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Review

# Cognitive Spectrum Sharing: An Enabling Wireless Communication Technology for a Wide Use of Smart Systems

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**Abstract:** A smart city is an environment where a pervasive, multi-service network is employed to provide citizens improved living conditions as well as better public safety and security. Advanced communication technologies are essential to achieve this goal. In particular, an efficient and reliable communication network plays a crucial role in providing continue, ubiquitous, and reliable interconnections among users, smart devices, and applications. As a consequence, wireless networking appears as the principal enabling communication technology despite the necessity to face severe challenges to satisfy the needs arising from a smart environment, such as explosive data volume, heterogeneous data traffic, and support of quality of service constraints. An interesting approach for meeting the growing data demand due to smart city applications is to adopt suitable methodologies to improve the usage of all potential spectrum resources. Towards this goal, a very promising solution is represented by the Cognitive Radio technology that enables context-aware capability in order to pursue an efficient use of the available communication resources according to the surrounding environment conditions. In this paper we provide a review of the characteristics, challenges, and solutions of a smart city communication architecture, based on the Cognitive Radio technology, by focusing on two new network paradigms—namely, Heterogeneous Network and Machines-to-Machines communications—that are of special interest to efficiently support smart city applications and services.

**Keywords:** smart communications; cognitive radio; Heterogeneous Networks; machine-to-machine communications; spectrum sharing; spectrum sensing

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## 1. Introduction

The worldwide urbanization process represents a formidable challenge and attracts attention toward cities. In particular, in the near future, the quality of life of billions of people will depend on capability of cities of saving energy, reducing harmful emissions, improving the living conditions and increasing citizens security. These challenges need to be addressed through the implementation of Information and Communication Technology (ICT) intelligent solutions in the urban ecosystem. Indeed, the smart city concept is based on functional integration of software systems, network infrastructures, heterogeneous user devices, and collaboration technologies. Motivated by the fact that a reliable, robust, secure, and scalable communication architecture plays a crucial role for the successful operation of a smart environment, this paper provides an overview of the communication infrastructure of a smart city and the related enabling technologies. First, a review of main characteristics, challenges, and proposed solutions is provided. Then, the focus of the paper is moved on cognitive radio (CR) technology, which is considered an efficient methodology to address communication needs and challenges in many smart city contexts. In particular, in the final part of the paper, CR technology is investigated as a viable solution for mitigating the spectrum shortage that can arise from the use of two key technologies—Heterogeneous Networks (HetNets) and Machine-to-Machine (M2M) communications—that nowadays are envisaged as two promising communication paradigms for future smart cities, specifically characteristics, challenges, and literature solutions are discussed.

## 2. The Communication Infrastructure of a Smart City

The communication infrastructure of a smart city must be suitably designed to satisfy the specific requirements and needs of the considered environment. In particular, it has to support basic functionalities such as sensing, transmission, and control. Sensing is carried out by a large number of sensors and smart devices (even people can be sensors) that monitor the environment; this information is transferred to a control center that performs data elaboration, thus providing control instructions that are delivered to sensors/actuators. A basic characteristic of a smart city is that it is composed of multiple heterogeneous devices that are connected regardless of their locations in an autonomous and scalable way compliant with the Internet of Things (IoT) paradigm. Moreover, a smart environment usually spreads over large geographical areas, and hence requires a multilayer communication infrastructure that extends across the whole smart environment. At least three communication layers can be foreseen: "local area networks", "access networks", and "computing/application networks". The local area networks layer is responsible for monitoring the environment using heterogeneous devices and sensors (which can be embedded in vehicles, buildings, urban environment, and people, for example). The access layer represents the communication backbone that allows the transfer of information from the local networks to the control center. The computing layer is related to the applications that address the data collected by the sensing layer. Even if in some cases wired connections are possible, mobile and ubiquitous wireless connections are preferred for a wide class of services and applications. Mobile connections have the potential to provide remote control and monitoring without the addition of any cabling cost.

The previously described multilayer-structure can provide efficient, reliable, and secure communications if it is designed taking into account the specific needs and challenges of a smart city. Moreover, as a final consideration, we have to note that due to the complexity of the network infrastructure and its deployment costs, a suitable planning in relation to the short, medium, and long-term demands of smart services and applications must be pursued. In particular, future cellular networks should enable to realize a truly networked society with unlimited access to information for anyone. In that way, it will be possible to support various smart infrastructures and smart cities that are green, safe, mobile, connected, and informed.

### 2.1. Communication Challenges

The main challenges the smart city communication infrastructure has to deal with can be summarized as:

- Heterogeneity: heterogeneous communication technologies have to be integrated to provide reliable and functional access to the system elements in different environments. Indeed, in order to have a wide spread of smart city applications, it is required that people can use their own devices and not dedicated devices and software. This will allow low cost, flexible, and scalable solutions. The resulting communication infrastructure must integrate any technology that may be considered relevant by a smart city actor.
- Quality of Service: the diversity of smart city solutions determines the wide variability of supported services and applications. This leads to multiple traffic types within the network and, hence, the need to manage all of these respecting their different Quality of Service (QoS) requirements in terms of priority, delay, data rate, reliability, and security. Moreover, the amount

of data varies tremendously during a day, so the traffic conditions change quickly, and the system must be able to adapt itself to the scenario variability.
- Security: smart city networks have to carry reliable and real-time information toward monitoring and control centres. This exposes the system to outside attacks, unauthorized accesses, and data modifications. Data can be captured and carried over the system. This makes it necessary to foresee suitable mechanisms to prevent cyber attacks that might block the city functionalities and carry unwanted alarms or data theft.
- Energy consumption: smart cities are based on large diffusion of smart devices and sensors whose operations are strongly affected by their battery life. Hence, energy efficient communication protocols are needed, especially for local connections. Moreover, the use of energy harvesting solutions should be considered.
- Communication resource availability: smart cities and smart devices will have an explosive growth in the next years. Hence, the traffic generated by the applications running on smart systems will require a huge amount of bandwidth and network resources, thus challenging the communication infrastructure. Especially in wireless communications, having sufficient and dedicated spectrum resources for smart city applications will be infeasible. Therefore, the availability of sufficient spectrum to accommodate current and future needs of smart environments is expected to be a critical requirement.

