity of open spectrum access, and the quality of service they can offer, depend on the degree to which a radio can be designed to allocate spectrum efficiently.

xG networks can be designed for operation on unlicensed bands such that the efficiency is improved in this portion of the spectrum. The *xG network on unlicensed band* architecture is illustrated in Fig. 8. Since there are no license holders, all network entities have the same right to access the spectrum bands. Multiple xG networks coexist in the same area and communicate using the same portion of the spectrum. Intelligent spectrum sharing

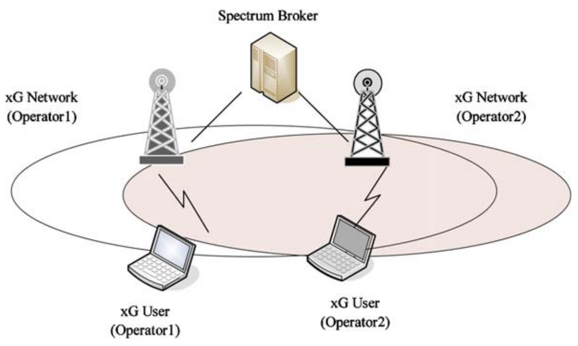

Fig. 8. xG network on unlicensed band.

algorithms can improve the efficiency of spectrum usage and support high QoS.

In this architecture, xG users focus on detecting the transmissions of other xG users. Unlike the licensed band operations, the spectrum handoff is not triggered by the appearance of other primary users. However, since all xG users have the same right to access the spectrum, xG users should compete with each other for the same unlicensed band. Thus, sophisticated spectrum sharing methods among xG users are required in this architecture. If multiple xG network operators reside in the same unlicensed band, fair spectrum sharing among these networks is also required.

3.2. xG network applications

xG networks can be applied to the following cases:

Leased network: The primary network can provide a leased network by allowing opportunistic access to its licensed spectrum with the agreement with a third party without sacrificing the service quality of the primary user [56]. For example, the primary network can lease its spectrum access right to a mobile virtual network operator (MVNO). Also the primary network can provide its spectrum access rights to a regional community for the purpose of broadband access.

Cognitive mesh network: Wireless mesh networks are emerging as a cost-effective technology for providing broadband connectivity [4]. However, as the network density increases and the applications require higher throughput, mesh networks require higher capacity to meet the requirements of the applications. Since the cognitive radio technology enables the access to larger amount of spectrum, xG networks can be used for mesh networks that will be deployed in dense urban areas with the possibility of significant contention [38]. For example, the coverage area of xG networks can be increased when a meshed wireless backbone network of infrastructure links is established based on cognitive access points (CAPs) and fixed cognitive relay nodes (CRNs) [6]. The capacity of a CAP, connected via a wired broadband access to the Internet, is distributed into a large area with the help of a fixed CRN. xG networks have the ability to add temporary or permanent spectrum to the infrastructure links used for relaying in case of high traffic load.

Emergency network: Public safety and emergency networks are another area in which xG networks can be implemented [41]. In the case of natural disasters, which may temporarily disable or destroy existing communication infrastructure, emergency personnel working in the disaster areas need to establish *emergency networks*. Since emergency networks deal with the critical information, reliable communication should be guaranteed with minimum latency. In addition, emergency communication requires a significant amount of radio spectrum for handling huge volume of traffic including voice, video and data. xG networks can enable the usage of the existing spectrum without the need for an infrastructure and by maintaining communication priority and response time.

Military network: One of the most interesting potential applications of an xG network is in a military radio environment [47]. xG networks can enable the military radios choose arbitrary, intermediate frequency (IF) bandwidth, modulation schemes, and coding schemes, adapting to the variable radio environment of battlefield. Also military networks have a strong need for security and protection of the communication in hostile environment. xG networks could allow military personnel to perform spectrum handoff to find secure spectrum band for themselves and their allies.

3.3. Existing architectures

The main representative examples of the xG network architectures are described in this section.

Spectrum pooling: In [61,62], a centralized spectrum pooling architecture is proposed based on orthogonal frequency division multiplexing (OFDM). This architecture consists of an xG base-station and mobile xG users. OFDM has the advantage of feeding certain sub-carriers with zeros resulting in no emission of radio power on the carriers that are occupied by the licensed users. The licensed user detection is performed through detection frames that are periodically broadcast by the base-station. During the detection frames, the mobile users perform spectrum sensing. The sensing information is then gathered at the base-station. Mobile terminals modulate a complex symbol at maximum power in the sub-carriers where a licensed user appears. Through this operation, the base-station receives an amplified signal on all sub-carriers with new licensed users. Physical and MAC layer issues, such as detection of spectral access, scheduling, and handoff are ongoing investigations in this architecture.

CORVUS: In [8,14], a cognitive radio approach for usage of virtual unlicensed spectrum (CORVUS) system is presented to exploit unoccupied licensed bands. In CORVUS, based on the local spectrum sensing, the primary user detection and the spectrum allocation are performed in a coordinated manner. This cooperative effort greatly increases the system's ability in identifying and avoiding primary users. In CORVUS, a group of users form a secondary user group (SUG) to coordinate their communication. Each member of this group senses the spectrum pool, which is divided into sub-channels. A universal control channel is used by all groups for coordination and separate group control channels are used by the members of a group to exchange sensing information and establish secondary user links. The performance of the physical and link layers are evaluated through the CORVUS testbed [44]. Moreover, recently, a reliable link maintenance protocol is proposed within CORVUS to maintain the quality of secondary user communication [64].

IEEE 802.22: IEEE 802.22 is the first worldwide standard based on the cognitive radio technology [16,31] and is now in the process of standardization. This project, formally called the standard for wireless regional area networks (WRAN), focuses on constructing fixed point-to-multipoint WRAN that will utilize UHF/VHF TV bands between 54 and 862 MHz. Specific TV channels as well as guard bands will be used for communication in IEEE 802.22. The IEEE 802.22 system specifies a fixed point-to-multipoint wireless air interface whereby a base-station manages its own cell and all associated users, which are denoted as consumer premise equipments (CPEs). IEEE 802.22 base-station manages a unique feature of distributed sensing. This is needed to ensure proper incumbent protection and is managed by the base-station, which instructs the various CPEs to perform distributed measurement activities. The IEEE 802.22 system specifies spectral efficiencies in the range of 0.5–5 bit/s/Hz. A distinctive feature of IEEE 802.22 WRAN as compared to the existing IEEE 802 standards is the base-station coverage range, which can go up to 100 km if the power is not an issue. Current specified coverage range is 33 km at 4 W CPE effective isotropic radiated power (EIRP) [66]. Table 1 depicts the capacity and coverage of IEEE 802.22 WRAN system. IEEE 802.22 working group was formed in 2004 and has finalized the specification of technical requirements. The first draft of IEEE 802.22 standard will be ready around mid 2006.

DIMSUMnet: The dynamic intelligent management of spectrum for ubiquitous mobile network (DIMSUMnet) [10] implements statistically multi-

Table 1
IEEE 802.22 WRAN system capacity and coverage [65]

RF channel bandwidth	6 MHz
Average spectrum efficiency	3 bit/s/Hz
Channel capacity	18 Mbit/s
System capacity per subscriber (forward)	1.5 Mbit/s
System capacity per subscriber (return)	384 kbit/s
Forward/return ratio	3.9
Over-subscription ratio	50
Number of subscribers per forward channel	600
(FDD operation is assumed to maximize system capacity for large coverage distances, TDD would reduce capacity to 75% per TV channel)	
Minimum number of subscribers	90 subs.
Assumed early take-up rate	3 bit/s/Hz
Potential number of subscribers	1800 subs.
Assumed number of persons per household	2.5 persons
Total number of persons per coverage area	4500 persons
WRAN base station EIRP	98.3 W
Radius of coverage for WRAN system	30.7 km
Minimum population density covered	1.5 person/km^2

Assuming 1.5 Mbit/s forward and 384 kbit/s return in a 6 MHz channel with 3 bit/s/Hz and 50:1 over-subscription, each TV channel can provide service to up to 600 subscribers. The area that the Wireless Regional Area network (WRAN) operator needs to cover should include enough subscribers to make it economically viable early in the process when the take-up rate is low. This will define the potential subscriber base and the population density for a sustainable business case.

plexed access (SMA) to spectrum in the coordinated access band (CAB). While the CAB improves the spectrum access efficiency and fairness, the SMA is focused on improving the spectrum utilization. CAB is a contiguous chunk of spectrum reserved by regulating authorities. A spectrum broker permanently owns the CAB and leases it according to requests. 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. The base-station registers with its designated radio access network manager (RANMAN), which negotiates a lease with a spectrum information and management (SPIM) broker for an appropriate portion of the spectrum. If the lease is successfully obtained, the RANMAN configures the leased spectrum in the base-station. The base-station sends the spectrum information received from the RANMAN to its users for the configuration of client. The spectrum utilization of DIMSUMnet is currently measured in existing Code Division Multiple Access (CDMA) and Global System for Mobile communication (GSM) cellular networks, aimed at characterizing feasibility of CAB and SMA [35]. Recent work focuses on the spectrum pricing and allocation functions for spectrum brokers [11].

DRiVE/OverDRiVE project: The European Dynamic Radio for IP Services in Vehicular Environments (DRiVE) project focuses on dynamic spectrum allocation in heterogeneous networks by assuming a common coordinated channel [75]. The follow-up project, Spectrum Efficient Uni- and Multicast Over Dynamic Radio Networks in Vehicular Environments (OverDRiVE) aims at UMTS enhancements and coordination of existing radio networks into a hybrid network to ensure spectrum efficient provision of mobile multimedia services [26]. Two aspects of dynamic spectrum allocation were investigated in DRiVE/OverDRiVE, i.e., *temporal dynamic spectrum allocation (DSA)*, and *spatial DSA* [39]. In the case of the temporal DSA, a radio access network (RAN) can use the spectrum that is not currently being used by other RANs, at that time. On the other hand, spatial DSA allows spectrum allocations to adapt to regional fluctuations in traffic demands. The efficiency of these DSA schemes depends on the ability to predict the traffic load. Although these projects have shown significant potential for increasing spectral efficiency, the reconfigurable system implementation for temporal and spatial DSA is still a major challenge.

