Challenges Implementing Internet of Things (IoT) Using Cognitive Radio Capabilities in 5G Mobile Networks

Konstantinos Katzis and Hamed Ahmadi

Abstract This chapter aims at identifying the main design and operation constraints, that smart environments are expected to experience within a 5G wireless/mobile network and how these constraints can be addressed using cognitive radio networks. This chapter first provides a general description of 5G wireless/mobile networks and stresses their role in the future wireless communications with emphasis given on smart environments. Then, the smart environments are presented based on their architecture characteristic and the applications associated with their operation. In addition, an overview of various current standards related to IoT applications is presented followed by the concept of cognitive radio networks and the available experimental platforms stressing the benefits of employing this technology in the future 5G wireless/mobile networks. Finally, the research challenges associated with integrating 5G wireless/mobile networks and IoT are outlined.

1 Introduction

Future communications envisage a plethora of wireless, connected, sometimes 'smart' devices that will communicate in real time with each other. This is referred to as the 'Internet of Things'. Such devices will not only be used for human interaction alone, but it is expected that there will be a significant demand for machine type communications. The number of such devices is expected to rise in the order of tens of billions by 2020 [1], suggesting that there will be a constantly increasing demand for reliable, wireless connections. These connections are

K. Katzis (✉)
Department of Computer Science and Engineering, European University Cyprus,
6 Diogenes Street, Engomi, Nicosia 2404, Cyprus
e-mail: K.Katzis@euc.ac.cy

H. Ahmadi
School of Electrical and Electronic Engineering, University College Dublin,
Belfield, Dublin 4, Ireland

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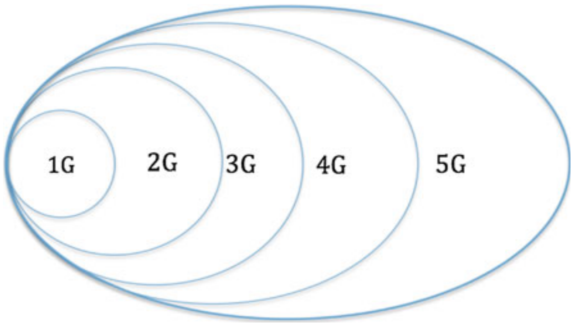

Fig. 1 5G is expected to feature voice, data, always on connectivity—everything that 1G to 4G offered so far but better

expected to achieve latencies low enough that the radio interface will not be the bottleneck.

Discussion around 5G indicates that there are two schools of thought regarding its operational characteristics and requirements [2]. The first view presents a service-led view, which sees 5G as a superset of 2G, 3G, 4G, Wi-Fi and other wireless standards, integrating greater coverage and always-on reliability. The second view foresees greater data speeds and significant reduction in end-to-end latency. However, these views support contradictory requirements, which further implicate the process of defining 5G requirements. In any case, people have high expectations regarding the services that 5G will offer and they expect no less that the services they've received so far ranging from simple voice in 1G to high data speeds in 4G (illustrated in Fig. 1).

Various scenarios have been coined by numerous researchers in academia and industry in an effort to accurately represent the requirements of such a large-scale, complex system. Visualizing the future smart environment that is discerned by polymorphic characteristics, future wireless networks might not necessarily require a 'gigabit experience' across their coverage but users might operate at lower data-rates depending on the application in reference. Nevertheless, both user data-rates and network capacity consist the main driver for technological evolution and both academia and industry are working towards the development of high capacity and high data-rate wireless networks. Further to the higher capacities and speeds that future wireless networks are called to support, they will also be required to provide better performance, cell densification and access to new, broader carriers in new spectrum.

Part of the capacity growth can be addressed with the existing 3G/4G systems, but by 2020, it is expected that limits will be reached and 5G technologies will be needed. Nokia [3] and Ericsson [4] introduced a number of new services and use cases that will drive the technology such as mobile broadband, mobile media, connected and self-driving cars, heavy machinery controlled over distances, IoT and finally massive machine type communications (very large number of meters/sensors embedded in the field). These use-cases define the operation parameters that 5G wireless networks will be required to fulfill. As illustrated in Fig. 2, these parameters are: throughput, capacity, number of devices, cost, latency

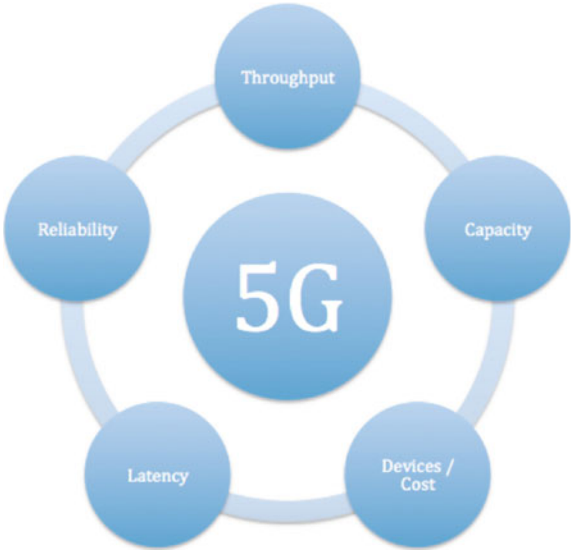

Fig. 2 5G Main operation parameters

and reliability. Like any other wireless network, performance is subject to spatial and temporal variations.

Depending on the application, optimization is required focusing on multiple parameters or just a single parameter with one key performance indicator (KPI). 5G networks are requested to support such diversity in performance optimization in a flexible and reliable way. More specifically, 5G is expected to fulfill the following key performance indicators (KPI's) [5]:

- Provide 1000 times higher wireless area capacity
- Enhance service capabilities
- Save up to 90 % of energy per service provided
- Reduce the average service creation time cycle from 90 h to 90 min
- Create a secure, reliable and dependable Internet with a "zero perceived" downtime for services provision
- Facilitate highly dense deployments of wireless communication links to connect over 7 trillion wireless devices serving over 7 billion people.
- Enabling advanced user-controlled privacy.