### 2.2. Related Works

The problem of communication infrastructures able to efficiently support smart city applications and services in complex, distributed, and diverse environments has been, and continues to be, the subject of intense research investigations. For this reason, in the literature there are several papers related to this topic, especially for the smart grid context. Among others, the aim of [1,2] is to offer a comprehensive review of the application of wireless communication technologies to smart environments by discussing their challenges, future trends, and standardization activities. In [3], various communication technologies, both wired and wireless, are compared, and their suitability for deployment in multiple smart grid applications is evaluated on the basis of specific network requirements. The candidate technologies for a smart grid communication network are also presented and critically discussed in [4]. Moreover, this paper presents a multilayer communication architecture based on IP that integrates heterogeneous technologies by using the ubiquitous sensor network (USN) architecture [5]. The framework includes a decentralized middleware that has to coordinate all the smart system functions, as well as the network management model based on USNs. The integration of heterogeneous technologies is also discussed in detail in [6], where the authors propose a simple and flexible architecture for wireless communications and illustrate how the architecture can be employed. In particular, the paper analyzes the key results obtained from experimental evaluations made using open source software, low cost wireless routers, and open/low cost sensor technology.

Another important challenge is to have secure data transmissions, thus preventing cyber attacks that can block or alter the city functions. A survey on security and privacy issues in smart environments is provided in [7,8], while several solutions are proposed in the literature; e.g., a security framework from wireless sensor networks (WSNs) is proposed in [9]. This framework combines a hierarchical attack detection scheme based on chance discovery and an access control policy. Security is also the focus of [10], which presents a secure IoT architecture. In particular, the authors present an architecture containing four basic IoT blocks that mitigates cyber attacks beginning at the IoT nodes themselves.

The ability to provide heterogeneous services with suitable QoS requirements is investigated in [11–13]. Specifically, [11] presents a survey on the state of the art of cross-layer QoS approaches in WSNs for critical applications. While, in [13], the authors propose four different IP-based IoT network architectures for potential smart city applications, defining the corresponding performance metrics in order to maintain QoS guarantee. As a special case, participatory sensing, as well as its related network architecture and QoS, is separately presented. Differently, in [12], the focus is on access policies of hierarchical WSNs. A new time division multiple access protocol is proposed to improve the quality control of smart cities applications, where diverse traffic is required and loss or delay in data traffic is unacceptable.

Sensors and smart objects composing the smart environment can be subject to power consumption constraints; thus, energy conservation can be essential to extend their lifetime. A comprehensive survey of smart grid-driven approaches in energy-efficient communications and data centres, and of the interaction between smart grid and information and communication infrastructures is provided in [14]. In [15], the problem of energy conservation of smart sensors is considered; the authors propose an approach that is based on a combination of several existing mechanisms of energy saving by addressing more particularly data routing, introducing a hierarchical organization of the network.

To make viable new smart services, it is needed to use the available spectrum more efficiently—both in terms of frequency and with regard to when and where it is needed. A very promising solution is represented by CR technology [16], which allows the support of large-size and time-sensitive multimedia data with limited spectrum resources. In particular, dynamic spectrum access (DSA) enabled by CR technology can provide opportunistic access to unused spectrum, both licensed and unlicensed, making CR technology a necessary component for smart system communication infrastructure. For these reasons, CR is a potentially highly attractive communication technique that, in some contexts, can efficiently address the needs and challenges of a smart city. The rest of the paper focuses on CR as a key enabling communication technology for the smart city.

## 3. Cognitive Radio for Smart City

As stated before, wireless technologies are considered a promising solution for the communication infrastructure of a smart city despite several challenges, such as trade-offs between wireless coverage and capacity as well as limited spectral resources. For this reason, new communication paradigms are needed, and among these, CR networks (CRNs) are highly promising for providing timely wireless communications by utilizing all available spectrum resources.

### *3.1. Cognitive Radio Concepts*

The efficiency of spectrum usage in smart systems should be increased, allowing the sharing of radio resources with other systems. CR allows wireless systems acquiring a context-awareness and reconfigure themselves according to the surrounding environments and their own properties [16]. In the same radio resources, two (or more) systems coexist: “primary” and “secondary”. Primary system refers to a licensed system with legacy spectrum. This system has the exclusive privilege to access the assigned spectrum. Secondary system refers to the unlicensed cognitive system and can only opportunistically access the spectrum holes which are not used by the primary system.

It is well known that CR methodologies are an interesting research area, but, despite this, until now there has been a lack of wide scale applications of CR techniques. A current attempt is the use of TV white spaces. However, the use of CR schemes in future communication systems for smart cities is mandatory to make spectrum sharing effective among different smart services and communications providers, and foreseen new services [17].

In general, CR technology is based on two main characteristics: “cognitive capability” and “reconfigurability”. Cognitive capability refers to the ability to acquire knowledge about the surrounding environment. Reconfigurability enables the secondary network to be dynamically adapted to the radio environment. More specifically, the cognitive radio can be designed to adapt its transmission by means of power control algorithms and/or suitable resource allocation schemes. Two different cognitive approaches can be identified: “Opportunistic” and “Underlay”. Following an “opportunistic approach”, the secondary system can use portions of radio resources that are unused by the primary system in a given time and space. Hence, the secondary cognitive system uses the radio resources dynamically on an opportunistic and non-interfering basis, exploiting the frequency holes left unused by the primary system. A different cognitive approach is represented by the "underlay cognitive approach". The secondary system is allowed to share the channel simultaneously with the primary, mainly adopting constraints on the power emissions to lower (or avoid) mutual interference. In both cases, the secondary system has to sense the radio channel to estimate which resources are not used among the available ones, or which resources can be used, introducing a limited amount of interference. The cognitive system has to adapt to the changes in the surrounding environment. This means that sensing and reconfigurability must be repeated periodically.