Nautilus: Nautilus project is designed to emphasize distributed coordination enabled spectrum sharing, without relying on centralized control [48]. In the Nautilus project, a distributed, scalable and efficient coordination framework for open spectrum ad hoc networks is proposed, which accounts for spectrum heterogeneity while not relying on the existence of a pre-defined common channel for control traffic [73,74]. Based on this framework, three different collaborative spectrum access schemes are presented. In [73], a graph coloring based collaborative spectrum access scheme is proposed, where a topology-optimized allocation algorithm is used for the fixed topology. In mobile networks, however, the network topology changes due to the node mobility. Using this global optimization approach, the network needs to completely recompute spectrum assignments for all users after each change, resulting in high computational and communication overhead. Thus, distributed spectrum allocation based on local bargaining is proposed in [15], where mobile users negotiate spectrum assignment within local self-organized groups. For the resource constrained networks such as sensor and ad hoc network, rule-based device centric spectrum management is proposed, where unlicensed users access the spectrum independently according to both local observation and predetermined rules. Currently, this project focuses on selecting the best channel for data transmission using proposed distributed coordination framework.

OCRA network: In [5], an OFDM-based cognitive radio (OCRA) network is proposed. OCRA network considers all possible deployment scenarios over the heterogeneous xG network environment and develops cross-layer operations for the OFDM based dynamic spectrum access. OCRA network architecture and its components are shown in Fig. 6. For the spectrum decision and the spectrum handoff, OCRA network provides a novel concept of an OFDM-based spectrum management over the heterogeneous spectrum environment. Based on this physical layer (PHY) structure, a dual-mode spectrum sharing framework is proposed, which enables access to existing networks as well as coordination between xG users. Furthermore, a new routing paradigm that considers joint re-routing and spectrum handoff is proposed. Moreover, OCRA network introduces multi-spectrum transport techniques to exploit the available but non-contiguous wireless spectrum for high quality communication. In [5], the testbed design for evaluation and integration of the OCRA network is proposed. The OCRA testbed is based on IEEE 802.11a/g technology, which exploits the OFDM technology. Moreover, a standalone cognitive sensing unit is developed to emulate the spectrum sensing capabilities of the cognitive radio.

4. Spectrum sensing

An important requirement of the xG network is to sense the spectrum holes. As explained in Section 2, a cognitive radio is designed to be aware of and sensitive to the changes in its surrounding. The spectrum sensing function enables the cognitive radio to adapt to its environment by detecting spectrum holes.

The most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range of an xG user. In reality, however, it is difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter. Thus, the most recent work focuses on primary transmitter detection based on local observations of xG users.

Generally, the spectrum sensing techniques can be classified as transmitter detection, cooperative detection, and interference-based detection, as shown in Fig. 9. In the following sections, we describe these spectrum sensing methods for xG networks and discuss the open research topics in this area.

4.1. Transmitter detection (non-cooperative detection)

The cognitive radio should distinguish between used and unused spectrum bands. Thus, the cognitive radio should have capability to determine if a signal from primary transmitter is locally present in a certain spectrum. Transmitter detection approach is based on the detection of the weak signal from a primary transmitter through the local observations of xG users. Basic hypothesis model for transmitter detection can be defined as follows [25]:

$$x(t) = \begin{cases} n(t) & H_0, \\ hs(t) + n(t) & H_1, \end{cases} \tag{1}$$

where $x(t)$ is the signal received by the xG user, $s(t)$ is the transmitted signal of the primary user, $n(t)$ is the AWGN and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand, H_1 is an alternative hypothesis, which indicates that there exist some licensed user signal.

Three schemes are generally used for the transmitter detection according to the hypothesis model [53]. In the following subsections, we investigate *matched filter detection*, *energy detection* and *cyclostationary feature detection* techniques proposed for transmitter detection in xG networks.

4.1.1. Matched filter detection

When the information of the primary user signal is known to the xG user, the optimal detector in stationary Gaussian noise is the matched filter since it maximizes the received signal-to-noise ratio (SNR) [53]. While the main advantage of the matched filter is that it requires less time to achieve high processing gain due to coherency, it requires a priori knowledge of the primary user signal such as the modulation type and order, the pulse shape, and the packet format. Hence, if this information is not accurate, then the matched filter performs poorly. However, since most wireless network systems have pilot, preambles, synchronization word or spreading codes, these can be used for the coherent detection.

4.1.2. Energy detection

If the receiver cannot gather sufficient information about the primary user signal, for example, if the power of the random Gaussian noise is only known to the receiver, the optimal detector is an energy detector [53]. In order to measure the energy of the received signal, the output signal of bandpass filter with bandwidth W is squared and integrated over the observation interval T. Finally, the output of the integrator, Y, is compared with a threshold, λ,

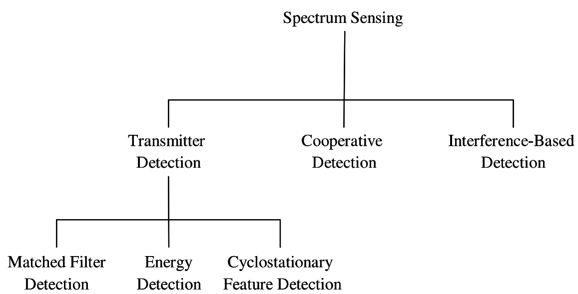

Fig. 9. Classification of spectrum sensing techniques.

to decide whether a licensed user is present or not [17].

If the energy detection can be applied in a non-fading environment where h is the amplitude gain of the channel as shown in (1), the probability of detection P_d and false alarm P_f are given as follows [17]:

$$P_d = P\{Y > \lambda | H_1\} = Q_m\left(\sqrt{2\gamma}, \sqrt{\lambda}\right), \quad (2)$$

$$P_f = P\{Y > \lambda | H_o\} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)}, \quad (3)$$

where γ is the SNR, $u = TW$ is the time bandwidth product, $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are complete and incomplete gamma functions and $Q_m()$ is the generalized Marcum Q-function. From the above functions, while a low P_d would result in missing the presence of the primary user with high probability which in turn increases the interference to the primary user, a high P_f would result in low spectrum utilization since false alarms increase the number of missed opportunities. Since it is easy to implement, the recent work on detection of the primary user has generally adopted the energy detector [23,53].

In [25], the shadowing and the multi-path fading factors are considered for the energy detector. In this case, while P_f is independent of Γ, when the amplitude gain of the channel, h, varies due to the shadowing/fading, P_d gives the probability of the detection conditioned on instantaneous SNR as follows:

$$P_d = \int_x Q_m\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) f_\gamma(x)\, dx, \quad (4)$$

where $f_\gamma(x)$ is the probability distribution function of SNR under fading.

However, the performance of energy detector is susceptible to uncertainty in noise power. In order to solve this problem, a pilot tone from the primary transmitter is used to help improve the accuracy of the energy detector in [53]. Another shortcoming is that the energy detector cannot differentiate signal types but can only determine the presence of the signal. Thus, the energy detector is prone to the false detection triggered by the unintended signals.

4.1.3. Cyclostationary feature detection

An alternative detection method is the cyclostationary feature detection [12,22,57]. Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. These modulated signals are characterized as cyclostationarity since their mean and autocorrelation exhibit periodicity. These features are detected by analyzing a spectral correlation function. The main advantage of the spectral correlation function is that it differentiates the noise energy from modulated signal energy, which is a result of the fact that the noise is a wide-sense stationary signal with no correlation, while modulated signals are cyclostationary with spectral correlation due to the embedded redundancy of signal periodicity. Therefore, a cyclostationary feature detector can perform better than the energy detector in discriminating against noise due to its robustness to the uncertainty in noise power [57]. However, it is computationally complex and requires significantly long observation time.

For more efficient and reliable performance, the enhanced feature detection scheme combining cyclic spectral analysis with pattern recognition based on neural networks is proposed in [22]. Distinct features of the received signal are extracted using cyclic spectral analysis and represented by both spectral coherent function and spectral correlation density function. The neural network, then, classifies signals into different modulation types.

4.2. Cooperative detection

The assumption of the primary transmitter detection is that the locations of the primary receivers are unknown due to the absence of signalling between primary users and the xG users. Therefore, the cognitive radio should rely on only weak primary transmitter signals based on the local observation of the xG user [72,73]. However, in most cases, an xG network is physically separated from the primary network so there is no interaction between them. Thus, with the transmitter detection, the xG user cannot avoid the interference due to the lack of the primary receiver's information as depicted in Fig. 10(a). Moreover, the transmitter detection model cannot prevent the hidden terminal problem. An xG transmitter can have a good line-of-sight to a receiver, but may not be able to detect the transmitter due to the shadowing as shown in Fig. 10(b). Consequently, the sensing information from other users is required for more accurate detection.