To satisfy the KPI listed above, a new architecture along with new communication technologies, and new hardware will be required. The requirements that this architecture is requested to fulfill are listed below [2]:

- 1–10 Gbps connections to end points in the field
- 1 ms end-to-end round trip delay (latency)
- 1000x bandwidth per unit area
- 10–100x number of connected devices
- (Perception of) 99.999 % availability

- (Perception of) 100 % coverage
- 90 % reduction in network energy usage
- Up to 10 years of battery life for low power, machine-type devices

Technically it is difficult for a single platform to address all 8 requirements simultaneously. This is not a major problem for the future of 5G. As discussed in [2], it is not necessary to address all 8 requirements since no use-case, service or application has been identified that requires all eight performance attributes across an entire network. Furthermore, 6 out of the 8 requirements are not generation-defining attributes. They are mostly considered as economic and business case decisions. More specifically, availability and coverage as well as bandwidth per unit area and number of connected devices are expected to be met by networks that include 5G as an incremental technology, but also require continued support of pre-existing generations of network technology. In addition, reduction in energy usage related to the network operation and improving battery life, consist an important economic and ecological target for future wireless technologies. Again, the level of improvement for the reduction of power consumption will depend mostly on the operators and at what level they will make use of the 5G technologies replacing some of the existing network equipment.

For smart environments, all 8 requirements are important and must be considered, but each requirement will receive a different level of priority.

2 Smart Environments in 5G Wireless Networks

Some say that 5G will arrive by 2020 and will be able to handle 1000 times more mobile data than today's cellular systems. It is also expected that 5G will become the backbone for Internet of Things (IoT) linking up myriads of fixed and mobile devices, thus forming an ecosystem of smart devices. This section defines what smart environments are and what are the architectures currently available/under consideration.

2.1 Defining Smart Environments

These smart devices are expected to form the future smart environments [6] which will be characterized by three main components [7]: the first one involves smart objects interacting with the environment they live in, the second component comprises of the interconnection of smart objects with the network and thirdly the procedure of life-logging in this interconnected smart environment.

Smart environments such as smart homes, smart offices, smart schools, smart cars and so on, aim to provide computing and communication services in a convenient, seamless, and enjoyable way. To achieve this, users are expected to be able to remotely access and control such devices and obtain useful information about their current state, through various services resulting from the integrated cooperation of possibly heterogeneous communication-enabled smart devices [8]. This digital eco-system has been formed in the last couple of decades and it is consisted of computers, smartphones, sensors, cars, appliances, buildings, etc. These devices will gradually become "smarter" with advanced communicating and cognitive capabilities enabling them in detecting the nature of the environment they are living in. Data transfer patterns for such devices are expected to fundamentally differ from existing 'human-to-human' (H2H) internet. M2M communications will feature low-bandwidth, upload-biased traffic. Many M2M critical applications are expected to deliver and process information in real time, whereas power limited nodes will have to be extremely low-power or self-powered (e.g. solar powered) devices [9].

Research and academic institutions are working towards the composition of such devices that will have the ability to form a sophisticated, ad hoc and cooperative computational and communications structure operating on technological and human-centered perspectives. The concepts and technologies that IoT is based on, have been available for some time now in one form or another. Concepts, some of which are currently available, are machine-to-machine (M2M) communications, Radio Frequency Identification (RFID), Location based services (LBS), Lab-on-chip (LOC) sensors, augmented reality (AR), robotics and vehicle telematics [1]. All these technologies are expected to form an ecosystem of smart environments, which will feature some sort of communication intelligence running data over a mix of wired and wireless networks with and without IP. To understand the smart environment system architecture and the network requirements behind it, it is important first to picture how smart objects and devices interact with the network infrastructure in order to be constantly operational.

As illustrated in Fig. 3, the smart environment ecosystem is expected to provide connectivity to a wide range of devices through a large number of existing technologies. From 3G, 4G to Wi-Fi and Wi-Max, and from ZigBee to RFID, the

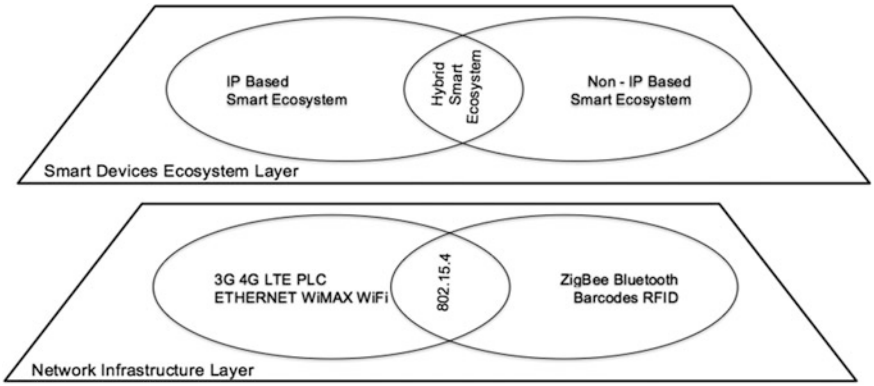

Fig. 3 Smart environment ecosystem operating on current network infrastructure

current infrastructure is called to become a single unified platform that the smart environment ecosystem is expected to evolve.

Multi-service environments pose a series of research and technical challenges for future wireless networks. Some of these challenges are: how users can discover services when moving in new environments and how these service interfaces can be described to allow seamless operation for users moving from one environment to the other. Another one is how smart objects, part of the smart environment and with limited capabilities, are able to connect to a wireless or wired network with and without IP [7]. Are there enough resources to support seamless, speedy, uninterrupted operation of users in multi-service smart environments? Is the current pool of wireless technologies adequate to support this vision or is it necessary that these services must be supported from the 5G mobile networks? According to Zhiguo Ding [6], what currently stands in the way of the IoT are disconnected systems, which require a unified framework for seamless connection. 5G is a good opportunity to provide this unified framework in order to prevent fragmented and vulnerable networks.