Spectrum sensing is a critical aspect for cognitive systems, especially if the involved devices have low complexity and cannot have multiple radios and powerful processors, like in many smart city environments. Therefore, sophisticated spectrum sensing algorithms cannot be used. Moreover, the sensing duration should be minimized as much as possible to have energy-efficient devices. The trade-off between required resources and sensing accuracy should be addressed for any specific cognitive smart city. Furthermore, to satisfy the QoS requirements of smart city applications, it is needed to have efficient spectrum sharing policies related to medium access control functionalities. More details on these aspects, and a critical discussion related to solutions proposed in the literature is provided in Section 4.

### *3.2. Benefits of Cognitive Radio in Smart City*

CR has the potential to flexibly support a wide range of applications and can be useful to deal with several communications challenges in a smart city

- Communication resource availability. CR improves spectrum utilization and communication capacity to support large-scale data transmissions. Indeed, the unlicensed spectrum (*i.e.*, Industrial, Scientific, and Medical, ISM) mainly used in local area connections is becoming dramatically crowded and interfered, while other licensed frequency bands are fixedly assigned and utilized in an inefficient way. In addition, the application of CR can also alleviate the burden of purchasing licensed spectrum for utility providers. CR uses the existing spectrum through opportunistic access to the licensed bands without interfering with the licensed users. CR determines the spectrum portions unoccupied by the licensed users—known as spectrum holes or white spaces—and allocates the best available channels for communicating.
- Heterogeneity. Heterogeneous communication technologies have to be integrated to provide reliable and efficient access to the system elements in different environments. As a consequence, devices should be able to acquire context awareness and to reconfigure themselves. Hardware reconfigurability can help to manage communications in areas where different technologies are present.
- Quality of Service. Communications over white spaces can provide dedicated low-latency communications for critical data.
- Energy consumption. CR can be used to reduce power consumption, and hence to have energy efficient systems, by sensing the environment and then adaptively adjusting the transmission power, avoiding energy waste.

### *3.3. Related Literature Review*

Supporting smart cities through CR communications is becoming an interesting area of research, especially in the context of smart grids and smart vehicular networks.

Several surveys on smart systems based on CR can be found in the literature. The application of CR to future generation networks is provided in [18]. The authors in [19] focus on the main features of cognitive vehicular networks, providing an overview of the state of the art, especially in terms of spectrum sensing and open research problems. Similarly, in [17,20], application scenarios, motivations, and challenges of using CR for smart grids are reviewed. Moreover, the authors in [17,20] provide a survey of possible architectures and spectrum sensing techniques. CR technology is also reviewed in [21,22] as a possible solution for implementing effective smart grid networks.

General communication architectures for smart grids based on CR are discussed in several papers, as in [23–25]. In particular, [23] provides an overview of the current state of communication technologies for smart grids, and then the possibility of applying CR is discussed together with a high level network architecture based on IEEE 802.22 standard. In [24,25], the authors present a CR-based communication architecture, organized in three tiers depending on the service area (*i.e.*, home, neighbourhood, wide). Moreover, in [24], dynamic spectrum access and sharing in each subarea are considered, evidencing the necessity of joint resource management in different subareas in order to achieve network scale performance optimization.

Despite the benefits of CR, when many unplanned networks simultaneously access a common pool of frequency channels, high background interference occurs. In [26], a beamforming technique based on minimum mean squared error (MMSE) is proposed to mitigate the interference in CR systems based on the IEEE802.22 standard for smart meter. Another problem that arises in CR is security of sensed data, this is discussed in [27], where a two-stage scheme for defence against spectrum sensing data falsification attacks is proposed.

CR is also investigated as a viable solution to have efficient WSNs, which are considered to be one of the best solutions as a monitoring platform for many smart systems. Dynamic and opportunistic spectrum access capabilities of CR can address many of the unique requirements and challenges of WSNs: propagation conditions, heterogeneous spectrum characteristics varying over time and space, reliability and latency requirements, and energy constraints. For example, in [28], spectrum-aware WSNs are proposed to overcome spatio-temporally varying spectrum characteristics and harsh environmental conditions for smart grid applications: potential applications, challenges, and protocol design principles are reviewed. The performance of a WSN in a smart meter communication system in terms of average service time and average waiting time is evaluated in [29], where an overlay cognitive implementation strategy is adopted, treating the WiFi system as the primary user.

Scheduling problems in CR smart grids are addressed in [30–32], where different priority-based solutions are proposed considering the heterogeneity of the traffic generated by the specific environments.

CR technology is also investigated as a viable solution for mitigating the spectrum shortage that can arise from the use of some key technologies that could enable efficient smart city environments. In particular, HetNets and M2M communications are two paradigms particularly suited for future smart cities, but their effectiveness is related to the capability of exploiting the available spectrum in an efficient way. In the remaining part of this paper, we focus on CR technology applied to these new and promising communication paradigms.