In the case of non-cooperative detection explained in Section 4.1, the xG users detect the primary transmitter signal independently through their local observations. Cooperative detection refers to

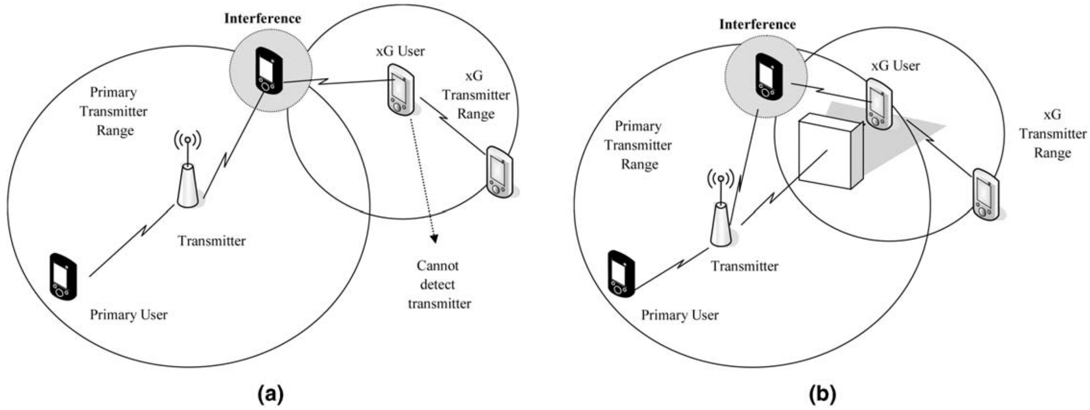

Fig. 10. Transmitter detection problem: (a) Receiver uncertainty and (b) shadowing uncertainty.

spectrum sensing methods where information from multiple xG users are incorporated for primary user detection. Cooperative detection can be implemented either in a centralized or in a distributed manner [23,71]. In the centralized method, the xG base-station plays a role to gather all sensing information from the xG users and detect the spectrum holes. On the other hand, distributed solutions require exchange of observations among xG users.

Cooperative detection among unlicensed users is theoretically more accurate since the uncertainty in a single user's detection can be minimized [25]. Moreover, the multi-path fading and shadowing effect are the main factors that degrade the performance of primary user detection methods [44]. However, cooperative detection schemes allow to mitigate the multi-path fading and shadowing effects, which improves the detection probability in a heavily shadowed environment [25].

In [55], the limitation of non-cooperative spectrum sensing approaches is investigated. Generally, the data transmission and sensing function are co-located in a single xG user device. However, this architecture can result in suboptimal spectrum decision due to possible conflicts between data transmission and sensing. In order to solve this problem, in [55], two distinct networks are deployed separately, i.e., the *sensor network* for cooperative spectrum sensing and the *operational network* for data transmission. The sensor network is deployed in the desired target area and senses the spectrum. A central controller processes the spectrum information collected from sensors and makes the spectrum occupancy map for the operational network. The operational network uses this information to determine the available spectrum.

While cooperative approaches provide more accurate sensing performance, they cause adverse effects on resource-constrained networks due to the additional operations and overhead traffic. Furthermore, the primary receiver uncertainty problem caused by the lack of the primary receiver location knowledge is still unsolved in the cooperative sensing. In the following section, we explain interference-based detection methods, which aim to address these problems.

4.3. Interference-based detection

Interference is typically regulated in a transmitter-centric way, which means interference can be controlled at the transmitter through the radiated power, the out-of-band emissions and location of individual transmitters. However, interference actually takes place at the receivers, as shown in Fig. 10(a) and (b).

Therefore recently, a new model for measuring interference, referred to as *interference temperature* shown in Fig. 11 has been introduced by the FCC [21]. The model shows the signal of a radio station designed to operate in a range at which the received power approaches the level of the noise floor. As additional interfering signals appear, the noise floor increases at various points within the service area, as indicated by the peaks above the original noise floor. Unlike the traditional transmitter-centric approach, the interference temperature model manages interference at the receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver could tolerate. In other words, the interference temperature model accounts for the cumulative RF

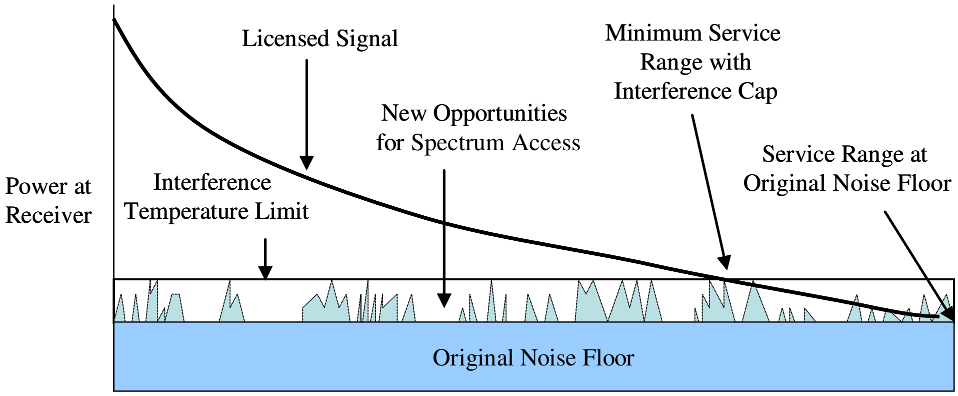

Fig. 11. Interference temperature model [21].

energy from multiple transmissions and sets a maximum cap on their aggregate level. As long as xG users do not exceed this limit by their transmissions, they can use this spectrum band.

However, there exist some limitations in measuring the interference temperature. In [9], the interference is defined as the expected fraction of primary users with service disrupted by the xG operations. This method considers factors such as the type of unlicensed signal modulation, antennas, ability to detect active licensed channels, power control, and activity levels of the licensed and unlicensed users. However, this model describes the interference disrupted by a single xG user and does not consider the effect of multiple xG users. In addition, if xG users are unaware of the location of the nearby primary users, the actual interference cannot be measured using this method.

In [63], a direct receiver detection method is presented, where the local oscillator (LO) leakage power emitted by the RF front-end of the primary receiver is exploited for the detection of primary receivers. In order to detect the LO leakage power, low-cost sensor nodes can be mounted close to the primary receivers. The sensor nodes detect the leakage LO power to determine the channel used by the primary receiver and this information is used by the unlicensed users to determine the operation spectrum.

4.4. Spectrum sensing challenges

There exist several open research challenges that need to be investigated for the development of the spectrum sensing function.

- *Interference temperature measurement*: The difficulty of this receiver detection model lies in effectively measuring the interference temperature. An xG user is naturally aware of its transmit power level and its precise location with the help of a positioning system. With this ability, however, its transmission could cause significant interference at a neighboring receiver on the same frequency. However, currently, there exists no practical way for a cognitive radio to measure or estimate the interference temperature at nearby primary receivers. Since primary receivers are usually passive devices, an xG user cannot be aware of the precise locations of primary receivers. Furthermore, if xG users cannot measure the effect of their transmission on all possible receivers, a useful interference temperature measurement may not be feasible.
- *Spectrum sensing in multi-user networks*: Usually, xG networks reside in a multi-user environment which consists of multiple xG users and primary users. Furthermore, the xG networks can also be co-located with other xG networks competing for the same spectrum band. However, current interference models [9,21] do not consider the effect of multiple xG users. Multi-user environment makes it more difficult to sense the primary users and to estimate the actual interference. Hence, spectrum sensing functions should be developed considering the possibility of multi-user/network environment. In order to solve the multi-user problem, the cooperative detection schemes can be considered, which exploit the spatial diversity inherent in a multi-user network.
- *Detection capability*: One of the main requirements of xG networks is the detection of the primary users in a very short time [24,53]. OFDM-based xG networks are known to be excellent fit for the physical architecture of xG

networks [5,57,62]. Since multi-carrier sensing can be exploited in OFDM-based xG networks, the overall sensing time can be reduced. Once a primary user is detected in a single carrier, sensing in other carriers is not necessary. In [57], a power-based sensing algorithm in OFDM networks is proposed for detecting the presence of a primary user. It is shown that the overall detection time is reduced by collecting information from each carrier. However, this necessitates the use of a large number of carriers, which increases the design complexity. Hence, novel spectrum sensing algorithms need to be developed such that the number of samples needed to detect the primary user is minimized within a given detection error probability.

5. Spectrum management

In xG networks, the unused spectrum bands will be spread over wide frequency range including both unlicensed and licensed bands. These unused spectrum bands detected through spectrum sensing show different characteristics according to not only the time varying radio environment but also the spectrum band information such as the operating frequency and the bandwidth.

Since xG networks should decide on the best spectrum band to meet the QoS requirements over all available spectrum bands, new spectrum management functions are required for xG networks, considering the dynamic spectrum characteristics. We classify these functions as *spectrum sensing*, *spectrum analysis*, and *spectrum decision*. While *spectrum sensing*, which is discussed in Section 4, is primarily a PHY layer issue, *spectrum analysis* and *spectrum decision* are closely related to the upper layers. In this section, spectrum analysis and spectrum decision are investigated.

5.1. Spectrum analysis

In xG networks, the available spectrum holes show different characteristics which vary over time. Since the xG users are equipped with the cognitive radio based physical layer, it is important to understand the characteristics of different spectrum bands. Spectrum analysis enables the characterization of different spectrum bands, which can be exploited to get the spectrum band appropriate to the user requirements.

In order to describe the dynamic nature of xG networks, each spectrum hole should be characterized considering not only the time-varying radio environment and but also the primary user activity and the spectrum band information such as operating frequency and bandwidth. Hence, it is essential to define parameters such as interference level, channel error rate, path-loss, link layer delay, and holding time that can represent the quality of a particular spectrum band as follows:

- *Interference*: Some spectrum bands are more crowded compared to others. Hence, the spectrum band in use determines the interference characteristics of the channel. From the amount of the interference at the primary receiver, the permissible power of an xG user can be derived, which is used for the estimation of the channel capacity.
- *Path loss*: The path loss increases as the operating frequency increases. Therefore, if the transmission power of an xG user remains the same, then its transmission range decreases at higher frequencies. Similarly, if transmission power is increased to compensate for the increased path loss, then this results in higher interference for other users.
- *Wireless link errors*: Depending on the modulation scheme and the interference level of the spectrum band, the error rate of the channel changes.
- *Link layer delay*: To address different path loss, wireless link error, and interference, different types of link layer protocols are required at different spectrum bands. This results in different link layer packet transmission delay.
- *Holding time*: The activities of primary users can affect the channel quality in xG networks. Holding time refers to the expected time duration that the xG user can occupy a licensed band before getting interrupted. Obviously, the longer the holding time, the better the quality would be. Since frequent spectrum handoff can decrease the holding time, previous statistical patterns of handoff should be considered while designing xG networks with large expected holding time.

