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Energy-Harvesting Cognitive Radios in Smart Cities

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1.1 Introduction

Wireless communication has been experiencing tremendous advancements. These developments have triggered new wireless networking paradigms and communication services. For instance, 5G is being studied by the research community to provide mobile broadband communications in wireless networks. Recently, the concept of IoT (Atzori et al., 2010), which is one of the key elements of 5G wireless networks, has been proposed to connect every device to the Internet, such as wireless sensor nodes, RFID tags, household appliances, etc.

As these technologies grow, they have been applied to various real-world problems. One of the most important application areas is the management of cities in a more efficient and smarter way. The smart city is a vision that extracts information from systems in the city to take measures for its management. This vision can be realized if information and communication technologies are employed in these systems to observe and manage them. Wireless sensors can be utilized as key elements for observing systems such as hospitals, highways, transportation networks, and power grids (Su et al., 2011). The transmission of the sensor observations about the city needs Internet connection to inform city officials. This fact leads to the utilization of the IoT since it can integrate all the facilities of the city with the Internet. Hence, the realization of the smart city vision becomes possible since the systems can be sensed, analyzed, and integrated with the use of communication technologies (Jalali et al., 2015). This enables the ability of managing the city in a cleverer and more efficient way in terms of city infrastructure, services, communication, business, energy, water, and so forth.

The smart city uses information and communication technologies to manage cities in an integrated manner (Zhang, 2010). The holistic view of the smart city can be seen in Figure 1.1.1, where smart grid, smart Transportation, smart communication, smart building, smart home, and smart infrastructure are bound together. With the use of next-generation information technologies, core systems are sensed, and the extracted information is analyzed for better management of the city and for improving quality of life in cities. To this end, it is envisioned that sensors are being deployed in different

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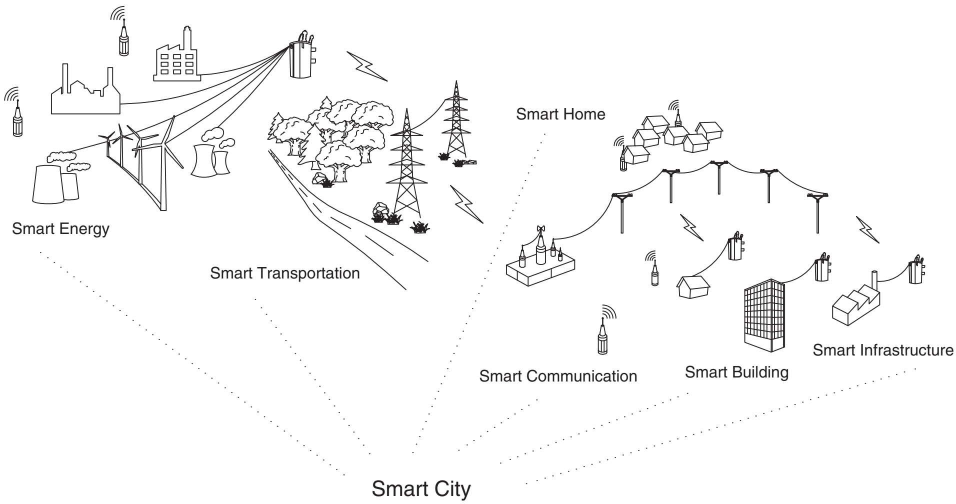

Figure 1.1.1 Smart city architecture.

key areas of the cities, such as power grids, water and underground systems, oil and gas pipelines, railways, roads, schools, hospitals, stations, airports, and so on.

The application areas of the smart city are diverse, and they connect every corner of the city to the Internet. This provides global intelligence over the management, and it paves the road for "Internet + Internet of things = smart planet" (Zhang et al., 2010). The smart city is the application of the concept of the smart planet to a specific region. The surveillance of infrastructure and environments of the city with the help of sensor technology achieves intelligent urban management and services (Su et al., 2010). The features of the smart city provide development of efficient urban strategies such as construction of smart homes, wireless cities, and smart transportation systems (Su et al., 2010).