### *3.4. Cognitive M2M*

Smart systems are characterized by a large diversity of devices and machines that have to be interconnected and able to exchange information autonomously in order to make the environment smart. This makes M2M communications a dominant paradigm, especially in contexts such as in-home applications, vehicular telematics, healthcare, and public safety [33–36]. However, M2M communications present multiple differences with respect to current Human-to-Human (H2H) information production, processing, and exchange. M2M communications are characterized by massive transmissions, small bursty traffic, low power, low cost, and low mobility. Moreover, while H2H communications access the network following resource scheduling policies based on traditional bandwidth request mechanisms, M2M communications need to be separately considered. Indeed, these are characterized by a high number of nodes that exchange low data rate information. Hence, the spectrum usage is very limited and short in time. However, the main challenge for M2M communications is due to the high number of involved devices, which excessively increases the access requests to the network and, without countermeasures, gives rise to network congestion. Indeed, even if each device transmits only a very small amount of data, the huge number of connected devices will dramatically increase the signaling overhead, thus leading to a network overload and deteriorating the QoS of other H2H applications. A viable solution is to develop an autonomous M2M communication system that shares the resources with other H2H communication systems without causing congestion. This is a new paradigm, called Cognitive M2M (CM2M) communications [37,38]. The exploitation of CR technology for setting up M2M communications is a promising trend. Indeed, a cognitive approach can lead to the definition of a scenario where M2M nodes are constrained to send data in specific bands and time intervals, reducing the congestion issues. CM2M communications concern with the presence of a primary H2H communication system that coexists with a secondary CM2M system in an almost transparent way, avoiding interference and introducing low performance degradation thanks to the cognitive approach. The cognitive engine of an M2M network can operate in a distributed manner (among all the devices of the network) or in a centralized manner at the network gateway, which is in general supposed to be a more powerful node. A more detailed discussion on CM2M solutions is provided in Section 4.

### *3.5. Cognitive HetNets*

As stated in Section 2, one of the main characteristics of the communication architecture of a smart system is that, in general, it spreads over large geographical areas and, hence, requires an infrastructure characterized by a multilayer network with different access points in order to provide network access in local areas for in-home applications up to wide areas, for communications with command and control centres. A promising technology is represented by the HetNets deployment, which is a key networking paradigm in 5G mobile networks based on the idea of increasing the number of access points with a high diffusion of short-range, low-power, and low-cost base stations (BSs) overlapped to the main 5G macro-cellular network infrastructure [39,40]. This allows to provide high data rates, to offload traffic from the macro cell, and to provide dedicated capacity to smart cities [41,42]. In HetNets, a broad variety of cells, such as micro, pico, metro, and femto cells, as well as advanced wireless relays and distributed antennas, can be deployed practically anywhere. Since the ranges are short due to low transmission power, the small cells are typically deployed in close proximity to the users and can be used for creating hot-spots for access to smart services and applications, increasing in-home connectivity, providing accurate localization, and integrating macro-cellular coverage. However, the deployment of two overlapped layers of cells (*i.e.*, macro and small cells) requires networks able to self-organize and to manage the inter-cell interference. Indeed, interference mitigation between the two network layers is one of the key issues to be solved before the effective application of the HetNet concept. The introduction of small cells in current cellular networks is based mainly on coordinated approaches where the small cell is directly installed by the network operator, and it is possible to adopt coordinated resource allocation strategies, thus avoiding inter-cell interference. However, in smart city environments, small cells will be deployed *ad-hoc* in a flexible and scalable way, depending on the system's needs and, hence, without a coordination with the network operators. In this way, a more cost-effective communication system will be achieved, reducing the costs for RF planning, site acquisition, and efficient backhauling [39]. This trend is in general expected for future 5G mobile networks where the number of small cell nodes will increase significantly, and many user-deployed small cells will be used in homes, small offices, and enterprises. If coordination among macro and small cells in the resource assignment is unavailable, the concept of Cognitive HetNets (CHetNets) [43,44] assumes high relevance. The macrocell is the primary system that has higher priority on the resource usage and the cognitive small cell (CSC) represents the secondary system that has lower priority and should transmit without affecting the primary system reception. The CSC radio access network must be equipped with a cognitive engine able to sense the environment and to adapt transmissions by means of DSA schemes and advanced signal processing methods. Some examples of cognitive approaches used by the small cell cognitive engine (SMCE) are provided in Section 4.

### *3.6. Cognitive Communication Architecture for Smart City*

As a conclusion of this section, we want to suggest how CHetNets and CM2M communications could be integrated in the communication infrastructure of a smart environment, proposing a high level architecture based on a 4G/5G cellular network. Indeed, even if different technologies will be used to support smart city communications, it is reasonable to assume that cellular networks will have a predominant role for multiple reasons—such as the performance they can guarantee in terms of data rate, delay and security, coverage, and the fact that they already exist and are widespread so can be used anywhere and at any time without extra costs to deploy a smart environment. The drawback is that the users of the cellular networks are continuously increasing in number and the demand of capacity is expected to grow exponentially in the near future. This could determine congestion and a consequent loss of performance of the smart system. To resolve these challenges, it is essential to adopt a network infrastructure that can efficiently integrate multiple disruptive wireless technologies and enable interworking of existing and deployed technologies. For this reason, we consider CR, HetNets, and M2M technologies.

The architecture we propose is represented in Figure 1. This is able to provide both local and backbone connectivity to the smart city in an efficient way. We exploit the multi-layer nature of the communication infrastructure of a smart city, proposing a model where the cellular network, with its main macro-cellular coverage provides wide area connections, while in areas where smart services and applications are concentrated, the communications are supported by small cells deployed *ad-hoc*. Hence, where peaks of traffic are expected, the radio access is guaranteed by dedicated cognitive small cells (DCSC) that provide service only to the smart city users. Moreover, devices in close proximity can directly communicate (device-to-device, D2D) among them, thus offloading traffic from the BS. This enables the creation of another layer in the smart system communication architecture which is represented by the CM2M layer, thus supporting the massive diffusion of connected devices usually characterizing a smart city. In the CM2M layer, machines can communicate among themselves by opportunistically using the spectrum both in underlay or overlay mode. Then, the data collected and processed by the CM2M network are forwarded toward the control centre using gateway nodes that have two air interfaces and are able to connect with the DCSC. This follows the capillary network concept [45].