2.2 Smart Environment Architectures and Applications

Smart home is one of the most popular smart environments. Smart homes accommodate a variety of smart applications which include, smart energy metering/consumption, smart multimedia and smart home healthcare. Each of these applications requires different services from the network. For example, smart multimedia system needs high downstream data rate while smart energy application that reports the energy consumption to the provider transmits a small upstream amount of data. To satisfy these requirements different network architectures have been proposed in the literature for smart homes.

Studying the network architecture of smart homes is important because they have the biggest market among the smart environments and the network architecture of smart homes can also be used for other smart environments that have similar features like smart offices and smart schools. Therefore, we review some of the proposed network architectures for smart homes.

A cognitive gateway centric architecture is proposed in [10] for a smart home network. In this architecture there are multiple subnets, which are managed and connected to the outside world through the proposed cognitive gateway. The main subnets that are considered in this architecture are body areas, personal areas and local areas. The differences of these subnets are their range, power limitations, required rate and their technology. The authors of [11] envision a cloud-based architecture for the IoT-based smart environments. This architecture encompasses a wide range of devices from low-cost/low-power to compute-rich/high-performance ones. Other bases of the architecture in [11] are ultra-scalable connectivity and cloud-based mass device management which support a mix of legacy and new services and devices. This architecture considers gateways/aggregation points that bring the installed short-range sensors online and provide interworking with different wireless technologies. In other words, the aggregation points are performing the same task as the cognitive gateway does in [10].

A Long Term Evolution-A (LTE-A) oriented architecture for infrastructure based smart environments is proposed in [3]. The authors propose making use of user and/or operator deployed femtocells (Home evolved NodeB, H-eNB) to provide coverage for machine type communication (MTC) devices and absorb their traffic. This looks like a more general version of the proposed architecture in [10]. Additionally in [12] the authors have foreseen a mid-level gateway known as H-eNB gateway which directs the traffic of all H-eNBs to the serving gateway, while the macro-eNB that is directly connected to the serving gateway. The proposed architecture in [12] enable the interconnection with non-3GPP access points by connecting the trusted non-3GPP Access Points (APs) to H-eNB gateway. The APs exchange data through the non-3GPP interface with the served MTC devices, while they appear like H-eNBs to the H-eNB gateway. This reduces the latency of communications between the APs, and increases the scalability. Figure 4 shows the proposed architecture in [12].

Smart grids belong to a class of smart environments that the considered architectures for smart homes cannot be easily applied to them. Unlike smart homes, smart grids cover a large geographical area. The authors of [13] envision an architecture that consists of Neighborhood Area Network (NAN), Building area

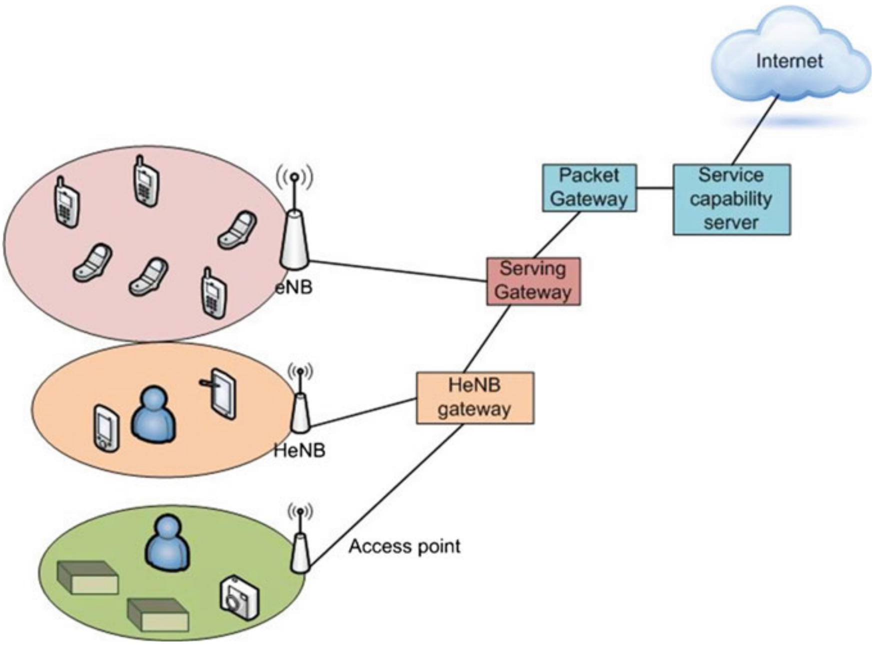

Fig. 4 A candidate architecture for smart home environment

network (BAN), and Home Area Network (HAN). In this architecture HAN connections are wireless over the unlicensed bands using zigbee or Bluetooth. Every building connected to the smart power grid has its own BAN that consists of a number of apartments (HANs). HANs are connected to the BAN gateway by wire or wirelessly. For the wireless connection LTE is considered as the main candidate. A number of BANs create a NAN. The BANs in this architecture are connected to the NAN gateway wirelessly using LTE.

3 Smart Environment Resources

Many of the devices in smart environments are powered by batteries and regardless of how accessible these devices are, changing their batteries is costly. This operation will cost more if the number of the devices is huge and they are in remote places, for example highways equipped with lot of smart sensors. Therefore, the energy efficiency of machines and the communication protocols significantly affects the operational costs of the network for the smart environments.