The use of IoT to realize the smart city vision brings important challenges. With IoT technology, it is estimated that the number of devices connected to Internet will reach to 16 billion in 2020 (EU, 2010). Due to this increase, wireless data traffic that is being fulfilled in cities will reach excessive levels, and the available spectrum will become scarcer. Ever-growing demand in wireless communications has also increased the spectrum scarcity problem. Furthermore, fixed allocation of the spectrum worsens the problem of inefficient spectrum use. While the licensed spectrum bands are underutilized, the unlicensed ones are crowded, and the wireless communication is no longer feasible in these bands. To overcome the spectrum inefficiency and scarcity problems, CR technology is proposed (Mitola and Maguire, 1999). CR-capable wireless devices can access the licensed spectrum bands opportunistically and hence increase the spectrum utilization efficiency (Haykin, 2008). On the other hand, wireless nodes in these systems are resource constrained. Even though the majority of sensor nodes have duty cycling, a conventional battery in a sensor node depletes in less than a year. Therefore, an auxiliary or even a completely distinct source, such as heat, light, motion, and electromagnetic (EM) waves must be exploited to ensure sensors' operation. In this regard, EH technologies come into prominence to build wireless sensor networks (WSNs) that are free from battery constraints (Sudevayalam and Kulkarni, 2011). Hence, these challenges promote novel methodologies for obtaining the spectrum efficiency and delivering the power to the wireless devices. The most promising answers that obviate these problems are CR and EH technologies.

1.1.1 Cognitive Radio

Excessive use of wireless devices has caused spectrum scarcity problem in industrial, scientific, and medical (ISM) bands (FCC, 2002). This problem has revealed a new access technology to the EM spectrum. The enabling technology is CR (Mitola and Maguire, 1999). The most important feature of CR is the ability to adapt its operating frequency to certain frequency bands for wireless communication. Hence, this feature provides a scheme enabling dynamic access to the spectrum. With this feature, wireless devices can access to the licensed spectrum bands opportunistically. Hence, CR nodes could coexist with license holders, which are primary users.

Dynamic spectrum access has one constraint, which is interference to the licensed users. There are two interference schemes. The first one is that CR must cause no interference to the primary users. The second one is that CRs may cause interference within a certain threshold. The interference is avoided with the help of cognitive cycle operations of CR-enabled wireless devices. These operations are spectrum sensing, spectrum decision, and spectrum handoff, which are explained in detail as follows.

- **Spectrum sensing:** Spectrum sensing is the most important feature of CR due to the ability to get information about the usage of the spectrum bands. It reveals unused spectrum bands, i.e., spectrum opportunity for the wireless devices. They share these spectrum bands without causing interference to the licensed users. There are different methods to identify the spectrum opportunities, which are energy detection, waveform detection, cyclo-stationary detection, and matched filter detection.
- **Spectrum decision:** After detecting the vacant spectrum bands, CR nodes should decide on which spectrum band to transmit their data. The spectrum band for the communication is determined according to the requirement of the CR networks. The decision is performed in a centralized or distributed manner. However, the dynamic radio environment poses challenges since a common control channel, which is proposed generally in literature, may not be present most of the time. The exchange of spectrum sensing results may degrade the communication quality of CR nodes since the control packets may overwhelm the CR network.
- **Spectrum handoff:** This functionality prevents the interference caused by secondary transmission to the primary users. It provides the ability to stop the transmission of secondary users when a primary user arrives.

The features of CR increase overall spectrum utilization by using the underutilized licensed spectrum bands without causing any interference to the licensed users. Furthermore, they relieve the traffic jam in ISM bands. This also increases the energy efficiency since they decrease collisions among the secondary nodes, i.e., CR, by using the underutilized licensed spectrum bands.