Channel capacity, which can be derived from the parameters explained above, is the most important factor for spectrum characterization. Usually SNR at the receiver has been used for the capacity estimation. However, since SNR considers only local observations of xG users, it is not enough to avoid interference at the primary users. Thus, spectrum characterization is focused on the capacity estimation based on the interference at the licensed receivers. The interference temperature model [21] given in Section 4.3 can be exploited for this approach. The interference temperature limit indicates an upper bound or cap on the potential RF energy that could be introduced into the band. Consequently, using the amount of permissible interference, the maximum permissible transmission power of an xG user can be determined.

In [63], a spectrum capacity estimation method has been proposed that considers the bandwidth and the permissible transmission power. Accordingly, the spectrum capacity, C, can be estimated as follows:

$$C = B\log\left(1+\frac{S}{N+I}\right), \quad (5)$$

where B is the bandwidth, S is the received signal power from the xG user, N is the xG receiver noise power, and I is the interference power received at the xG receiver due to the primary transmitter.

Estimating spectrum capacity has also been investigated in the context of OFDM-based cognitive radio systems in [57]. Accordingly, the spectrum capacity of the OFDM-based xG networks is defined as follows [57]:

$$C = \int_{\Omega} \frac{1}{2}\log_2\left(1+\frac{G(f)S_0}{N_0}\right)\mathrm{d}f, \quad (6)$$

where Ω is the collection of unused spectrum segments, $G(f)$ is the channel power gain at frequency f, S_0 and N_0 are the signal and noise power per unit frequency, respectively.

The recent work on spectrum analysis, as discussed above, only focuses on spectrum capacity estimation. However, besides the capacity, other factors such as delay, link error rate, and holding time also have significant influence on the quality of services. Moreover, the capacity is closely related to both interference level and path loss. However, a complete analysis and modeling of spectrum in xG networks is yet to be developed. In order to decide on the appropriate spectrum for different types of applications, it is desirable and an open research issue to identify the spectrum bands combining all characterization parameters described above.

5.2. Spectrum decision

Once all available spectrum bands are characterized, appropriate operating spectrum band should be selected for the current transmission considering the QoS requirements and the spectrum characteristics. Thus, the spectrum management function must be aware of user QoS requirements.

Based on the user requirements, the data rate, acceptable error rate, delay bound, the transmission mode, and the bandwidth of the transmission can be determined. Then, according to the decision rule, the set of appropriate spectrum bands can be chosen. In [73], five spectrum decision rules are presented, which are focused on fairness and communication cost. However, this method assumes that all channels have similar throughput capacity. In [36], an opportunistic frequency channel skipping protocol is proposed for the search of better quality channel, where this channel decision is based on SNR. In order to consider the primary user activity, the number of spectrum handoff, which happens in a certain spectrum band, is used for spectrum decision [37]. Spectrum decision constitutes rather important but yet unexplored issues in xG networks, which are presented in the following subsection.

5.3. Spectrum management challenges

There exist several open research issues that need to be investigated for the development of spectrum decision function.

- *Decision model*: Signal to noise ratio (SNR) is not sufficient to characterize the spectrum band in xG networks. Besides the SNR, many spectrum characterization parameters would affect the quality, as investigated in Section 5.1. Thus, how to combine these spectrum characterization parameters for the spectrum decision model is still an open issue. Moreover, in OFDM based xG networks, multiple spectrum bands can be simultaneously used for the transmission. For these reasons, a decision framework for the multiple spectrum bands should be provided.
- *Multiple spectrum band decision:* In xG networks, multiple spectrum bands can be simultaneously used for the transmission. Moreover, the xG networks do not require the selected multiple bands to be contiguous. Thus, an xG user can send packets over non-contiguous spectrum bands. This multi-spectrum transmission shows less quality degradation during the spectrum handoff compared to the conventional transmission on single spectrum band [5]. For example, if a primary user appears in a particular spectrum band,

the xG user has to vacate this band. However, since the rest of spectrum bands will maintain the communication, abrupt service quality degradation can be mitigated. In addition, transmission in multiple spectrum bands allows lower power to be used in each spectrum band. As a result, less interference with primary users is achieved, compared to the transmission on single spectrum band [5]. For these reasons, a spectrum management framework should support multiple spectrum decision capabilities. For example, how to determine the number of spectrum bands and how to select the set of appropriate bands are still open research issues in xG networks.

- *Cooperation with reconfiguration*: The cognitive radio technology enables the transmission parameters of a radio to be reconfigured for optimal operation in a certain spectrum band. For example, if SNR is fixed, the bit error rate (BER) can be adjusted to maintain the channel capacity by exploiting adaptive modulation techniques, e.g., cdma2000 1x EVDO [1,18]. Hence, a cooperative framework that considers both spectrum decision and reconfiguration is required.
- *Spectrum decision over heterogenous spectrum bands*: Currently, certain spectrum bands are already assigned to different purposes while some bands remain unlicensed. Thus, the spectrum used by xG networks will most likely be a combination of exclusively accessed spectrum and unlicensed spectrum. In case of licensed bands, the xG users need to consider the activities of primary users in spectrum analysis and decision in order not to influence the primary user transmission. Conversely, in unlicensed bands, since all the xG users have the same spectrum access rights, sophisticated spectrum sharing techniques are necessary. In order to decide the best spectrum band over this heterogeneous environment, xG network should support spectrum decision operations on both the licensed and the unlicensed bands considering these different characteristics.

6. Spectrum mobility

xG networks target to use the spectrum in a dynamic manner by allowing the radio terminals, known as the cognitive radio, to operate in the best available frequency band. This enables *"Get the Best Available Channel"* concept for communication purposes. To realize the *"Get the Best Available Channel"* concept, an xG radio has to capture the best available spectrum. *Spectrum mobility* is defined as the process when an xG user changes its frequency of operation. In the following sections, we describe the spectrum handoff concept in xG networks and discuss open research issues in this new area.

6.1. Spectrum handoff

In xG networks, *spectrum mobility* arises when current channel conditions become worse or a primary user appears. Spectrum mobility gives rise to a new type of handoff in xG networks that we refer to as *spectrum handoff*. The protocols for different layers of the network stack must adapt to the channel parameters of the operating frequency. Moreover, they should be transparent to the *spectrum handoff* and the associated latency.

As pointed out in earlier sections, a cognitive radio can adapt to the frequency of operation. Therefore, each time an xG user changes its frequency of operation, the network protocols are going to shift from one mode of operation to another. The purpose of spectrum mobility management in xG networks is to make sure that such transitions are made smoothly and as soon as possible such that the applications running on an xG user perceive minimum performance degradation during a *spectrum handoff*. It is essential for the mobility management protocols to learn in advance about the duration of a *spectrum handoff*. This information should be provided by the sensing algorithm. Once the mobility management protocols learn about this latency, their job is to make sure that the ongoing communications of an xG user undergo only minimum performance degradation.

Consequently, multi-layer mobility management protocols are required to accomplish the spectrum mobility functionalities. These protocols support mobility management adaptive to different types of applications. For example, a TCP connection can be put to a wait state until the *spectrum handoff* is over. Moreover, since the TCP parameters will change after a *spectrum handoff*, it is essential to learn the new parameters and ensure that the transition from the old parameters to new parameters are carried out rapidly. For a data communication e.g., FTP, the mobility management protocols should implement mechanisms to store the packets that are transmitted during a *spectrum handoff*, whereas for a real-time application there is no need to store the packets as the stored packets, if delivered later, will be stale packets and can not be used by the corresponding application.

6.2. Spectrum mobility challenges in xG networks

The followings are the open research issues for efficient spectrum mobility in xG networks.

- At a particular time, several frequency bands may be available for an xG user. Algorithms are required to decide the best available spectrum based on the channel characteristics of the available spectrum and the requirements of the applications that are being used by an xG user.
- Once, the best available spectrum is selected, the next challenge is to design new mobility and connection management approaches to reduce delay and loss during spectrum handoff.
- When the current operational frequency becomes busy (this may happen if a licensed user starts to use this frequency) in the middle of a communication by an xG user, then applications running on this node have to be transferred to another available frequency band. However, the selection of new operational frequency may take time. Novel algorithms are required to ensure that applications do not suffer from severe performance degradation during such transitions.
- Spectrum handoff may occur due to reasons other than the detection of the primary user. Thus, there exist various other spectrum handoff schemes in xG networks. If an xG user moves from one place to another, spectrum handoff may occur just because the available spectrum bands change. Thus the desired spectrum handoff scheme should integrate inter-cell handoff. Apart from this, spectrum handoff between different networks, referred to as *vertical handoff* is also likely to occur in xG networks. Under such a diverse environment, it is essential that spectrum handoff scheme takes all the above mentioned possibilities into consideration.
- *Spectrum mobility in time domain*: xG networks adapt to the wireless spectrum based on available bands on the spectrum. Since these available channels change over time, enabling QoS in this environment is challenging. The physical radio should "move" through the spectrum to meet the QoS requirements.
- *Spectrum mobility in space*: The available bands also change as a user moves from one place to another. Hence, continuous allocation of spectrum is a major challenge. in xG networks.

7. Spectrum sharing

In xG networks, one of the main challenges in open spectrum usage is the spectrum sharing. Spectrum sharing can be regarded to be similar to generic medium access control (MAC) problems in existing systems. However, as we will investigate in this section, substantially different challenges exist for spectrum sharing in xG networks. The coexistence with licensed users and the wide range of available spectrum are two of the main reasons for these unique challenges. In this section, we delve into the specific challenges for spectrum sharing in xG networks, overview the existing solutions and discuss open research areas.

In order to provide a directory for different challenges during spectrum sharing, we first enumerate the steps in spectrum sharing in xG networks. The challenges and the solutions proposed for these steps will then be explained in detail. The spectrum sharing process consists of five major steps.