Smart environments depending on their applications use different spectrum bands. End-user deployed smart environments (mainly smart homes) normally consist of short-range devices that transmit on the industrial, scientific and medical (ISM) band. However, for time sensitive applications like smart health care at home technologies that guarantee a maximum delay are considered (for instance LTE). These technologies/standards use licensed frequency bands. Smart grids, smart cities and other wide range smart environments require longer distance coverage. Some portion of this is covered by wired connected access points while for some other parts long distance wireless connection is a must. Cellular communication using the licensed spectrum is one of the main candidates while cognitive communication on TV white space is another promising solution. Cognitive radio technology can use the underutilized spectrum of TV bands for opportunistic radio transmission. Although this technology does not require paying for the expensive spectrum license, it requires avoiding the interference with the licensed users [14].

Computational power is a resource that significantly affects the power and spectrum requirements of a smart environment. Cheaper devices normally have lower computation power, which means that they have to transmit raw data to the nodes that can process the data to information. Although this is not necessarily a negative point, the designers of smart environments must carefully select their equipment. A fiber-connected smart home can easily benefit from various cloud services while a smart sensor-and-controller unit in a remote location should be able to balance the energy that it spends on processing the collected data and transmitting them.

4 Cognitive Radio Networks and Platforms

One of the main forces pushing towards the deployment of cognitive radio (CR) devices and networks is what appears to be spectrum shortage. Current radio technologies employ portions of the radio spectrum through long-term licenses and it is impossible for new users to make use of them. Although the radio spectrum seems to be highly occupied with hundreds of bands allocated to various companies, organisations etc., spectrum scarcity largely depends not on how many frequencies are available but on the technologies that can be deployed and how these frequencies can be utilised.

Currently there is a high demand for high-speed broadband technologies. These technologies require a substantial radio spectrum for their operation. Furthermore, operating frequencies must be able to support a mobile, heavily loaded, urban propagation environment such as we find in 3G and 4G technologies. Alternatively, there are technologies such as IEEE802.11 (Wi-Fi) and IEEE802.16 (WiMax), which pose as examples of modern broadband wireless networks. Both of them operate in the ISM bands. These bands are internationally reserved for purposes other than telecommunications, which can sometimes cause electromagnetic interference with communication systems that are using them. Nevertheless, using advanced mitigation interference techniques, it has been possible to make the most of these frequency bands and enjoy fast wireless broadband connectivity. Since these frequencies have been free to use (unlicensed), Wi-Fi has grown to become a cheap yet fast and reliable alternative to wired networks allowing connectivity to the internet or even locally for devices such as laptops, smartphones, TVs, DVD players, cameras etc.

It is therefore clear that the technological market is currently driving the research and development of communications towards an ever more wireless, high speed, high capacity types of network that will be able to support smart environments featuring polymorphic characteristics depending on the application/use-case. The bad news for the wireless community is that the spectrum map is highly congested and it is almost impossible to increase the bandwidth of the existing wireless standards. The good news is that recent studies showed that the spectrum map is also underutilized [15]. The underutilization of the electromagnetic spectrum lead to the use of the term “spectrum holes” which is defined in [16] as:

“A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user.” Spectrum holes are also presented in [17] as potential opportunities for non-interfering use of spectrum and can be considered as multidimensional regions within frequency, time, and space. This is provided that the CR systems are able to sense these holes within a given range of frequencies. Spectrum holes are classified into three categories. The black spaces, the grey space and the white spaces [18]. Black spaces represent the spectra that are occupied by high power local interferers for some of the time. Furthermore, grey spaces refer to partially occupied spectra by low power interferers. Finally, white spaces are free of interferers except from any ambient noise in the area such as thermal noise, transient reflections, impulse noise and broadband thermal noise [18].

Detecting spectrum holes can be tricky and requires capable hardware and software to carry out this task. Some of the main issues regarding spectrum hole detection are listed in [18] as the environmental factors, exclusive zones and prediction algorithms. Environmental factors such as path-loss can reduce significantly the received signal power whereas shadowing can cause fluctuations about the path loss by a multiplication factor. In [17], authors propose quantile models for uncertain probability distributions (e.g. for shadowing) while secondary radio positions have been considered unconstrained. From the results, assuming multi-user settings, the degree of shadowing correlation has proven highly uncertain. Authors suggest that it might be easier to achieve a firm consensus regarding the correlation of shadowing across different frequencies for a single radio than it is to achieve a consensus regarding the shadowing correlation across users. "Weighted Probability of Area Recovered" (WPAR) is the proposed metric that employs a discounting-function to weigh the probability of recovering area at a given distance away from a single primary transmitter.

Some issues that are addressed in [17] disclose areas of spectrum hole detection that must be addressed in the future. These are the cooperative sensing strategies, the tradeoffs between the time-overheads and space-overheads. In addition, how the signal to noise ratio (SNR) walls must be understood in the context of the proposed WPAR algorithm.

The possibility of employing new technologies for exploiting the spectrum holes in order to fulfill the requirements of future wireless mobile communications has been enticing and it formed the basis for developing future cognitive radio networks.

4.1 Cognitive Radio Definition

There are numerous definitions of Cognitive Radio (CR) and since this area is still under development, more definitions are expected to emerge. CR has been defined by Mitola [19] and later by Haykin [18] as an intelligent wireless communication system that is aware of its surrounding environment and uses the methodology of understanding by building to learn from the environment and adapt its internal states based on new statistical variations. Another definition [15] states that a CR uses intelligent signal processing (ISP) at the physical layer of a wireless system and this is achieved by combining ISP with software defined radio (SDR). The CR makes use of its flexible radio and intelligence in order to adapt to fast changing environments, allows new operating requirements set by the user and follows requirements dictated by regulations that safeguard the requirements of other radio users sharing the spectrum environment.

These characteristics, enable CR devices to determine which portions of the spectrum are available, detect the presence or absence (spectrum holes) of licensed (primary) or unlicensed CR (secondary) users. CR users are capable operating in a licensed band (spectrum sensing) by choosing the best available channel and coordinate access to this channel with other users. Secondary CR users are required to vacate the channel when a licensed user is detected. Cognitive radios can offer numerous advantages compared to the legacy wireless and mobile networks. They can provide more efficient spectrum usage, ensure connectivity while constantly monitoring their surroundings for spectrum availability, they are able to dynamically tune to spectrum, based on the location and the time of day, they have reduced power consumption etc. A radio can be as intelligent and flexible as the current technology permits. CR is expected to evolve through time until we reach the full cognitive radio that Mitola described in [19].