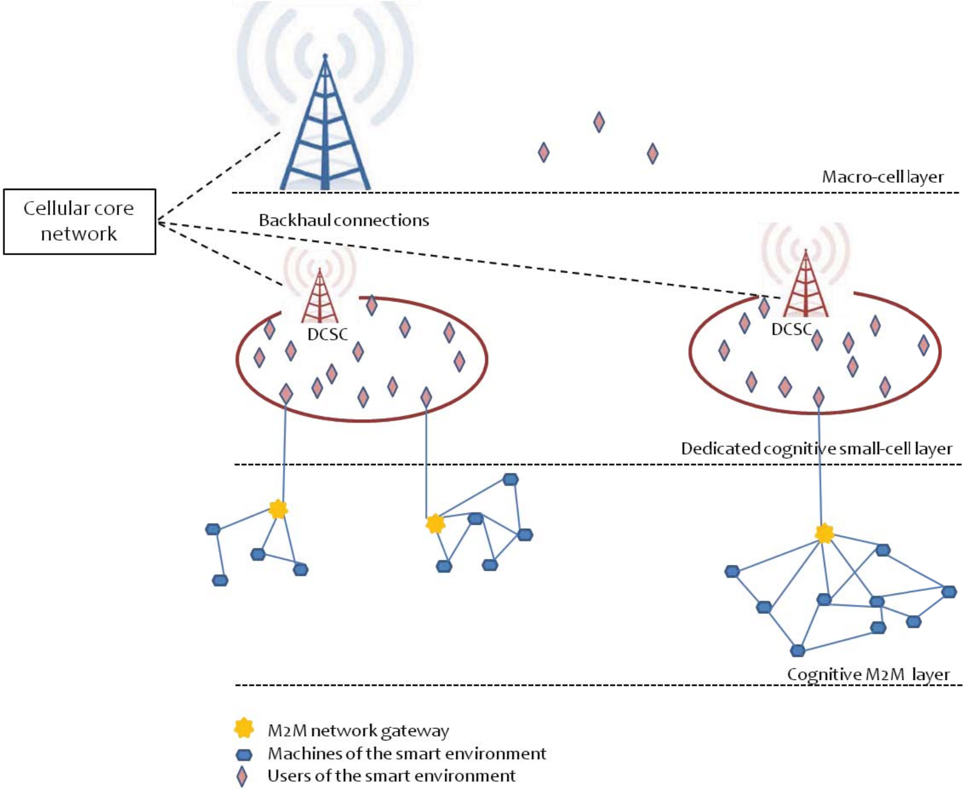

**Figure 1.** Cognitive communication architecture for smart city. M2M: Machine-to-Machine; DCSC: dedicated cognitive small cell.

To efficiently work CHetNets and CM2M, networks have to resort to suitable cognitive solutions, for which a critical review of possible approaches is provided in the next section.

## 4. Cognitive Solutions for HetNets and M2M Communications

This section deals with some possible solutions to be applied to CHetNets and CM2M communications in a smart city, where one of the main challenges related to the use of CR technologies is spectrum sensing. Indeed, as stated previously, when sensing involves low complexity devices as in a smart environment, it is necessary to find a suitable trade-off between the amount of resources requested by the sensing operation (in terms of computational complexity and energy) and the sensing accuracy (in terms of the probability of correct detection and sensing time). As a consequence, depending on the cognitive node capabilities, different CR approaches should be selected. For this reason, we critically review different solutions distinguishing between two classes of cognitive systems that differ in the speed of changing of the primary system resource usage, and hence for the complexity of sensing operation:

1. long-term (*i.e.*, seconds) cognitive systems;
2. short-term (*i.e.*, milliseconds) cognitive systems.

In the first case, the primary and the secondary systems share portions of the available spectrum (sub-bands) indicated as $B_i$ in Figure 2, whose occupancy changes due to significant modifications in the environment. This is the case of future 5G cellular systems, where the need for wide frequency bands and the unavailability of large free spectrum portions will lead to the dynamic aggregation of multiple, even non-contiguous, sub-bands ("carrier aggregation") [46] to satisfy the requested capacity. Hence, each primary cellular system adaptively changes the number of used sub-bands depending on the traffic load and the interference level with neighbour cells. Together with carrier aggregation, future 5G systems also foresee the exploitation of unlicensed spectrum portions (*i.e.*, the ISM spectrum) to increase the capacity of small cells in HetNets, thus reducing the interference generated towards the macrocell. The use of unlicensed spectrum is subject to its availability and therefore sensing must be repeated periodically to find unused sub-channels [47]. Another interesting case is represented by the IEEE 802.22 standard for wireless regional area networks, which is based on the opportunistic usage of available portions of TV spectrum (TV white spaces) that are unused in a given area and in a given time. In all these cases, cognitive secondary systems must be able to detect the use of a given sub-band performing suitable spectrum sensing. The sub-bands where no activity of the nearby primary system is detected are used to communicate with the secondary users. In this case, it is reasonable to assume that the primary system sub-bands occupancy does not change frame-by-frame, but it is performed periodically when the network load changes significantly, or when new cells are activated in the same area.

Short-term cognitive approaches are more challenging in terms of sensing because they foresee the exploitation of the smallest resource units (RUs) in which a sub-band can be divided (indicated as $RU_{i,j}$ in Figure 2), and these are allocated frame-by-frame requiring instantaneous sensing and decisions. Indeed, current and next generation wireless communication systems are characterized by a high flexible and dynamic resource usage. Therefore, the available sub-bands are divided into small RUs (For example, the Physical Resource Blocks in LTE-A.) that are instantaneously allocated to users in a dynamic way depending on the users' requests and channel propagation conditions.

In summary, the main difference between the two approaches is the time scale. In the first case, we can assume that the transmission opportunities last for some frames, while in the second case the resource assignment changes frame-by-frame. The short-term cognitive approach is more efficient because it works with a higher granularity of the resources and, hence, it permits to exploit all the resources left unused by the primary system. On the other hand, this approach is very challenging for the sensing phase, which must be very quick and repeated with high frequency. Conversely, in long-term operations, sensing requirements can be relaxed: sensing duration is longer and frequency of sensing is lower.