1.1.2 Cognitive Radio Sensor Networks

WSNs have an event-driven communication nature that results in "bursty" traffic depending on event characteristics. Dynamic spectrum access proposes a spectrum-efficient solution for the problems related to spectrum limitations of WSNs. Dynamic change of operating spectrum to utilize the unused licensed spectrum by the CR-enabled sensor nodes improves the overall spectrum utilization. Hence, a new networking paradigm is proposed in Akan et al. (2009), named CRSNs. This networking paradigm has changed the fixed spectrum utilization adopted by the WSN nodes.

CR capability of the sensor nodes provides coexistence with the licensed users, which enables sensor observations to be conveyed in a multi-hop manner over the available licensed spectrum bands. The advantages of CR capability of sensor nodes are dynamic spectrum access, opportunistic channel usage for bursty traffic, and adaptability for reducing power consumption. Hence, CR decreases the probability of collision and packet loss, which accordingly decreases the energy consumption of the sensor nodes.

The advantages of the CR usage in WSNs reveal a number of possible application areas of CRSNs. They may be listed as indoor sensing applications, multimedia applications, multiclass heterogeneous sensing applications, and real-time surveillance applications.

1.1.3 Energy Harvesting and Energy-Harvesting Sensor Networks

Sensor nodes have an important constraint, which is limited battery power. This restricts the operation duration of sensor networks. Because of the CR capability, the sensor nodes require more energy as the cognitive cycle operations are energy-requiring processes. Hence, they drain the battery sooner, and the lifetime of the sensor network is decreased.

One of the solutions to this problem is EH. It enables to power the wireless devices from natural resources such as light, temperature gradient, and different ambient sources such as radio frequency signals and EM fields (Weddell et al., 2013). The practicality of this method comes from the fact that the sensor nodes no longer need to have their batteries replaced or recharged when they are depleted. The harvested energy from the ambient resources is utilized to run the wireless devices autonomously. This provides more energy for the communication, which results in higher quality of service (QoS). Furthermore, cognitive cycle operations can be performed with higher precision due to increased energy budget thanks to harvesting.

In this chapter, we overview all the mentioned solutions to overcome the challenges related to the realization of the smart city, and therefore we explore EH-CR wireless nodes. To this end, we first explain CRSNs and how to combine the harvesting methods with them. The motivations for spectrum-aware and self-sustaining communications in the smart city are revealed. Furthermore, challenges posed by the use of these methods in the smart city are investigated. In the light of these discussions, we study a networking architecture for the IoT, i.e., Cognitive Energy-Harvesting IoT. By using this architecture, we also overview a general implementation framework for EH-CRs.

1.2 Motivations for Using Energy-Harvesting Cognitive Radios in Smart Cities

The smart city vision necessitates observing the key system elements in cities and extracting the information about these elements for better management of the cities. The most important aspect of this vision is the observation part, which is handled by the sensors that are deployed on different systems of the city such as hospitals, roads, bridges, and so on. This makes the city smarter, which means more efficient, sustainable, and livable (NRDC n. d.).

The advantages of the smart city motivate the utilization of information and communication technologies. However, cities present harsh environments, which poses challenges on the sensor technology. In the context of the smart city, sensor nodes are deployed in different remote geographical areas that make them inaccessible in case of battery depletion or failures. Hence, the utilization of EH-CRs is crucial in the smart city. Motivations of using these radios are explained in detail in the following subsections.

1.2.1 Motivations for Spectrum-Aware Communications

A CR node can sense the spectrum, find vacant bands, and change its transmission parameters to use these vacant bands for communication. This provides opportunistic spectrum access (OSA). Since the licensed spectrum is not fully utilized, these bands are used opportunistically. CRSN is a distributed network that senses the environment and collaboratively conveys their readings dynamically over available spectrum bands in a multi-hop manner to satisfy application-specific requirements (Akan et al., 2009).

The CR capability offers spectrum-aware communications. This type of communication provides licensed bands for the sensors for opportunistic access. Spectrum-aware communications utilize the most favorable channel among the idle spectrum bands after spectrum sensing. This helps reducing transmission errors and the number of retransmissions and increasing reliability of the communication. Furthermore, CR capability fulfills the delay requirement of the applications by utilizing the idle channels. This may reduce the number of hops to the destination in the network, which also decreases the total delay.