The cognitive radio operation is known as a cognitive cycle and it is presented as a series of processes that are executed by the cognitive engine in order to fulfill a set of requirements. Mitola [19] first proposed the CR cycle. Simon Haykin also presented his version of a CR cycle in [18]. Figure 5, illustrates a simple version of the cognitive cycle that runs continuously on the cognitive engine to observe spectral opportunities, examine these opportunities, decide what to do, and act to explore the best opportunities [20].

First step in the cycle is sensing. The CR must feature advanced awareness capability with respect to the transmitted waveform, RF spectrum. This will be achieved by measuring the electromagnetic activities due to the various radio transmissions over a range of spectrum bands and to capture useful information related to these bands. In order to save energy, a CR must make real-time decisions about which bands to sense, how often, and for how long. Second step is the spectrum analysis, which identifies potential spectral opportunities in the surrounding radio environment, also known as spectrum holes. Third step is to decode the operating parameters based on the analysis completed in the previous step and decide the set of transmission parameters to be adapted in the fourth step. More

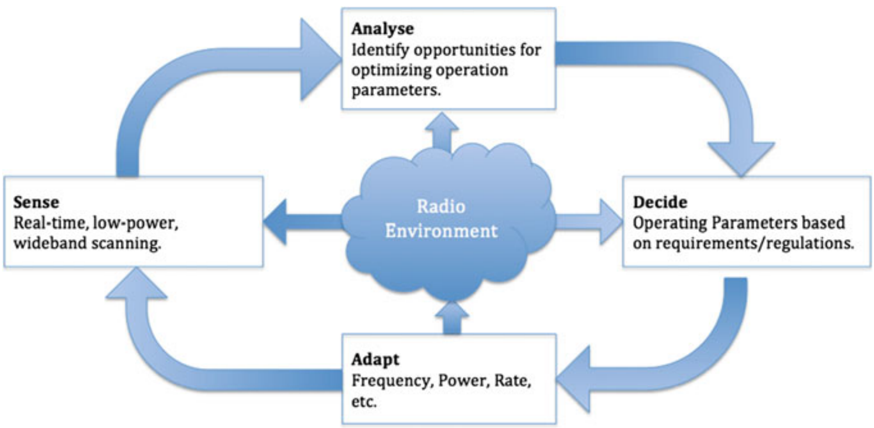

Fig. 5 Cognitive radio functional cycle

specifically, a cognitive radio utilizes the information gathered regarding the spectrum bands identified as available spectral opportunities to define the radio transceiver parameters for the upcoming transmission(s) over such frequency bands. The set of transceiver parameters to be decided are subject to the limitations of the underlying transceiver architecture. Operating parameters might involve the communication network, geography, locally available services, power availability, user needs, language and security policy.

A good performing CR is expected to:

1. Have low false alarm probability: Maximize secondary (CR) users
2. Low missed detection probability: Minimize primary (legacy) users experienced interference
3. Responsive in taking decisions in a limited amount of time (before interfering levels change again)
4. Form a Cognitive Radio Network (CRN) that can support an efficient secondary user network structure centralized or decentralized (distributed).
5. Have good integration with the upper layers.

Moving from a fully regulated spectrum to a loose and perhaps fully unregulated, requires to first convince the local regulatory bodies, that existing licensed systems will not be disturbed by CR devices. After all, this is a one-way street towards finding capacity for all these wireless devices and applications. Secondly it is necessary to present the benefits to the licensed service providers when they share their frequency bands. FCC in USA, led by its chair Michael Powell has been working to update the way spectrum is managed. This effort is based on three main strands [21]:

1. Spectrum reallocation: reallocation of bandwidth from government and other long-standing users to new services such as mobile communications, broadband internet access and video distribution.
2. Spectrum Leases: Permitting existing licensees to use their spectrum for new or hybrid services or by leasing their spectrum to third parties.
3. Spectrum Sharing: This is the allocation of an unprecedented amount of spectrum that could be used for unlicensed or shared services.

Recently, there have been examples where regulators decided to change the way they manage various radio spectrum bands and allow new innovative wireless technology to deliver high-speed broadband communications. For example, FCC has recently announced it will adopt new rules and policies to make 150 MHz of spectrum available between 3550 and 3700 MHz for mobile broadband and other commercial use, which was previously locked up by the U.S. Department of Defense (DoD) [22]. It is expected that consumers, businesses, and government users will benefit from these changes in the spectrum allocation as the new rules proposed, will support protect incumbent radar systems from interference but most importantly it will make additional spectrum available for flexible wireless broadband use, leading to improved broadband access and performance for consumers. Furthermore, Ofcom (UK) announced that it will allow a new wireless technology access to the unused parts of the radio spectrum in the 470–790 MHz frequency band. Ofcom refers to the TV band and more specifically to the TV White Spaces (TVWS). It is expected, that new technology, known as white spaces devices, will share this band with the existing uses, Digital Terrestrial Television (DTT), including local TV, and Programme Making and Special Events (PMSE), including in particular wireless microphone users [14]. Related IEEE standards that are currently under development and look into developing cutting edge technologies to take advantage of this spectrum are IEEE 1900 coordinated by IEEE DySPAN-SC (formerly known as Standards Committee 41) [23] as well as IEEE802.11af [24], IEEE802.22 [25] etc.

4.2 CR Platforms and Testbeds

Cognitive Radios (CRs) and Cognitive Radio Networks (CRNs) can be used as the main platform for implementing a 5G wireless/mobile network. CRNs can support the polymorphic requirements of the future wireless/mobile applications and they can support IoT implementation.