Finally, in the short-term cognitive approach, the secondary network must use the same access technology of the primary network and has to be synchronized with it. Conversely, with the long-term cognitive approach, different technologies can be used in the secondary network, hence, it can also operate on sub-bands allocated to different primary systems, including licensed and unlicensed spectrum.

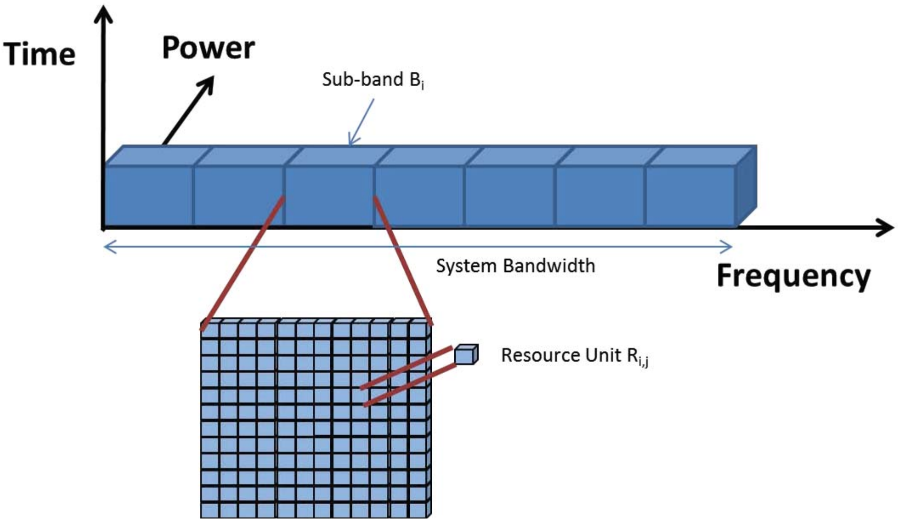

**Figure 2.** Spectrum Opportunities.

As a first consideration, we can state that in the smart city architecture described in Section 3.6, the long-term cognitive approaches are most suitable for the low complexity devices that compose the CM2M networks, while cognitive small cells have the capabilities of supporting both types of approaches. A critical discussion is provided in the next section.

### 4.1. Long-Term Cognitive Approaches

In long-term cognitive approaches, the main problem is making a cognitive device aware—in an autonomic manner—of which frequency sub-bands are not used by the primary system, and hence, able exploit the transmission opportunities. Therefore, the secondary system plans periodic sensing intervals during which it measures the energy in the whole sub-bands in order to detect primary system activity.

Several spectrum sensing approaches can be used among those proposed in the literature [48]. The spectrum sensing algorithms can be classified into blind detection and feature detection. The former is applicable to all the primary signals, even unknown, since prior information on the signal is not required. The most-known and simplest blind method is Energy Detector, but it has the drawback that it suffers heavy degradation in the case of noise uncertainty and in a low signal-to-noise ratio (SNR) regime. Differently, feature detectors such as matched filter, waveform-based, and cyclostationary sense specific characteristics of the primary signals that must be known “a priori”. These methods can provide accurate sensing performance even in the presence of noise. In particular, great attention has been devoted to the methods based on the cyclostationarity property of the signal induced by the Cyclic Prefix (CP) in Orthogonal Frequency Division Multiplexing (OFDM) signals, such the ones used in most of the current wireless systems (*i.e.*, LTE-A, WiFi, WiMAX). Different sub-optimal methods exploiting cyclostationarity have been proposed and evaluated to limit the computational complexity. In smart city environments, the selection of the sensing scheme should be suitably driven by the desired trade-off between implementation complexity, estimation time, and performance in terms of false alarm and detection probability. In particular, when low complexity devices are involved (*i.e.*, sensors), low complexity algorithms should be preferable—adopting different strategies, such as distributed sensing [49], to improve the reliability of the produced output.

In the literature, some examples of long-term cognitive approaches can be found. In [50], the authors proposed a selective method that permits the secondary user to exploit not only the sub-bands left unused by the primary system (Opportunistic approach) but also the sub-bands that result underutilized by adopting suitable subcarrier. This solution can be useful either in HetNets or M2M communications. However, underlay communications are particularly suitable for M2M applications characterized by short range communications, and therefore low power emissions. In particular, depending on the primary systems' signal strength, the CM2M network is able to determine the maximum power that can be used without causing high interference. This issue was considered in [51], where the authors analyzed the feasibility of implementing a CM2M network by using primary cellular bands. A hierarchical network structure was proposed, where cluster heads gather M2M traffic and forward it to the primary cellular network. In addition, the cluster head—on the basis of a previous sensing phase—estimates the maximum allowable power for M2M communications and broadcasts this information to all M2M devices within its area. In [38,52], CM2M communications have been investigated to be applied in smart environments. In [38], the authors designed a cognitive medium access control protocol, based on packet reservation multiple access. The protocol is centralized and utilizes a specialized frame structure for supporting the coexistence of the CM2M network with the primary H2H network. In this case, spectrum sensing is not performed by each machine, but a low-cost dynamic spectrum access solution realized in the form of master–slave operation is considered. It means that only the gateway of the M2M network, which is supposed to be a more powerful device, performs sensing and then makes a decision on the resource access. The gateway sends an enabling signal after obtaining a vacant channel and then other devices are allowed to transmit in vacant channels. The opposite approach was considered in the M2M network presented in [52], where smart objects were able to connect to each other in a distributed manner so that the sensing information could hop from one node to other nodes until it reached the gateway successfully. The focus of the paper was on improving the sensing capabilities of the system by using a differential evolution algorithm that exploits the sensing results coming from multiple objects. A HetNet deployment was proposed in [53] for a smart grid. It is based on the integration of heterogeneous access points and DSA. In this case, the selection of the best access point and of the spectrum resources is centralized. Indeed, a network controller uses average statistics to assign the BS to each device, and a spectrum manager maintains a database of available and leased open spectrum without the need for spectrum sensing operations. Differently [54] mainly focused on the capability of a secondary access point to detect the activity of the primary macrocell that operates following a carrier aggregation policy. Hence, the small cell performs suitable spectrum sensing based on low complexity cyclostationary detectors to understand to understand in an autonomic manner which frequency bands are available.