The smart city applications require efficient and timely data transfer from the systems of the city. Since the unlicensed bands are heavily used in the cities, the spectrum-aware communications become the most important solution to overcome the spectrum scarcity problem. Furthermore, the advantages of the spectrum-aware communications such as increased reliability and decreased latency further motivate its utilization. Hence, it fulfills the requirements of the smart city.

1.2.2 Motivations for Self-Sustaining Communications

Sensor technology is a key element for different IoT applications. Depending on the application, sensor nodes sense and transmit data either intermittently or in a periodic manner. Data transmission consumes a few milliwatts of power and microwatts of it during sleep mode (Moghe et al., 2009; Sudevalayam and Kulkarni, 2011). However, a typical sensor battery depletes in less than a year. If we consider the number of deployed sensors and their energy requirements in the domain, there is a clear need of an auxiliary or even a distinct source. However, this may or may not be an option for each application mostly due to size constraints, maintenance, and/or deployment costs. Large number of sensor node utilization and their individual energy demands require energy-efficient solutions and sustainable use of resources. Hence, this also promotes energy-efficient solutions by encouraging battery-less systems.

EH resolves the problem of limited lifetime of wireless devices such as sensor nodes (Moghe et al., 2009). This approach is very beneficial for the sensor nodes, which have limited battery power. It exploits the ambient resources, namely radio frequency (RF) signals, heat, and movement variations, vibrations, EM and sound waves, and so forth, and provides utilizable energy to the wireless devices.

The digital skin of the smart city, which is sensor networks deployed in different parts of the city, performs periodical monitoring and requires an excessive amount of energy. The sensor deployment in large numbers and the difficulty in replacing the battery motivate the use of EH approaches for the smart city. Hence, it stands as a way of providing more reliable, durable, and profitable alternative for the proper system operation.

1.3 Challenges Posed by Energy-Harvesting Cognitive Radios in Smart Cities

Sensor nodes have limited energy, memory, and processing power. Furthermore, CR operation increases the energy consumption of these nodes with additional operations such as spectrum sensing and spectrum management. These challenges are intensified by the smart city. In the following subsection, we list these challenges.

- *Bandwidth*: Depending on the application, the sensors in the smart city demand high bandwidth. For example, some applications require multimedia delivery. This poses an important challenge to overcome in a dynamic radio environment. The heterogeneity of spectrum bands and their dynamic availability change the bandwidth of the network, which requires flexibility in bandwidth of the licensed bands.
- *Quality of Service (QoS)*: CR offers flexibility to satisfy QoS requirements of the smart city. The QoS level depends on the application and the observed key elements of the cities. QoS is measured in terms of reliability, throughput, and delay. The most important factor for the change of QoS level is the licensed user activities.
- *Coverage area*: The smart city must provide coverage for very large geographical areas. However, the licensed user activity will vary spatially. This poses challenges for the coverage since the nodes in a region may not have any spectrum opportunity for some period of time due to licensed user activities. Hence, we cannot extract information from those regions, which degrades the vision of the smart city.
- *Scalability*: Monitoring such a large geographical area will be performed by large number of sensors. This requires scalable solutions to enable the smart city. Furthermore, this forces the communication infrastructure to be flexible and adaptive to any change in the network.
- *Reliability and delay*: The sensory information from the elements of the city should be reliably delivered in real time. However, the reliability of the communication may be degraded by the licensed user activities. This may distort the channel conditions and cause network outages and interference caused by the transmissions of primary users. Furthermore, intermittent connectivity of the CR nodes causes an increase in the delay.
- *Computational capability*: The computational capability of the CRSN nodes is limited, and this poses a challenge to perform complex tasks. The sensor nodes are also energy constrained, which exacerbates the limited computational complexity of the nodes.