1. *Spectrum sensing*: An xG user can only allocate a portion of the spectrum if that portion is not used by an unlicensed user. In Section 4, the solutions and the challenges for this problem, i.e., spectrum sensing, are described. Accordingly, when an xG node aims to transmit packets, it first needs to be aware of the spectrum usage around its vicinity.
2. *Spectrum allocation*: Based on the spectrum availability, the node can then allocate a channel. This allocation not only depends on spectrum availability, but it is also determined based on internal (and possibly external) policies. Hence, the design of a spectrum allocation policy to improve the performance of a node is an important research topic.
3. *Spectrum access*: In this step, another major problem of spectrum sharing comes into picture. Since there may be multiple xG nodes trying to access the spectrum, this access should also be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.
4. *Transmitter-receiver handshake*: Once a portion of the spectrum is determined for communication,

the receiver of this communication should also be indicated about the selected spectrum. Hence, a transmitter-receiver handshake protocol is essential for efficient communication in xG networks. Note that the term *handshake* by no means restricts this protocol between the transmitter and the receiver. A third party such as a centralized station can also be involved.

5. *Spectrum mobility*: xG nodes are regarded as "visitors" to the spectrum they allocate. Hence, if the specific portion of the spectrum in use is required by a licensed user, the communication needs to be continued in another vacant portion. As a result, spectrum mobility is also important for successful communication between xG nodes.

The existing work in spectrum sharing in xG networks aims to provide solutions for each step explained above. The existing solutions constitute a rich literature for spectrum sharing in xG networks. In Section 7.1, we classify the spectrum sharing techniques and describe the fundamental results about these techniques in xG networks. These work provide insight about how a spectrum sharing protocol can be designed. Accordingly, in Sections 7.2 and 7.3, we overview the solutions for spectrum sharing among multiple coexisting xG networks (*inter-network spectrum sharing*), and inside an xG network (*intra-network spectrum sharing*), respectively. Finally, in Section 7.4, the open research issues for spectrum sharing in xG networks are discussed.

7.1. Overview of spectrum sharing techniques

The existing solutions for spectrum sharing in xG networks can be mainly classified in three aspects: i.e., according to their *architecture assumption, spectrum allocation behavior*, and *spectrum access technique* as shown in Fig. 12. In this section, we describe these three classifications and present the fundamental results that analyze these classifications. The analysis of xG spectrum sharing techniques has been investigated through two major theoretical approaches. While some work uses optimization techniques to find the optimal strategies for spectrum sharing, game theoretical analysis has also been used in this area.

The first classification for spectrum sharing techniques in xG networks is based on the architecture, which can be described as follows:

- *Centralized spectrum sharing*: In these solutions, a centralized entity controls the spectrum allocation and access procedures [7,51,70]. With aid to these procedures, generally, a distributed sensing procedure is proposed such that each entity in the xG network forward their measurements about the spectrum allocation to the central entity and this entity constructs a spectrum allocation map.
- *Distributed spectrum sharing*: Distributed solutions are mainly proposed for cases where the construction of an infrastructure is not preferable [15,29,40,54,71–73]. Accordingly, each node is responsible for the spectrum allocation and access is based on local (or possibly global) policies.

The second classification for spectrum sharing techniques in xG networks is based on the access behavior. More specifically, the spectrum access can be *cooperative* or *non-cooperative* as explained below:

- *Cooperative spectrum sharing*: Cooperative (or collaborative) solutions consider the effect of the node's communication on other nodes [7,15,29,40,71]. In other words, the interference measurements of each node are shared among other nodes. Furthermore, the spectrum allocation algorithms also consider this information. While all the centralized solutions can be regarded as cooperative, there also exist distributed cooperative solutions.

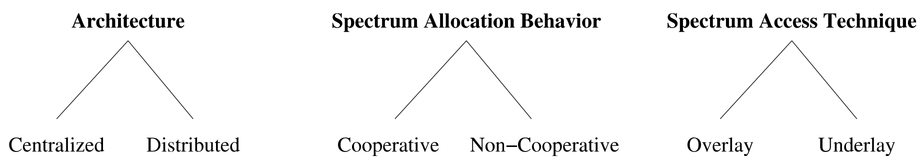

Fig. 12. Classification of spectrum sharing in xG networks based on architecture, spectrum allocation behavior, and spectrum access technique.

- *Non-cooperative spectrum sharing*: Contrary to the cooperative solutions, non-cooperative (or non-collaborative, selfish) solutions consider only the node at hand [54,72,73]. These solutions are also referred to as *selfish*. While non-cooperative solutions may result in reduced spectrum utilization, the minimal communication requirements among other nodes introduce a tradeoff for practical solutions.

These two solutions have generally been compared through their spectrum utilization, fairness, and throughput. The utilization and fairness in spectrum access has been investigated in [50], where the spectrum allocation problem is modeled as a graph coloring problem and both centralized and distributed approaches are investigated. Using this model, an optimization framework is developed. In this framework, secondary users allocate channels according to the interference that will be caused by the transmission. Both cooperative and non-cooperative approaches are considered such that cooperative approaches also consider the effect of the channel allocation on the potential neighbors. The simulation results show that cooperative approaches outperform non-cooperative approaches as well as closely approximating the global optimum. Moreover, the comparison of centralized and distributed solutions reveals that distributed solution closely follows the centralized solution. A similar analysis has also been provided in [74], where the effects of collaboration in spectrum access is investigated. An important assumption in these work is that secondary users know the location and transmit power of primary users so that the interference calculations can be performed easily. However, such an assumption may not always be valid in xG networks.

Game theory has also been exploited for performance evaluation of xG spectrum access schemes. Especially, the comparison between cooperative and non-cooperative approaches has been presented in [49] through game theoretical analysis. In [49], game theory is exploited to analyze the behavior of the cognitive radio for distributed adaptive channel allocation. It is assumed that users deploy CDMA and determine the operating channel and the coding rate by keeping transmission power constant. It is shown that the cooperative case can be modeled as an exact potential game, which converges to a pure strategy Nash equilibrium solution. However, this framework has been shown not to be applicable for non-cooperative spectrum sharing and a learning algorithm has been proposed. The evaluations reveal that Nash equilibrium point for cooperative users is reached quickly and results in a certain degree of fairness as well as improved throughput. On the other hand, the learning algorithm for non-cooperative users converge to a mixed strategy allocation. Moreover, the fairness is degraded when non-cooperative approach is used. While this approach results in slightly worse performance, the information exchange required by selfish users is significantly low.

Finally, the third classification for spectrum sharing in xG networks is based on the access technology as explained below:

- *Overlay spectrum sharing*: Overlay spectrum sharing refers to the spectrum access technique used. More specifically, a node accesses the network using a portion of the spectrum that has not been used by licensed users [7,15,40,54,71–73]. As a result, interference to the primary system is minimized.
- *Underlay spectrum sharing*: Underlay spectrum sharing exploits the spread spectrum techniques developed for cellular networks [29]. Once a spectrum allocation map has been acquired, an xG node begins transmission such that its transmit power at a certain portion of the spectrum is regarded as noise by the licensed users. This technique requires sophisticated spread spectrum techniques and can utilize increased bandwidth compared to overlay techniques.

The effects of underlay and overlay approaches in a cooperative setting are investigated in [19], where non-cooperative users are analyzed using a game theoretical framework. Using this framework, it is shown that frequency division multiplexing is optimal when interference among users is high. As a result, the overlay approach becomes more efficient than underlay when interference among users is high. The lack of cooperation among users, however, necessitates an overlay approach. The comparative evaluations show that the performance loss due to the lack of cooperation is small, and vanishes with increasing SNR. However, in this framework, the cost and inaccuracies of information exchange between users are not considered.

Another comparison of underlay and overlay approaches is provided in [42]. The comparison is based on the influence of the secondary system on the primary system in terms of outage probability and three spectrum sharing techniques have been considered. The first technique (spreading based underlay) requires secondary users to spread their transmit power over the full spectrum such as CDMA or Ultra Wide Band (UWB). The second technique (interference avoidance overlay) requires nodes to choose a frequency band to transmit such that the interference at a primary user is minimized. Also an hybrid technique (spreading based underlay with interference avoidance) is investigated where a node spreads its transmission over the entire spectrum and also null or notch frequencies where a primary user is transmitting. Consequently, first, the interference statistics for each technique are determined for outage probability analysis. Then, the outage probability for each technique is derived assuming no system knowledge, perfect system knowledge, and limited system knowledge. Similar to other existing work, when perfect system knowledge is assumed, the overlay scheme outperforms the underlay scheme in terms of outage probability. However, when interference avoidance is incorporated into spectrum sharing, the underlay scheme with interference avoidance guarantees smaller outage probability than the pure interference avoidance. In a more realistic case, when limited system knowledge is considered, the importance of the hybrid technique is exacerbated. The overlay schemes result in poor performance due imperfections at spectrum sensing. More specifically, a node can transmit at a channel where a primary user is transmitting. However, when underlay with interference avoidance is used, the interference caused to the primary user is minimized. Another important result is that a higher number of secondary users can be accommodated by the hybrid scheme than the pure interference avoidance scheme.

The theoretical work on spectrum access in xG networks reveals important tradeoffs for the design of spectrum access protocols. As expected, it has been shown that cooperative settings result in higher utilization of the spectrum as well as fairness. However, this advantage may not be so high considering the cost of cooperation due to frequent information exchange among users. On the other hand, the spectrum access technique, i.e., whether it is overlay or underlay, affects the performance in each setting. While an overlay technique focuses on the holes in the spectrum, dynamic spreading techniques are required for underlay techniques for interference-free operation between primary and secondary systems. Considering the tradeoff between system complexity and performance, hybrid techniques may be considered for the spectrum technique. In the following two sections, we explain the existing spectrum sharing techniques that are combinations of the three classifications we have discussed in this section.