Current research and development activities in the area of CRs, have been pushing towards the development of different versions of CR engines running on different types of platforms. In all cases the aim is to verify whether CRs disturb the primary (legacy) users or not as well as to prove its potential in terms of the overall system performance. The various types of CR platforms available ensure that there is enough competition to drive the research and development community into developing the best possible platform. Current CR platforms still have a long way to go to achieve a fully cognitive radio. This is because of the hardware limitations posed by the current technology as well as the spectrum sharing restrictions posed by the local spectrum regulator. Nevertheless, CRs have come a long way thanks to the reconfigurable platforms that are currently available in the market. The platforms have been based on digital radio and computer software. In fact, software CR platforms can be defined as the evolution of Software Defined Radios (SDRs). SDRs have been around for more than 20 years. They were first introduced in the analogue modem industry where manufacturers implemented the modulating and de-modulating algorithm in software rather than in hardware, thus enabling users to upgrade/change the communication standards using the existing hardware. SDRs nowadays have become faster, more flexible and in general better in utilizing the radio spectrum and allowing real-time reconfigurability. They have also improved compatibility and coexistence with different wireless standards. This has been achieved by implementing the CR functionality on a software-based platform, which performs the modulation and demodulation of the radio signals. Currently there is a considerable number of available software and hardware CR platforms mainly used for experimental purposes. Some of the main software platforms are: GNU Radio, IRIS, ASGARD. Combining these with the appropriate hardware RF front such as USRP2, BEE2, VESNA or WARP it is possible to create what is known as a CR testbed [26].

CR testbeds such as XG Program, CREW, VT-CORNET, VESNA, IRIS and FP7-SAMURAI have been designed and deployed in the last few years to evaluate and improve the overall performance for cognitive radio networks. Cognitive radio research community requires that these testbeds are equipped with appropriate capabilities to allow examining complex interaction between physical and network layers. In order to achieve this, cognitive radio testbeds must employ [27]:

1. Real-time baseband processing for spectrum sensing.
2. Agile transmission with high computational throughput and low latency.
3. Integration of physical and network layers on embedded processors.
4. Sufficiently wide bandwidth radio front end with spatial processing capabilities.
5. Central processing of information exchange between multiple radios for controlled physical and network layer development and analysis.
6. Ability to perform controlled experiments in different propagation environments such as indoors or outdoors.

The testbeds listed above have surfaced several potential issues concerning the design and implementation of the cognitive radio networks [26]. In order to achieve an optimal configuration, it is necessary to maximize the multiple objective fitness function [28, 29] that quantifies the advantages of choosing a given system (and network) configuration with respect to others. Such fitness function shows how well a given system configuration performs towards achieving its optimum operation [26].

Cognitive Radio Testbeds provide the means for evaluating CR systems and in extend future 5G networks and implementation of IoT/M2M/etc. Designing and implementing a testbed for 5G networks can be challenging. It requires well defined requirement analysis of the IoT/M2M/etc. application is intended for looking at availability, high throughput, reliability, energy efficiency, etc. Testbeds are based on software and hardware CR platforms that can play an important role towards the establishment of cognitive radios delivering 5G networks. They can demonstrate the operation of future 5G networks delivering IoT/M2M/etc. and its impact on legacy systems or other CRNs, but most of all they are contributing towards raising the confidence of regulators to proceed with the legal framework and allow potential use of the spectrum by CR enabled systems.

5 Current Standards and Application Scenarios

After introducing smart environments, their communications system architecture and their required resources, in this section we discuss the communication standards for these applications. Different communication standards are used based on the types of devices in the smart environment and their resources and limitations.

5.1 Indoor Smart Environments

In this type of smart environment, the devices are operating on ISM band and therefore spectrum price is not a challenge. However, congestion and efficiency will become an important issue. Since energy is an important issue for many of machine type communication devices standards, ZigBee and Bluetooth have taken that into account, while standards like Wi-Fi where more successful for the devices that needed higher transmission rate with lower energy limitations.

Bluetooth over IEEE 802.15.1 standard is designed for short-range transmission between cheap devices to replace cables [30]. This includes computer peripherals like mice, keyboards, and headsets. Bluetooth range is about 10 m and operates in the 2.4 GHz band. Bluetooth networks are master-slave, where slaves communicate only with their masters in a peer-to-peer fashion. A master device and one or more slave Bluetooth devices create a *piconet* and a collection of operational overlapping piconets form a *scatternet* that enables the information to flow beyond the coverage area of a piconet.

ZigBee over IEEE 802.15.4 supports low rate short-range communications for devices that are simple and low cost. ZigBee provides self-organized multi-hop and reliable mesh networking with long battery lifetime [30]. A ZigBee network has full-function and reduced-function devices. While full-function devices (FFD) can talk to other FFDs and reduced-function devices (RFD), RFDs can also communicate with FFDs. RFDs are normally ZigBee devices that are performing very simple operations. ZigBee considers a star network where an FFD can become its coordinator.

Wi-Fi over IEEE802.11 is one of the most popular communication standards. It enables broadband internet connectivity when the users are connected to an access point. Operating on 2.4 and 5 GHz bands, Wi-Fi supports both peer-to-peer and star topologies while its coverage area can extend to 100 m. As expected, its high data rate and larger coverage area comes with a price which is higher energy consumption.

All these standards have different applications in smart environments. While Wi-Fi is mainly used for the applications like wireless surveillance cameras that require high data rate and are connected to power supplies, ZigBee and Bluetooth are more popular for power-limited applications. The low power consumption of ZigBee devices and the number of devices that each smart environment can accommodate made it a promising technology for low-range smart applications like smart homes, smart offices and smart production lines [31]. Table 1 summarizes some of the main characteristics of these protocols.