- *Intermittency in available sources*: Consistency of available sources cannot be guaranteed. For example, in RF EH the energy is harvested from the ambient RF signals. However, these signals are not always present, and hence, harvestable energy is not continuous. This is also the case for different EH resources such as wind and light.
- *Integration of the sensor networks to the Internet*: For the realization of a smart city, the extracted data should be delivered to the city authorities or the citizens. However, in such a large geographical area with varying deployment conditions, the connection of the sensors to the Internet poses a challenge.
- *Service differentiation*: ZigBee, IEEE 802.15.4, 6LoWPAN, and similar technologies are utilized in the IoT domain. Various sensor types must cooperate with each other to achieve a desired goal in the smart city. Different sensor nodes deployed in a system of a city must be compatible with one gateway, which provides the Internet connection to the system.

CR and EH pose some significant challenges. These challenges are intensified by the physical conditions in the cities. Furthermore, the harsh environmental conditions of cities decrease the possibility to transmit the observed data to the cloud for the analysis and the evaluation of the critical data.

1.4 Energy-Harvesting Cognitive Internet of Things

1.4.1 Definition

The advancements in wireless technology make interaction between people and the digital world more powerful and sophisticated. Wireless communications technology plays a vital role for these advancements. In this respect, the IoT is one of the most innovative paradigms for next-generation wireless networks (Gubbi et al., 2013).

Every electronic device will be connected to the Internet as a result of the notion of the IoT (Gubbi et al., 2013). A clear definition has not been determined for the IoT despite the fact that concept of the IoT is obvious. It can be viewed as a union of next-generation wireless devices that sense the surrounding and gather information from the physical world (Castellani et al., 2010).

Connection of the wireless devices with each other and to the Internet results in congestion and a high volume of traffic in the EM spectrum. As these devices in the IoT mainly use already crowded ISM bands, the problem of spectrum scarcity is exacerbated by the introduction of the IoT. Furthermore, the licensed spectrum bands are under-utilized. CR technology has been proposed as a solution to the problems of spectrum scarcity in unlicensed spectrum bands and the under-utilization of licensed spectrum bands (EU, 2010). Wireless devices with CR capability can use the spectrum opportunistically. Unlicensed users, i.e., CR nodes, coexist with licensed users, i.e., primary users (PUs). Cognitive cycle operations enable CR nodes to use the licensed channels in an opportunistic manner. These operations provide scanning of the spectrum for an opportunity to transmit and ceasing the transmission if PU activities exist during communication. Hence, cognitive capability of devices increases the efficiency of the spectrum utilization and overcomes the spectrum scarcity problem. For instance, Wu et al. (2014) present the cognitive IoT (CIoT) to enable cognition in the IoT devices in terms of spectrum usage and the interaction with the physical and social worlds.

The wireless devices in IoT are resource constrained. Furthermore, cognitive cycle operations deplete the battery of the wireless devices sooner. Moreover, it is not possible to replenish their batteries. Hence, EH is an efficient method to power wireless devices in the CIoT. Therefore, the networking paradigm of Energy-Harvesting Cognitive Internet of Things, consisting of EH-CRs, is a key enabler of the smart city by satisfying its requirements.

1.4.2 Energy-Harvesting Methods in IoT

In this subsection, we overview the existing EH methods in the IoT domain. Harvesting methods can be separated into two groups depending on the energy demand and availability in harvestable resources, named Harvest-Use and Harvest-Store-Use, respectively (Sudevalayam and Kulkarni, 2011). Furthermore, the harvestable resources can be categorized according to their controllability and predictability. With the help of these categories, leading harvesting techniques are compared and their advantages and disadvantages are discussed in Table 1.1.

EH from light sources is a well-studied method of power provision that gathers energy from ambient lights, either from the sun or from artificial light sources, and is

Table 1.1 Comparison of Energy-Harvesting Techniques.