7.2. Inter-network spectrum sharing

xG networks are envisioned to provide opportunistic access to the licensed spectrum using unlicensed users. This setting enables multiple systems being deployed in overlapping locations and spectrum as shown in Fig. 13. Hence, spectrum sharing among these systems is an important research topic in xG networks. Up to date, inter-network spectrum sharing has been regulated via static frequency assignment among different systems or centralized allocations between different access points of a sys-

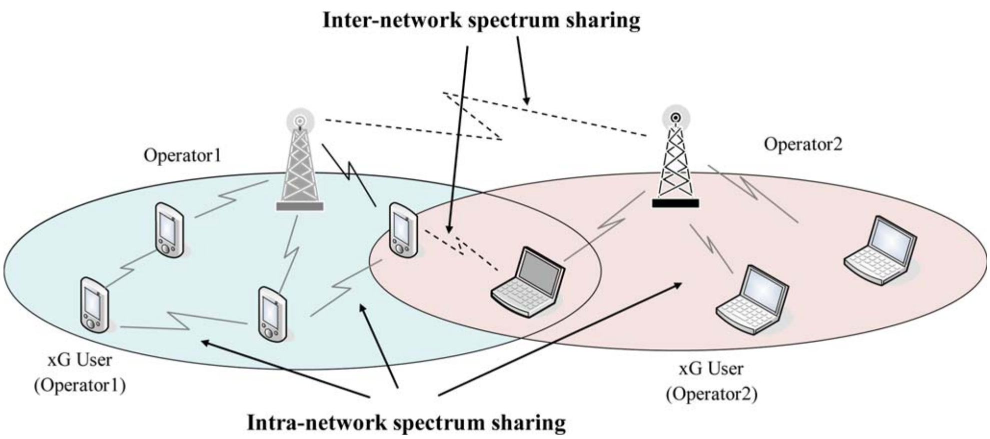

Fig. 13. Inter-network and intra-network spectrum sharing in xG networks.

tem in cellular networks. In ad-hoc networks, only the interference issues in the ISM band has been investigated focusing mostly on the coexistence of WLAN and Bluetooth networks. Consequently, intra-network spectrum sharing in xG networks poses unique challenges that have not been considered before in wireless communication systems. In this section, we overview the recent work in this research area.

7.2.1. Centralized inter-network spectrum sharing

As a first step for the coexistence of open spectrum systems, in [33], the common spectrum coordination channel (CSCC) etiquette protocol is proposed for coexistence of IEEE 802.11b and 802.16a networks. The reason we do not consider this work as a complete solution for xG networks is that it necessitates modifications in users using both of the networks. More specifically, each node is assumed to be equipped with a cognitive radio and a low bit-rate, narrow-band control radio. The coexistence is maintained through the coordination of these nodes with each other by broadcasting CSCC messages. Each user determines the channel it can use for data transmission such that interference is avoided. In case channel selection is not sufficient to avoid interference, power adaptation is also deployed. The evaluations reveal that when there is vacant spectrum to use frequency adaptation, CSCC etiquette protocol improves throughput by 35–160% via both frequency and power adaptation. Another interesting result is that when nodes are clustered around IEEE 802.11b access points, which is a realistic assumption, the throughput improvement of CSCC protocol increases.

In addition to the competition for the spectrum, competition for the users is also considered in [32]. In this work, a central spectrum policy server (SPS) is proposed to coordinate spectrum demands of multiple xG operators. In this scheme, each operator bids for the spectrum indicating the cost it will pay for the duration of the usage. The SPS then allocates the spectrum by maximizing its profit from these bids. The operators also determine an offer for the users and users select which operator to use for a given type of traffic. When compared to a case where each operator is assigned an equal share of the spectrum, the operator bidding scheme achieves higher throughput leading to higher revenue for the SPS, as well as a lower price for the users according to their requirements. This work opens a new perspective by incorporating competition for users as well as the spectrum in xG networks.

7.2.2. Distributed inter-network spectrum sharing

A distributed spectrum sharing scheme for wireless Internet service provides (WISPs) that share the same spectrum is proposed in [43], where a distributed QoS based dynamic channel reservation (D-QDCR) scheme is used. The basic concept behind D-QDCR is that a base station (BSs) of a WISP competes with its interferer BSs according to the QoS requirements of its users to allocate a portion of the spectrum. Similar to the CSCC protocol [33], the control and data channels are separated. The basic unit for channel allocation in D-QDCR is called *Q*-frames. When a BS allocates a *Q*-frame, it uses the control and data channels allocated to it for coordination and data communication between the users. The competition between BSs are performed according to the priority of each BS depending on a BSs data volume and QoS requirement. Moreover, various competition policies are proposed based on the type of traffic a user demands. Although thorough evaluations are not provided in [43], the D-QDCR scheme serves an important contribution for inter-network spectrum sharing.

The inter-network spectrum sharing solutions so far provide a broader view of the spectrum sharing solution including certain operator policies for the determination of the spectrum allocation. A major problem for the existing solutions in the xG network architecture is the requirement for a common control channel. We detail the potential problems and open research issues in this aspect in Section 7.4.

7.3. Intra-network spectrum sharing

A significant amount of work on spectrum sharing focuses on intra-network spectrum sharing, where the users of an xG network try to access the available spectrum without causing interference to the primary users. In this section, we overview the existing work and the proposed solutions in this area while providing a classification of existing protocols in terms of the classification provided in Section 7.1.

7.3.1. Cooperative intra-network spectrum sharing

A cooperative local bargaining (LB) scheme is proposed in [15] to provide both spectrum utilization and fairness. The local bargaining framework is formulated based on the framework in [50,74]. Local bargaining is performed by constructing local groups according to a poverty line that ensures a minimum spectrum allocation to each user and hence focuses on fairness of users. The evaluations reveal that local bargaining can closely approximate centralized graph coloring approach at a reduced complexity. Moreover, localized operation via grouping provides an efficient operation between a fully distributed and a centralized scheme.

Another approach that considers local groups for spectrum sharing is provided in [71], where a heterogeneous distributed MAC (HD-MAC) protocol is proposed. A potential problem in the solution provided in LB [15] is that a common control channel may not exist in xG networks or can be occupied by a primary user. In [71], it is shown that for a given topology, very limited number of common channels exist for each of the users in a network. However, when local neighbors are considered, a node shares many channels with its neighbors. Based on this observation, a clustering algorithm is proposed such that each group selects a common channel for communication, and distributed sensing and spectrum sharing is provided through this channel. Moreover, if this channel is occupied by a primary user at a specific time, the nodes reorganize themselves to use another control channel. The performance evaluations show that the distributed grouping approach outperforms common control channel approaches especially when the traffic load is high.

The notion of busy tones, which are mainly used in some ad-hoc network protocols, is extended to the xG networks in [40] with the dynamic open spectrum sharing MAC (DOSS-MAC) protocol. As a result, when a node is using a specific data channel for communication, both the transmitter and the receiver send a busy tone signal through the associated busy tone channel. In order to further eliminate control channel communication, FFT-based radio and the noncoherent modulation/demodulation-based radio designs are proposed which theoretically enable receivers to detect the carrier frequency and the bandwidth of a signal without any control information.

In addition to spectrum allocation, transmit power determination is also included in the spectrum sharing protocol in [29]. In this work both single channel and multi-channel asynchronous distributed pricing (SC/MC-ADP) schemes are proposed, where each node announces its *interference price* to other nodes. Using this information from its neighbors, a node can first allocate a channel and in case there exist users in that channel, then, determine its transmit power. As a result, this scheme can be classified as a hybrid of underlay and overlay techniques. While there exist users using distinct channels, multiple users can share the same channel by adjusting their transmit power. Furthermore, the SC-ADP algorithm provides higher rates to users when compared to selfish algorithms where users select the best channel without any knowledge about their neighbors' interference levels. Finally, it is shown that under high interference, the proposed algorithm outperforms underlay techniques.

So far, we have presented distributed solutions where a fixed infrastructure is not assumed. In [7], dynamic spectrum access protocol (DSAP), which is a centralized solution for spectrum sharing in xG networks, is presented. This solution is similar to the SPS approach [32] described in Section 7.2 with a focus on intra-network spectrum sharing. The dynamic spectrum access protocol (DSAP) proposed in this work enables a central entity to lease spectrum to users in a limited geographical region. DSAP consists of clients, DSAP server, and relays that relay information between server and clients that are not in the direct range of the server. Moreover, clients inform the server their channel conditions so that a global view of the network can be constructed at the server. By exploiting cooperative and distributed sensing, DSAP servers construct a *RadioMap*. This map is used for channel assignments which are leased to clients for a limited amount of time.

7.3.2. Non-cooperative intra-network spectrum sharing

An opportunistic spectrum management scheme is proposed in [73], where users allocate channels based on their observations of interference patterns and neighbors. In the device centric spectrum management scheme (DCSM), the communication overhead is minimized by providing five different system rules for spectrum allocation. As a result, users allocate channels according to these rules based on their observations instead of collaborating with other users. In case more than one node chooses the same channel in close proximity, random access techniques are used to resolve the contention. The comparative analysis of this scheme with the cooperative schemes show that rule-based spectrum access results in slightly worse performance. However, the communication overhead is reduced significantly.

A spectrum sharing protocol for ad-hoc xG networks, (AS-MAC), is proposed in [54]. AS-MAC exploits the RTS-CTS exchange and Network Allocation Vector (NAV) concepts of the IEEE 802.11 MAC protocol [30] in an open spectrum setting. Moreover, a common control channel is used such that transmitter receiver handshake is initiated through this channel. In this work, the xG network is assumed to coexist with a GSM network. Each node first listens to the broadcast channel of the GSM network as well as the control channel of the xG network, and each node then constructs its NAV and selects channels accordingly.

In addition to the spectrum allocation methods, a transmitter receiver handshake method is proposed in [72] as a part of a cross-layer decentralized cognitive MAC (DC-MAC) protocol. The details of this work is explained in Section 9. In the transmitter-receiver handshake method, each user is assigned a set of channels is continuously monitored by the user. A transmitter selects one of those channels and initiates communication. The actual data channel selection is then performed through this initial handshake channel.