Table 1 Bluetooth, Zigbee and Wi-Fi parameters comparison

Standard	Bluetooth	ZigBee	Wi-Fi
Frequency band	2.4 GHz	868/915 MHz, 2.4 GHz	2.4, 5 GHz
Nominal range (m)	10	10–100	100
Max signal rate	1 Mbps	250 Kbps	54 Mbps
Max number of cell nodes	8	65,000	2007

5.2 Outdoor/Long-Range Smart Environments

Cellular system is one of the main long distance communication technologies. However, its higher costs and energy requirements limited its applications in Machine to Machine (M2M) communications. 3GPP Long Term Evolution (LTE) standard release 12 introduced a new low complexity device category ("Cat-0"). This defines a set of reduced requirements enabling these devices to achieve lower complexity and cost [32]. However, the energy consumption and supporting the massive number of M2M are the challenges yet to be addressed by LTE-M.

Global System for Mobile communications (GSM) is attracting the attention of M2M community [33]. GSM is deployed almost all over the world, supports mobility and it has low energy consumption. These interesting economical and technical features make it a promising technology for M2M and smart environments. However, GSM and its extension for packet-switched data transmission, the General Packet Radio Service (GPRS), are designed for phone calls, web browsing and streaming applications, which are different from low-rate M2M applications.

IEEE 802.11af is the standard defined for spectrum sharing among unlicensed white space devices and licensed services in TV white space [34]. This standard which is also known as Super Wi-Fi or WhiteFi protects the licensed users by applying a geolocation database mechanism. IEEE 802.11af envisions a geolocation database that stores the frequencies and operating parameters of white space devices by their geographic location to fulfill the regulatory requirements. For smart environment applications, although IEEE 802.11af has lower coverage range compared to cellular solutions, its lower costs due to the spectrum price made it a promising candidate.

All the aforementioned standards and technologies have their specific strength and shortcomings for smart environment applications. However, scalability is still a challenge, which is not fully addressed.

Weightless is a new cognitive wireless standard for machine-to-machine (M2M) networking [26]. The network structure consists of master nodes (base-stations) connected to a high number of slave devices. The use of white spaces results in extended coverage, while the wireless protocol has been designed to be easily implemented in low-power and low-cost devices. Devices using this standard are not yet in the market. However, the consortium of companies that developed this standard claims that this solution addresses the scalability problem too.

5.3 IoT and Cognitive Radio Applications

Objects that have communication capabilities found in IoT/M2M/etc. or their devices are expected to have the capability to observe, think, and understand the physical and social environments they are asked to operate. They will be therefore equipped with Cognitive Radio characteristics. Cognitive Internet of Things (CIoT) represents a new paradigm where current IoT devices are equipped with five fundamental cognitive tasks: perception-action cycle, massive data analytics, semantic derivation and knowledge discovery, intelligent decision-making, and on-demand service provisioning [35]. Authors in [35] define CIoT as "a new network paradigm, where (physical/virtual) things or objects are interconnected and behave as agents, with minimum human intervention, the things interact with each other following a context-aware perception-action cycle, use the methodology of understanding-by-building to learn from both the physical environment and social networks, store the learned semantic and/or knowledge in kinds of databases, and adapt themselves to changes or uncertainties via resource-efficient decision making mechanisms". In [36], a cognitive management framework is presented, where IoT supports sustainable smart city development, through autonomic selection of the most relevant objects for the given application. The cognitive management framework focuses on how to hide heterogeneity of connected objects, how to ensure resilience of a dynamic service provisioning, how to instruct systems to assess proximity between IoT applications and "useful" objects and how to use cognitive technologies to provide intelligence while minimizing user's intervention. In [37], Cognitive Internet of Things (CIoT) is viewed as an integration of the current IoT with cognitive and cooperative mechanisms aiming at enhancing the overall performance and achieve intelligence.

Several IoT applications have emerged and many more are still to come due to the synergies formed between consumers, businesses, industry and the Internet [30]. These synergies will further enable the connection of intelligent things into our lives. These things are expected to produce and transmit useful data by sensing and monitoring the environment we live in, thus helping creating new services. These services would not be possible without this level of connectivity and analytical intelligence. The use of future IoT platforms is directly related to continuous evolving technologies such as cloud, things, and mobile. Further to these technologies, 5G and CRNs consist a decisive factor for the evolution of the future CIoT platforms and their applications.

Figure 6 illustrates how the device layer, that is consisted of sensing, embedded processing and the connectivity sections is managed by the software layer, which alters the physical parameters of the CIoT platform. The CIoT platform can be used as the basis for the implementation of a number of novel applications such as Smart Energy, Smart Parking, Smart Homes, Smart Grids, Smart Lighting, Smart Cars, Smart Tags, Smart Health, Air quality Control, Search and Rescue, Smart Fire Monitoring, etc.

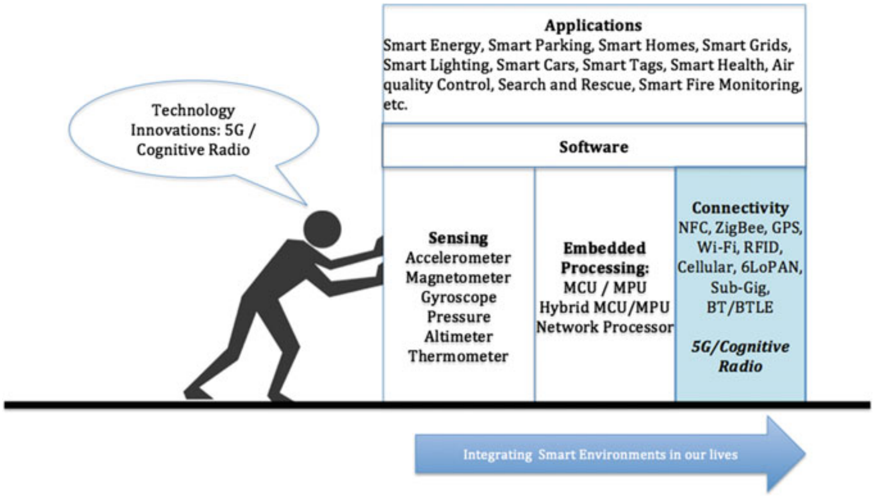

Fig. 6 5G and CR pushing towards rapid development of a CIoT platform carrying smart environments and associated applications

In all applications listed above, CIoT can ensure that the reconfigurable type of networks formed, along with the ability to intelligently sense their environment to make any appropriate decisions, can prove beneficial for both Quality of Experience (QoE) and energy conservation. Sensor nodes will hierarchically manage their communication to reach the end user through coordinated and optimized data aggregation.