Technique \ Features	Energy availability	Characteristics	Advantages	Disadvantages
Solar	poor	ambient, uncontrollable, predictable	environmental, independent of grid, high output voltage	depends on sunlight, deployment constraints
Thermal	poor	ambient, uncontrollable, unpredictable	environmental, independent of grid, scalability	depends on thermal gradient, requires efficient heat sinking
Airflow	good	non-ambient, uncontrollable, unpredictable	environmental, independent of grid	fluctuating density, hard to implement, requires construction
Motion	fair	non-ambient, controllable, unpredictable	no external power source, compact configuration, light weight	charge leakage, highly variable output
RF	good	Non-Ambient, uncontrollable, predictable	abundant in urban lands, allows mobility	scarcity in rural areas, low power density, distance dependent
M-field	good	non-ambient, controllable, predictable	no external power source, easy to implement, light weight	requires high current flow, safety vulnerabilities
E-field	excellent	non-ambient, controllable, predictable	no need of current flow, easy to implement, always available	capacitive, mechanical constraints

based on the phenomenon known as the photovoltaic (PV) effect (Sudevalayam and Kulkarni, 2011). Solar EH is performed by solar cell inlaid photovoltaic panels in mostly outdoor applications for the monitoring of overhead power lines (Moghe et al., 2009; Sudevalayam and Kulkarni, 2011). For indoor applications, specialized photovoltaic materials, which are better suited for diffused lights, are employed for taking advantage of the light emitted from ambient lighting elements.

Although the PV modules are getting cheaper, easier to use, and more efficient each passing day, due to the dramatic fluctuations on the output power and ongoing installation and maintenance costs, they have limited applicability in mission critical applications (Akan et al., 2017). Another EH method, kinetic energy harvesting (KEH), is the conversion of ambient movement energy into electrical power. Wind turbines and, on a smaller scale, anemometers are being utilized for exploiting airflow energy to enable wide-scale communications structured in open space; however, their performance is highly threatened by the environmental variables similarly to solar energy related techniques (Moghe et al., 2009; Sudevalayam and Kulkarni, 2011). Piezoelectric materials, similarly, are used often for gathering energy from highly random and mostly unpredictable motion variations driven by external factors (Matiko et al., 2009; Moghe et al., 2009). KEH is an applicable method for both indoor and outdoor domains, as there is a variety of sources that can be conveniently exploited to drive low-power wireless autonomous devices. However, constituting a generalized harvesting system, especially for vibrating sources, is an ongoing issue, because the conversion efficiency highly varies with the resonant frequency of the vibration, which makes necessary a specialized design for each source (Moghe et al., 2009; Sudevalayam and Kulkarni, 2011; Zhao et al., 2013).

Thermal energy harvesting, i.e., thermoelectric generation (TEG), is simply based on converting temperature gradients into utilizable electric power; this is based on the Seebeck effect, which occurs in semiconductor junctions. TEG is an innate power provision technique for Smart Grid communications, in which temperature swings between the grid assets and the environment are used to extract energy (Sudevalayam and Kulkarni, 2011). Similarly to environmental sources such as solar and airflow, it strictly depends on the ambient variables and therefore may fail to satisfactorily provide stable power in some cases. For less power-requiring sensor nodes; Peltier/thermoelectric coolers and thermocouples are widely used for building delay-tolerant wireless networks. Although harnessing power by using temperature gradient between the systems sounds promising, there is a fundamental limit, namely, the Carnot cycle, to the maximum efficiency at which energy can be harvested from a temperature difference (Akan et al., 2017).

Regarding the intensive use of GSM (global system for mobile) networks in urban areas, radio frequency (RF) signals attracted both academia and industry in recent years (Sudevalayam and Kulkarni, 2011). RF EH simply targets RF signals emitted from base stations, network routers, modems, smartphones, tablets, and any other wireless signal sources and collects them via large aperture power-receiving antennae, subsequently converting the gathered waves into utilizable DC power for the sensor nodes. An RF EH circuit includes a transducer for converting EM waves into alternating current (AC) and a rectifier for converting the AC power into the direct current (DC). In addition to them, RF filters, voltage multipliers, and couplers can be also utilized for more advanced harvesting procedures. Even though this method delivers reliable solutions regardless of the environmental variables, deployment inflexibility and low power provision efficiency hamper its utilization in some applications (Cetinkaya and Akan, 2017a; Sudevalayam and Kulkarni, 2011).