7.4. Spectrum sharing challenges

In the previous sections, the theoretical findings and solutions for spectrum sharing in xG networks are investigated. Although there already exists a vast amount of research in spectrum sharing, there are still many open research issues for the realization of efficient and seamless open spectrum operation. In the following, we detail the challenges for spectrum sharing in xG networks along with some possible solutions.

7.4.1. Common control channel (CCC)

Many spectrum sharing solutions, either centralized or distributed, assume a CCC for spectrum sharing [7,40,54]. It is clear that a CCC facilitates many spectrum sharing functionalities such as transmitter receiver handshake [40], communication with a central entity [7], or sensing information exchange. However, due to the fact that xG network users are regarded as *visitors* to the spectrum they allocate, when a primary user chooses a channel, this channel has to be vacated without interfering. This is also true for the CCC. As a result, implementation of a fixed CCC is infeasible in xG networks. Moreover, in a network with primary users, a channel common for all users is shown to be highly dependent on the topology, hence, varies over time [71]. Consequently, for protocols requiring a CCC, either a CCC mitigation technique needs to be devised or local CCCs need to be exploited for clusters of nodes [71]. On the other hand when CCC is not used, the transmitter receiver handshake becomes a challenge. For this challenge, receiver driven techniques proposed in [72] may be exploited.

7.4.2. Dynamic radio range

Radio range changes with operating frequency due to attenuation variation. In many solutions, a fixed range is assumed to be independent of the operating spectrum [15,71]. However, in xG networks, where a large portion of the wireless spectrum is considered, the neighbors of a node may change as the operating frequency changes. This effects the interference profile as well as routing decisions. Moreover, due to this property, the choice of a control channel needs to be carefully decided. It would be much efficient to select control channels in the lower portions of the spectrum where the transmission range will be higher and to select data channels in the higher portions of the spectrum where a localized operation can be utilized with minimized interference. So far, there exists no work addressing this important challenge in xG networks and we advocate operation frequency aware spectrum sharing techniques due the direct interdependency between interference and radio range.

7.4.3. Spectrum unit

Almost all spectrum sharing techniques discussed in the previous sections consider a *channel* as the basic spectrum unit for operation. Many algorithms and methods have been proposed to select the suitable *channel* for efficient operation in xG networks. However, in some work, the channel is vaguely defined as "orthogonal non-interfering" [73], "TDMA, FDMA, CDMA, or a combination of them" [50], or "a physical channel as in IEEE 802.11, or a logical channel associated with a spectrum region or a radio technology" [71]. In other work, the channel is simply defined in the frequency dimension as frequency bands [33,40,43,49,54]. It is clear that the definition of a channel as a spectrum unit for spectrum sharing is crucial in further developing algorithms. Since a huge portion of the spectrum is of interest, it is clear that properties of a *channel* may not be constant due to the effects of operating frequency. On the contrary, a channel is usually assumed to provide the same bandwidth as other channels [15,29,42,50,73].

Furthermore, the existence of primary users and the heterogeneity of the networks that are available introduce additional challenges to the choice of a spectrum unit/channel. Hence, different resource allocation units such as CSMA random access, TDMA time slots, CDMA codes, as well as hybrid types can be allocated to the primary users. In order to provide seamless operation, these properties need to be considered in the choice of a spectrum unit. In [28], the necessity of a *spectrum space* for a spectrum unit is also advocated. The possible dimensions of the spectrum space are classified as power, frequency, time, space, and signal. Although not orthogonal, these dimensions can be used to distinguish signals [28].

For this purpose, we describe a three dimensional space model for modeling network resources that has been proposed in [59]. Although this work focuses on heterogeneity in next generation/fourth generation (NG/4G) networks, as discussed in [59], it can be easily incorporated into xG networks. Based on this three dimensional *resource-space*, a novel *Virtual Cube* concept has been proposed in order to evaluate the performance of each network. The Virtual Cube concept defines a unit structure based on the resource allocation techniques used in existing networks.

The resource is modeled in a three dimensional *resource-space* with time, rate, and power/code dimensions as shown in Fig. 14. The *time dimension* models the time required to transfer information.

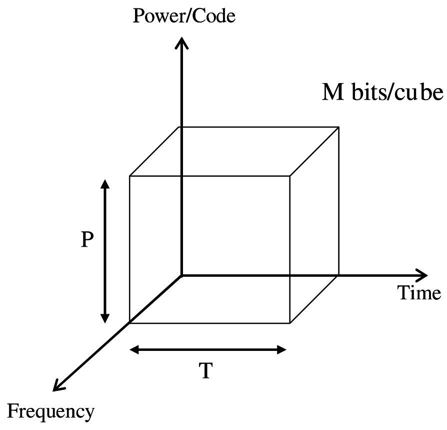

Fig. 14. Virtual cube model.

The *rate dimension* models the data rate of the network. Thus, the capacity of different networks with the same connection durations but different data rates are captured in the rate dimension. Furthermore, in the case of CDMA networks, the bandwidth increase due to the multi-code transmissions is also captured in this dimension. The *power/code dimension* models the energy consumed for transmitting information through the network. Note that, the resource in terms of available bandwidth can be modeled using the time and rate dimensions. However, the cost of accessing different networks vary in terms of the power consumed by the wireless terminal. Hence, a third dimension is required. Each network type requires different power levels for transmission of the MAC frames because of various modulation schemes, error coding and channel coding techniques. As a result, the resource differences in these aspects are captured in the power dimension.

Using this model, heterogeneous access types in existing networks as well as xG network spectrum can be modeled based on a generic spectrum unit. We advocate that determining a common spectrum unit is crucial for efficient utilization of the wireless spectrum and seamless operability with existing primary networks.

8. Upper layer issues

In addition to the unique challenges of xG networks in terms of spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing, upper layer issues such as routing, flow control and congestion control are also important for the realization of dynamic spectrum networks. In this section, we overview the challenges related to these areas.

8.1. Routing challenges

Routing constitutes a rather important but yet unexplored problem in xG networks. Especially in xG networks with multi-hop communication requirements, the unique characteristics of the open spectrum phenomenon necessitates novel routing algorithms to be developed. So far, the research on xG networks is primarily on spectrum sensing techniques and spectrum sharing solutions. However, we emphasize that the need for routing algorithms in open spectrum environment constitutes an important topic in xG network research. In this section, we overview two existing solutions for routing and discuss open research topics in this area.

A major design choice for routing in xG networks is the collaboration between routing and spectrum management. The dynamic spectrum that is intermittent in terms of both time and space necessitates such an approach [60,69]. Simulation-based comparisons are performed in [60,69] for cross-layer and decoupled approaches for routing and spectrum management. The results in both of these work reveal that a cross-layer solution that constructs routes and determines the operating spectrum jointly for each hop outperforms a sequential approach where routes are selected independent of the spectrum allocation [60,69].

In [60], the inter-dependence between route selection and spectrum management is investigated. First, a decoupled route selection and spectrum management methodology is proposed. In this scheme, the route selection is performed independent of the spectrum management using the shortest-path algorithm. The spectrum sharing is performed using the scheme in [71]. In this scheme, routing layer invokes path discovery to select routes. The spectrum management is then performed on each hop. A cross-layer solution that considers joint route selection and spectrum management is also proposed. In this approach, each source node uses DSR to find candidate paths and schedules a time and channel for each hop. This source-based routing technique is performed centrally using a global view of the network to show the upper bound in achievable performance. A similar comparison of layered and cross-layer approach is presented in [69] using a novel graph modeling technique, which will be discussed in the following. The simulations in both [60,69] reveal that cross-layer approach is advantageous for routing in xG networks since the availability of spectrum directly affects the end-to-end performance. These two solutions for routing in xG networks clearly show that cross-layer approaches that jointly consider route and spectrum selection is necessary for xG networks.

Another unique challenge for routing in xG networks is the development tools for analytical evaluation of routing protocols. Traditionally, routing protocols for ad hoc networks are analyzed using graph models. However, in these networks, the communication spectrum is fixed and continuous contrary to the dynamic nature of xG networks. Hence, a node can use the same set of static channel(s) for communication with all neighbors [69]. On the contrary, modeling network topology and connectivity of an xG network is challenging. In [69], a layered graph model is proposed for this challenge. In this model, each layer corresponds to a channel in the network. In each layer, each node is represented by subnodes forming the vertex in each layer. This model is exploited in [69] to construct routes. Using different cost functions for each edge, required constraints for routes such as interference avoidance can be achieved. This model provides an interesting solution for xG network modeling for relatively static link properties. However, as will be discussed in the following, time-varying nature of available links necessitates time dependent models for a complete analysis of xG networks.

Although these solutions provide interesting results for routing in xG networks, there are still major challenges and open research topics that has not been addressed before. Below, we summarize the open research issues for routing in xG networks:

- *Common control channel*: It has also been emphasized in Section 7.4 that the lack of a common control channel (CCC) in xG networks constitutes a major problem. Traditional routing protocols require either local or global broadcast messages for specific functionalities such as neighbor discovery, route discovery and route establishment. However, even broadcasting in xG networks is a major problem due to the lack of a CCC. Hence, solutions considering this fact is required in xG networks.
- *Intermittent connectivity*: In xG networks, the reachable neighbors of a node may change rapidly. This is due to two reasons. First, the available spectrum may change or vanish as licensed users exploit the network. Moreover, once a node selects a channel for communication it is no longer reachable through other channels. As a result, the connectivity concept used for wireless networks is different in xG networks and depends on the spectrum. For this purpose channel-based models such as the one in [69] is required as well as time-based solutions.
- *Re-routing*: In xG networks, due to the intermittent connectivity, a route established for a flow can change due to the available spectrum in addition to mobility. Hence, the re-routing algorithms considering the dynamic spectrum is necessary for routing in xG networks. A spectrum-aware routing adapts route selection to spectrum fluctuations [73].