### 4.2. Short-Term Cognitive Approaches

Short-term cognitive approaches represent a very promising solution due to their specific features. However, many challenging issues have to be overcome to make viable their use in future smart systems. A short-term cognitive algorithm has to operate quickly in order to be aware of the spectrum resource usage by the primary systems in real time and then has to make quick and efficient access decisions for the secondary devices. Moreover, a short-term cognitive approach works in different modes depending which link—*i.e.*, UpLink (UL) or DownLink (DL)—is considered. The access point of a cognitive secondary system listens the environment in order to acquire knowledge about the UL transmission of the primary system. This information can be used to allocate the resources in the successive UL transmission. The DL knowledge, however, must be acquired by the terminals during a given time interval and sent back to the access point, which performs the allocation in the following DL transmission. This introduces a certain latency between the acquisition of the information and its use, which must be accurately evaluated in accordance with the working speed of the scheduler. This could be critical in Time Division Duplexing (TDD) systems where the cognitive terminal has to wait the UL sub-frame before sending the information back to the access point. Despite this, TDD based systems are attractive for the use of short-term cognitive methods because for them the channel reciprocity is applicable, that allows to keep valid the channel estimates performed in the DL also for the UL and viceversa. The main differences between long-term and short-term cognitive approaches are reported in Table 1. It is evidenced that short-term approaches are mainly suitable for CHetnNets to be used in the access layer of a smart city, while is not suitable for the sensing layer; however, there is a special case based on a partial knowledge of the primary system scheduling information that can also be suitable for CM2M applications, as detailed later.

**Table 1.** Cognitive Approaches. CM2M: Cognitive machine-to-machine; CHetNet: Cognitive heterogeneous networks.

| Cognitive approaches features | Long-Term | Short-Term |
|---|---|---|
| Smart city communication layer | local and access layer (CM2M and CHetNets) | access layer (CHetNets) |
| Sensing period | several frames | scheduling period |
| Transmission opportunity | sub-bands | Resource Units |
| Technical challenges | suitable trade off: cost-accuracy of sensing | fast sensing<br>feedback information<br>joint resource allocation |
| Spectrum efficiency | Low | High |
| Secondary Network Requirements | no | synchronization and legacy terminal |
| Distributed sensing | yes | no |

Most of the research activity concerning short-term cognitive approaches focuses on finding efficient (e.g., optimal) resource allocation strategies to minimize the interference of cognitive small cells towards the primary macrocell system without losing performance for the secondary devices. The resource allocation schemes benefit from the flexibility given by multiuser diversity; when working on a RU basis, different secondary users have different spectrum opportunities available. Indeed, depending on their positions, the secondary users receive and produce different levels of interference from/towards the primary users. This means that if a primary user is communicating by using a given resource, a proximity secondary user senses this resource as occupied, but another secondary user that is far from the primary one senses the resource as free and can use it for communicating. To use this multiuser diversity property, the spectrum sensing must perform joint spatial–temporal resource detection.

Awareness of the macrocell resource usage can be achieved in two different ways: by receiving the scheduling information from the macrocell BS, or by actively sensing the environment. In the first case, a limited level of signaling exchange among the BSs is required, while in the second case, the information is acquired using sensing procedures without any type of information exchange. The first method is not completely cognitive because there is only limited cooperation between the BSs, but the information exchange represents only one-sided cooperation, and interference management mainly relies on cognitive approaches. In addition, use of the scheduling information sent by the macrocell has the drawback that the multiuser diversity remains unused. Indeed, when a resource is declared as used by the primary system, it is considered busy by all secondary users and cannot even be used by a user located far away from the primary system, which could in fact operate without interference. The second method is completely cognitive, but presents more challenges in the sensing phase, not only in terms of accuracy of the results, but also in terms of latency between acquisition of the context awareness and its use and channel reciprocity between the UL and the DL. In some cases, hybrid techniques can represent a viable solution whenever limited knowledge of the network is available, and therefore only partial coordination among the cells is possible.

The method proposed in [55] first detects channel occupation by estimation of the energy in the UL sub-channels, and then allocates the sub-channels with the lowest interference signatures to the small cell users. The hypothesis here is that the same resource scheduling process is used in both UL and DL transmissions. However, it is more likely that the DL and the UL are characterized by asymmetric traffic, and thus adopt different resource allocation policies. Therefore, UL sensing cannot be used for DL allocation. An alternative approach is proposed in [43] by considering a hybrid sensing scheme in which the scheduled macrocell BS information is available at the small cell BS (SBS) in order to increase the spectrum sensing accuracy. In this way, the secondary system finds more spectrum opportunities by identifying nearby macrocell users. Inter-layer interference can also be limited or prevented using optimal power allocation and using underlay cognitive approaches, as in [56], where the SBS senses both the UL and DL of the macrocell to be aware of both the resource occupancy and nearby macrocell users. The algorithm then adapts the power on each resource element to maximize the achievable small cell throughput and fulfill the macrocell users' outage constraints.