Wireless networks can also be powered by exploiting EM fields, i.e., magnetic and electric fields, emitted from current-carrying and/or tension-holding conductive materials (Sudevalayam and Kulkarni, 2011; Zhu et al., 2009). Magnetic field (M-field) EH is based on coupling magnetic fields surrounding the AC current-carrying conductors by simply clamping them with current transformers. This technique provides an adequate rate of power, and its utilization is less complex; however, the availability of energy is affected severely by the current density on the power line. As the M-field occurs due to an AC current, the line must be loaded to allow sufficient current flow. Furthermore, mostly due to space limitations, it might not be an efficient solution for applications in which it is not that practical to clamp the conductor. As the field density decreases quadratically with the distance from the field-emitting source, this approach also requires very close placement for the most effective EH performance. In wide open spaces, such as Smart Grid and smart city applications, this approach performs sufficiently in scavenging power from the targeted/attached assets to operate remote monitoring devices. However, gathering energy in a safe way from a high current–carrying asset that has physical contact with the harvester is still a challenging issue. To mitigate the safety concerns, M-field-based methods need to be equipped with advanced protection mechanisms and components.

Similar to M-field-related approaches, electric field (E-field) EH (EFEH) also targets surrounding, unutilized field flow for operating low-power autonomous devices. E-field EH is simply based on obstructing the free charges that are being emitted by a conductor with voltage potential and draining them via the displacement current. E-field EH was first tried on high and middle voltage overhead power lines by utilizing the E-field in abundance (Moghe et al., 2009; Moghe et al., 2015; Zhangl et al., 2009; Zhao et al., 2013). First results revealed the potential of this method in powering wireless devices placed for condition monitoring procedures and accordingly encouraged further efforts for building advanced Smart Grid services. Later, it was applied to low voltage systems as mounting single-phase AC power cords with metallic sheets (Cetinkaya and Akan, 2017a; Chang et al., 2012; Choi et al., 2014; Honda et al., 2015). These efforts disclosed that it is also possible to constitute an applicable EFEH methodology for applications in which E-field intensity is considerably low. In short, E-field is the only source that is neither intermittent nor dependent on the load. As the voltage and the frequency are firmly regulated and exactingly maintained, the E-field is therefore stable and predictable in its behavior. Thus, it can be regarded as the most promising way to compose long-term and self-sustainable communication systems notwithstanding the ambient factors (Cetinkaya and Akan, 2017b). A detailed comparison of the aforementioned methods is illustrated in Table 1.1.

1.4.3 System Architecture

In the system architecture, the nodes transmit their readings opportunistically to the access point or the sink that has the Internet connection. Furthermore, the sink or the access point has the CR capability.

Network topologies may differ according to the application. These topologies are explained as follows.

Ad hoc CRSN in the IoT: In this architecture, there is no central entity for regulating the spectrum-aware communications. Hence, the nodes exchange control packets among themselves to perform interference free communication. The readings of the sensors are transmitted in multiple hops in an ad hoc manner. Spectrum management is performed cooperatively between the nodes.

Clustered CRSN in the IoT: In a dynamic radio environment, the nodes can only communicate according to their spectrum availability. The nodes located within a neighborhood have similar vacant channels. It is highly possible that they have common channels among them. This provides a common control channel between the cluster members to exchange the control data for spectrum-aware communications. This is the most convenient architecture to support the communication.

Heterogeneous CRSN in the IoT: In this architecture, some special nodes that have more power sources are deployed. These nodes may have special responsibilities such as spectrum bargaining (Haykin 2008).

Mobile CRSN in the IoT: In addition to the dynamic radio environment, the nodes are mobile in this CRSN architecture. This makes the operation of CRSN more dynamic. Solutions for dynamic spectrum access should also consider the mobility in this architecture.