- *Queue management*: The queue management in xG networks is another challenge which has not been addressed to date. An xG terminal may have multiple interfaces for communication with different nodes. Since the available spectrum varies over time, these interfaces may become unavailable requiring the packets served through that interface moved to other interfaces. In addition, the quality of service requirements may deploy various priorities on different traffic types. Hence, the implementation of a single queue or multiple queues for each traffic type of each interface needs to be investigated.

8.2. Transport layer challenges

Transport protocols constitute an unexplored area for xG networks since there exist no work on this area yet. Several solutions have been proposed to improve the performance of TCP and UDP in conventional wireless networks in recent years [2]. These studies focus on mechanisms to limit the performance degradation of TCP and UDP that arise because of wireless link errors and access delays. However, the xG networks impose unique challenges for transport protocols as explained below:

The performance of TCP depends on the packet loss probability and the round trip time (RTT). Wireless link errors and, hence, the packet loss probability not only depends on the access technology, but also on the frequency in use, interference level, and the available bandwidth. Therefore, the wireless TCP and UDP protocols that are designed for existing wireless access technologies cannot be used in dynamic spectrum assignment based xG networks.

On the other hand, RTT of a TCP connection depends indirectly on the frequency of operation. For example, if the packet error rate (or equivalently, the frame error rate) is higher at a particular frequency band, a higher number of link layer retransmissions are required to successfully transport a packet across the wireless channel. Moreover, the wireless channel access delay in xG networks depends on the operation frequency, the interference level, and the medium access control protocol. These factors influence the RTT of a TCP connection. Therefore, based on the frequency of operation, RTT and packet loss probability observed by a TCP protocol will vary. Hence, transport protocols need to be designed to adapt to these variations.

The operation frequency of a cognitive radio in xG networks may vary from time to time due to spectrum handoff as explained in Section 6. When an xG terminal changes its operating frequency, this results in a finite amount of delay before the new frequency can be operational. This is referred to as the *spectrum handoff latency*. The spectrum handoff latency can increase the RTT, which leads to retransmission timeout (RTO). Conventional transport protocols can perceive this RTO as packet loss and invoke its congestion avoidance mechanism resulting in reduced throughput. To eliminate the adverse effects of spectrum mobility, transport protocols need to be designed such that they are transparent to *spectrum handoff*.

9. Cross-layer design

The communication challenges outlined above necessitate new communication protocols to be designed for spectrum-aware communication in xG networks. As explained before, the performance of xG networking functionalities directly depend on the properties of the spectrum band in use. This direct relationship necessitates a cross-layer design in the entire xG networking protocol stack. In particular, the effects of the selected spectrum band and the changes due to spectrum mobility need to be carefully considered in the design of communication protocols. Moreover, the spectrum management functionalities such as spectrum sensing and spectrum handoff should work in collaboration with the communication protocols. Based on this motivation, in the following sections, we overview the challenges for the cross-layer design in xG networks.

9.1. Cross-layer challenges in spectrum management

The dynamic nature of the underlying spectrum in xG networks necessitates communication protocols to adapt to the wireless channel parameters. Moreover, the behavior of each protocol affects the performance of other protocols. For example, different medium access techniques used in xG networks, directly affect the round trip time (RTT) for the transport protocols. Similarly, when re-routing is done because of link failures arising from spectrum mobility, the RTT and error probability in the communication path change accordingly. The change in error probability also affects the performance of the medium access protocols. Consequently, all these changes affect the overall quality of the user applications.

The spectrum management function cooperates with the communication layers, as shown in Fig. 2. In order to decide the appropriate spectrum band, the spectrum management requires the information regarding QoS requirement, transport, routing, scheduling, and sensing. Hence, these interdependencies among functionalities of the communication stack, and their close coupling with the physical layer necessitate a cross layer *spectrum management* function which considers medium access, routing, and transport, and application requirements as well as available spectrum in the selection of the operating spectrum.

9.2. Cross-layer challenges in spectrum handoff

Spectrum handoff results in latency, which affects the performance of the communication protocols. Thus, the main challenge in spectrum handoff is to reduce the latency for spectrum sensing. The spectrum handoff latency has adverse effects on the performance of transport protocols. Moreover, during spectrum handoff, the channel parameters such as path loss, interference, wireless link error, and link layer delay are influenced by the dynamic use of the spectrum. On the other hand, the changes in the PHY and MAC channel parameters can initiate spectrum handoff. Moreover, the user application may request spectrum handoff to find a better quality spectrum band.

As shown in Fig. 2, the spectrum mobility function cooperates with spectrum management function and spectrum sensing to decide on an available spectrum band. In order to estimate the effect of the spectrum handoff latency, information about the link layer and sensing delays are required. Transport and application layer should also be aware of the latency to reduce the abrupt quality degradation. In addition, the routing information is also important for the route recovery using spectrum handoff. For these reasons, the spectrum handoff is closely related to the operations in all communication layers.

9.3. Cross-layer challenges in spectrum sharing

The performance of spectrum sharing directly depends on the spectrum sensing capabilities of the xG users. Spectrum sensing is primarily a PHY layer function. However, in the case of cooperative detection, xG users should use ad hoc connection for exchanging sensing information, which necessitates a cross-layer design between spectrum sharing and spectrum sensing. It is clear that the performance of communication protocols depends on spectrum sensing, i.e., getting information about the spectrum utilization. Two major challenges exist in this aspect.

The first challenge is the interference mitigation. While interference occurs at a receiver, spectrum scanning alone only provides information about transmitters [33]. Hence, cooperative techniques that necessitate transmitters to consider both their interference to other users and the interference at their receivers are required. The superiority of cooperative techniques in terms of system performance has already been demonstrated in many studies [15,29,40,71]. On the other hand, such a collaboration increases the communication overhead and may lead to overall system performance degradation when channel capacity or energy consumption is considered. Consequently, effective spectrum sharing techniques that enable efficient collaboration between different xG nodes in terms of spectrum sensing information sharing are required.

The second challenge about spectrum sensing is that the whole spectrum cannot be sensed all the time. More specifically, due to the huge range of spectrum foreseen for xG networks, a significant amount of time is required to sense the whole spectrum. Since sensing consumes energy this process has to be carefully scheduled. As a result, it may not be practical to assume that a node has an accurate knowledge about the spectrum at all times. Moreover, current radio technologies prevent continuous spectrum sensing if only a single radio is deployed on a device. During communication, spectrum sensing has to be stopped to switch to the required channel and perform communication. Hence, this operation requires cross-layer interaction between the physical layer and the upper layers. More specifically, communication attempts need to be coordinated with spectrum sensing events. As an alternative, the effect of using multiple radios has been investigated in [54], where a two transceiver operation is considered such that a transceiver always listens to the control channel for sensing. This operation improves the system performance, however, the complexity and device costs are high.

The spectrum sharing techniques discussed in Section 7 decouples spectrum allocation and spectrum sensing. In decentralized cognitive MAC (DC-MAC) scheme proposed in [72], a cross-layer approach for spectrum allocation and spectrum sensing is considered. Contrary to many work, in [72], limited spectrum sensing is addressed, where only a portion of the whole spectrum can be sensed. Moreover, spectrum sensing is jointly performed with spectrum allocation and application layer such that the node senses a portion of the spectrum only if it will allocate a channel due to a request from the application layer. First, an optimal approach for channel allocation is provided followed by a greedy suboptimal approach. A node is assumed to be able to sense one channel among N possible channels. Through performance evaluation, it is shown that the greedy approach closely approximates the optimal solution. Moreover, this solution is also robust to inaccuracies in spectrum sensing and limited knowledge.

9.4. Cross-layer challenges in upper layers

Since available spectrum bands in xG networks with multi-hop communication are different for each hop, spectrum sensing information is required for topology configuration in xG networks. Moreover, a major design choice for routing in xG networks is the collaboration between routing and spectrum decision. If the optimal route from an xG user to another results in interference to the primary users, end-to-end latency or packet losses can be affected along the route due to this interaction. To mitigate the degradation, multiple spectrum interfaces at intermediate nodes may be selected. Therefore, end-to-end route may consist of multiple hops traversing different spectrum bands.

Finally, re-routing needs to be performed in a cross-layer fashion. If a link failure occurs due to spectrum mobility, the routing algorithm needs to differentiate this failure from a node failure. Furthermore, intermediate xG users can perform re-routing by exploiting the spectrum information available from spectrum sensing functionality select better routes method.

Due to the dynamic frequency of operation, the RTT and packet loss rates vary in xG networks, which leads to variations in packet transmission delay. Moreover, medium access schemes introduce access delay. All these factors influence the round trip time of a connection, which in turn affect the performance of transport protocols. Moreover, the latency associated with a *spectrum handoff* increases the instantaneous RTT of the packet transmission. Consequently, transport protocols for xG networks should be designed in a spectrum aware approach that introduces cooperative operation with the other communication layers.

10. Conclusions

xG networks are being developed to solve current wireless network problems resulting from the limited available spectrum and the inefficiency in the spectrum usage by exploiting the existing wireless spectrum opportunistically. xG networks, equipped with the intrinsic capabilities of the cognitive radio, will provide an ultimate *spectrum-aware* communication paradigm in wireless communications. In this survey, intrinsic properties and current research challenges of the xG networks are presented. We investigate the unique challenges in xG networks by a bottom-up approach, starting from the capabilities of cognitive radio techniques to the communication protocols that need to be developed for efficient communication. Moreover, novel spectrum management functionalities such as spectrum sensing, spectrum analysis, and spectrum decision as well as spectrum mobility are introduced.

The discussions provided in this survey strongly advocate spectrum-aware communication protocols that consider the spectrum management functionalities. This cross-layer design requirement necessitates a rethinking of the existing solutions developed for wireless networks. Many researchers are currently engaged in developing the communication technologies and protocols required for xG networks. However, to ensure efficient spectrum-aware communication, more research is needed along the lines introduced in this survey.

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