Exploitation of multi-antenna technologies is an additional opportunity to use information related to the primary and secondary users' position in order to allow co-channel frequency allocation between primary and secondary systems. A useful approach is to use beamforming at the small cell transmitter in order to maximize the secondary system performance while the interference on the primary system receiver is minimized [57]. This operation is named Cognitive Beamforming (CB) and requires complex numerical solutions and the knowledge of all propagation channels. This could be impracticable in actual scenarios, as the two systems operate in an independent mode that prevents each of them from detecting the presence of the other. Hence, it is necessary to resort to sub-optimal solutions that can work with a partial knowledge of the channel state information and with some information exchange between primary and secondary networks. A viable low complexity CB approach is based on the exploitation of the direction of arrival (DoA): the secondary system can transmit avoiding interference on the primary user by placing nulls in its direction. However, the knowledge of DoA of multiple signals can be challenging in multipath propagation channels and strongly depends on the number of antenna elements used at the receiving end. In [58], a method is proposed for CHetNets based on DoA estimation and zero forcing beamforming that focuses on problems that arise in actual propagation channels. This method can be applied either in UL or DL, assuming a correlated spatial information among the two links. Finally, CB methods can be combined with opportunistic resource allocation algorithms that assign each $RU$ to the secondary user that is sufficiently far from the corresponding primary. Thus, the interference can be minimized with beamforming. An example based on DoA information is sketched in Figure 3. In this method, the knowledge of the DoA can be acquired by the SBS during the UL transmission and then used either for the UL reception or for the DL transmission. However, for the DL transmission, two issues must be taken into account: the channel reciprocity in the spatial information between DL and UL and the need of the SBS to know the scheduling map (*i.e.*, the resource assignment to the users) of the primary system. This could be achieved with a limited amount of information exchange among the BSs.

A context where the knowledge of the scheduling maps of the primary system is particularly interesting is the CM2M. In addition to the problems related to the sensing delay, in CM2M networks, spectrum sensing operation requires digital processing and energy consumption that can be unaffordable. Indeed, the machines involved in autonomous M2M communications in a smart city are usually characterized by low complexity and low cost nodes, with reduced computation capabilities and with stringent requirements on battery life (for example, sensor nodes or metering devices). Moreover, the large number of nodes could occur in a huge amount of signaling required to exchange sensing reports. As already stated, in CM2M communications, spectrum sensing can be a very hard task. A viable solution is proposed in [59], where a CM2M network aims to exploit the time-frequency holes left in the H2H communication frame for implementing an independent network. Toward this goal, the proposed system uses the in-band signaling broadcast by the primary system to discover the unused spectrum parts for the cognitive capability of the M2M network. Indeed, a specific field within the H2H is used for notifying in broadcast to the users on the spectrum allocation. In particular, [59] proposes a novel M2M MAC technique suitable to support M2M communications, with the aim of allowing the multiple access to secondary users while avoiding interferences to the already-planned primary network; the secondary CM2M devices are supposed to have a legacy interface so that the in-band signaling of the overlaid network can be exploited in a suitable way. In addition, it is important to underline that using the scheduling MAPs to detect idle RUs has the disadvantage that the multiuser diversity is not exploited, and when a resource is used by the primary system it cannot be used by the secondary. Neither can it be used by a secondary user that is far from the primary system, and hence it could operate without interference.

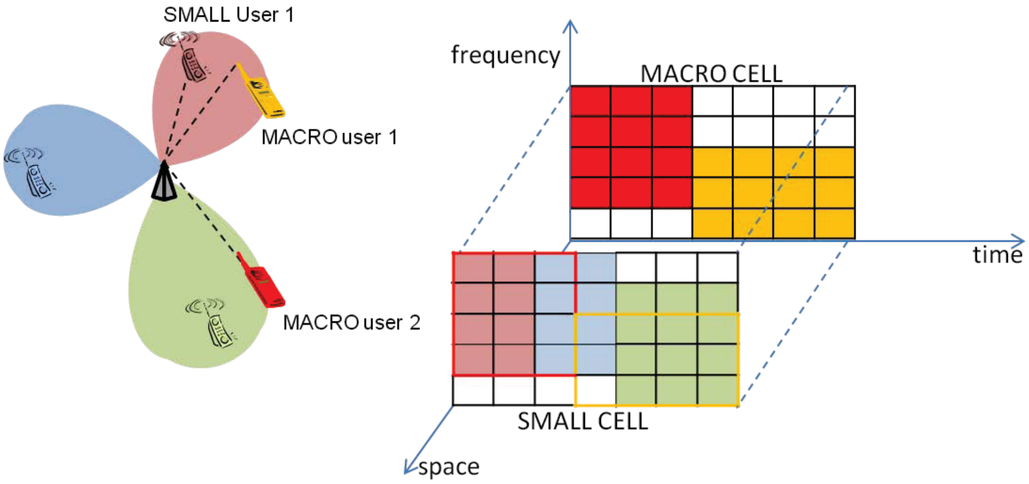

**Figure 3.** Cognitve Beamforming and Resource allocation.

Table 2 presents a summary of characteristics of the short-term cognitive approaches based on sensing or on the knowledge of the primary system's scheduling map.

**Table 2.** Short-term cognitive approaches comparison.

| **Cognitive approaches features** | **Sensing** | **Signaling (Scheduling maps)** |
|---|---|---|
| Computational Complexity | high | low |
| Challenges | real-time sensing | scheduling map availability |
| Applications | HetNets | HetNets and M2M |
| Spectrum Efficiency | high | medium |

## 5. Conclusions

In the near future, the quality of life of billions of people will depend on the capability to efficiently use information and communication technologies to build smart environments able to save energy, reduce harmful emissions, improve health care and increase citizen security. A smart city is based on a functional integration of software systems, network infrastructures, heterogeneous user devices, and collaboration technologies. Among these components, a high performance, reliable, robust, secure, and scalable communication architecture plays a crucial role for the successful operation of a smart environment. The capability of wireless communication systems to satisfy the smart city requirements is related to their capacity to efficiently exploit the spectrum resources, and to introduce new communication paradigms particularly suitable for this kind of environment. For this reason, in this paper, after a review of communication challenges and solutions, cognitive ratio technology has been introduced as a key feature to make effective smart environments, and in particular to mitigating the potential spectrum shortage arising from the use of HetNets and M2M communications. Related literature has been also reviewed and critically discussed in order to highlight the effectiveness of these key technologies in a smart city environment.

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