A CR type of wireless network is expected to be employing a loose type of channel assignment algorithm that enables IoT or any other type of wireless nodes to freely choose the best possible channel for their communication. After all, CR networks philosophy is to embrace the freedom of frequency allocation. Nevertheless, taking advantage of this kind of freedom does not suggest anarchy for the radio spectrum usage. Not at all; as each CR node, is expected to follow a list of rules. Avoiding any of these rules can end up in denying services to the node in reference.

Simply put, the primary purpose of managing radio spectrum is to develop an adaptive strategy for the efficient and effective use and reuse of radio spectrum by the large number of IoT nodes. This will lead to highly reliable communications whenever and wherever needed. Inspired on existing wireless communication systems, whether these are cellular or not, the channel assignment algorithm for CR networks must be able to cope with the increased signaling of a large number of CIoT nodes building on the spectrum holes detected by the radio-scene analyzer and the output of transmit-power controller. Then, select the modulation strategy that adapts to the time-varying conditions of the radio environment and the requirements of the application of the IoT sensors/devices in reference. The radio scene analyzer proposed in [18] involves the estimation of interference temperature and detection of spectrum holes. Information gathered based on these two techniques are sent back to the transmitter through the feedback channel. It also involves the deployment of an adaptive beamforming mechanism that saves power by not radiating in all directions thus minimizing interference due to the action of other transmitter.

6 Research Challenges in Resource Management for IoT in 5G Mobile Networks

Building a platform that will support billions of things/devices expected to connect to the Internet involves sorting out some serious resource management issues. These issues become even more obvious when the platform is designed to operate wirelessly. A great number of these things/devices are expected to be connected wirelessly since communications through wires can be messy and highly inconvenient when used in various places such as houses, buildings, factories, ships, cars etc. In the next few years, we expect that IoT success will largely depend on the evolution of wireless/mobile/cellular networks. 5G is expected to address many of these issues and become the first platform to support millions, billions of wireless/mobile things/devices. So, as users, whom their houses are fully controlled through the Internet, and cars are remotely monitored to check on their kids whether they are speeding, a very important thing to address is security. Security is important but there must always be some reasoning behind the levels of security as this dictates the complexity of the thing/device itself. Small sensors that measure your fish tank temperature might not require such a high level of security, not as high as you would expect on a home healthcare related device. High security also implies high complexity and this needs to be addressed wisely. Beside security, another critical issue for guaranteeing the success of IoT, is to make sure that there are enough resources available to support its operation. Considering 5G as the future platform for IoT, resources at great extend refer to radio resources. As the number of these things/devices increases, it is expected that the levels of interference will also increase. The same is expected to happen with the network traffic due to the increased signaling. Furthermore, distributed types of networks will be required to be self-organized to ensure optimum operation, while provided they employ CR capabilities, they will be able to sense their environment and critically decide which part of the spectrum and which modulation to use to establish their wireless connection.

In [38] authors state that there are several research challenges (from system/device design and testing to network management) to fulfill the requirements of 5G systems. Among these are measurements and test challenges for 5G systems in view of higher frequencies and multiple channel bandwidths together with much larger antenna arrays and the use of different transmission modes. Also, they outline the research challenges such as improved energy efficiency by energy-aware communication and energy harvesting, simultaneous transmission-reception, densification of existing cellular networks, cloud radio access networks (C-RAN), and virtualization of wireless resources. More specifically, they present interference management in heterogeneous networks as a major issue due to the dense deployment of heterogeneous nodes along with the coverage and traffic load imbalance due to varying transmit powers of different BSs in 5G networks. Furthermore, full-duplex communication addresses issues related to cross-layer resource management, power allocation/control, synchronization and time adjustment to establish full-duplex transmission, dynamic mode selection and designing a MAC protocol to support the polymorphic requirements. For the cloud radio access network (C-RAN): to deploy C-RANs, there are many research challenges, such as optimally utilizing the processing resource, efficiently using the fronthaul links which connect base band processing units (BBUs) with remote radio heads (RRHs), and centralized control of the propagation signal. To achieve wireless network virtualization, efficient resource utilization is required along with inter-slice isolation, and customizable intra-slice resource allocation. Along with wireless network virtualization, there are issues related to resource discovery, isolation, pricing-based allocation, and mobility management. Regarding energy-aware communication and energy-harvesting, one of the main challenges in 5G networks is to improve the energy efficiency aiming at prolonging the battery life of battery-powered wireless devices. To achieve this, harvesting energy from energy sources is an attractive concept, which could significantly improve the performance of battery-powered devices in IoT.

7 Conclusions

Future 5G cellular networks are expected to support IoT along with many other services. To achieve this, 5G must combine different enabling technologies. The biggest challenge here is to integrate all these enabling technologies and provide seamless connectivity with the highest possible QoE. This chapter has presented the main design and operation constraints, that smart environments are expected to experience within a 5G wireless/mobile network and how these constraints can be addressed using cognitive radio networks. The chapter stressed the role of future 5G wireless/mobile networks on smart environments. It has presented the smart environments based on their architecture characteristic and the applications along with communication standards associated with their operation. The concept of cognitive radio networks and the available experimental platforms stressing the benefits of employing this technology in the future 5G wireless/mobile networks has also been presented. Finally, the research challenges associated with integrating 5G wireless/mobile networks and IoT have been outlined.

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