1.4.4 Integration of Energy-Harvesting Cognitive Radios with the Internet

CRSNs are distributed networks having no central entity regulating the communication. Due to the large operation coverage of the smart city, sensor observations are conveyed in a multi-hop manner. Furthermore, some nodes can reach the sink or access point in one hop. The CRSNs are the main components of devices that can extract information from the environment; hence, they are the main pillar of the IoT. The harvested information by the CRSN nodes is important for the actions to be taken and the information processing. The integration of CRSN with the mobile networks or the Internet realizes the IoT and manages communications in CRSNs. To this end, we overview architectures (Alcaraz et al., 2010; Honda et al., 2015) to enable the connection of CRSNs with the Internet.

Stack-based (Christin et al., 2010) and topology-based (Alcaraz et al., 2010) solutions are the two approaches that integrate WSNs to the Internet. The stack-based integration approaches require similarity between the network stacks of the sensor network and the Internet. Front-end solution, gateway solution, and TCP/IP solution are the stack-based integration approaches. There is independency between the Internet and the sensor networks in the front-end solution. In this approach, the sensor network uses its own protocol. On the other hand, the Internet uses TCP/IP. The gateway approach supports tunneling for the exchange of information and the integration between the sensor networks and the Internet. In the TCP/IP approach, sensor networks and the Internet use the same protocol, which is the TCP/IP solution advocating the integration by utilizing the same networking protocols in both sides. On the other hand, the topology-based approaches depend on the deployment of the Internet-connected nodes in the sensor networks.

The spectrum awareness by CR capability makes an important difference for the stack-based integration solutions. The access point or the base station, which provides the Internet connection, must behave as a CR node and operate in an opportunistic manner. They are not resource limited, which makes them capable of complex operations. In a front-end solution, the base station has two interfaces: one for CRSN and one for Internet connectivity. The packets from CRSN nodes are gathered at the base station by spectrum-aware communications. The base station sends the collected information to the cloud or to a user via an Internet connection using TCP/IP. The Internet connection of the CRSN nodes is achieved by the base stations at the edge of the network. This architecture is the classical approach existing in the literature.

The gateway approach supports the addressing of the CRSN nodes such that a user on the Internet communicates with specific nodes in the network. However, the bottleneck in this approach is again the base station since IP tunneling is implemented, and the information must traverse the base station. This approach uses extra bits for the encapsulation of the IP packet. This degrades the benefits of this approach.

The full integration with the Internet is achieved by the TCP/IP solution. A user on the Internet can access any node in CRSN. For this approach, IPv6 is very promising for sensor networks, as it enables sensor nodes to be directly connected to the Internet (Hui and Culler, 2008). The use of IPv6 can realize the TCP/IP solution for CRSNs and increase the possibility of usage CRs in the smart city. It provides interoperability between CRSN and different network systems in the smart city, which will emulate always-on link communication (Hui and Culler, 2008).

In the topology-based integration solutions, location and deployment of the nodes, as well as the base stations, which are directly connected to the Internet, are all important (Christin et al., 2009). Multiple nodes have access to the Internet in hybrid solutions, which are one of the topology-based integration approaches. These nodes are the neighbors of base stations. In an access point solution, sensor nodes have direct access to the access points.

1.5 A General Framework for EH-CRs in the Smart City

1.5.1 Operation Overview

As its definition implies, this concept of smart city emerges from the need of better management of the cities. Hence, many national governments are pushed to adopt information and communications technologies to provide better services in the cities, which realizes the smart city concept (Schaffers, 2011). With the application of the smart city, city resources are efficiently utilized, costs of the city are reduced, and the life quality of the city residents is increased (Zanella et al., 2014).

The adoption of the IoT in the smart city also provides new services for the citizens and the governments. These services may be structural health, waste management, air quality and traffic congestion monitoring, and smart lighting and parking, to name a few (Zanella et al., 2014). IoT networks will find a number of deployment areas in the city to realize the concept of the smart city. These areas include transport systems, bridges, electric grid, hospitals, schools, cultural sites, and so forth. Hence, with the IoT concept, the Internet becomes even more pervasive, which also helps realizing the smart city. Every device will be connected to each other and the Internet.

The business side of the smart city is studied in terms of the public actors and the city governments (Walravens and Ballon, 2013). However, there are some open issues

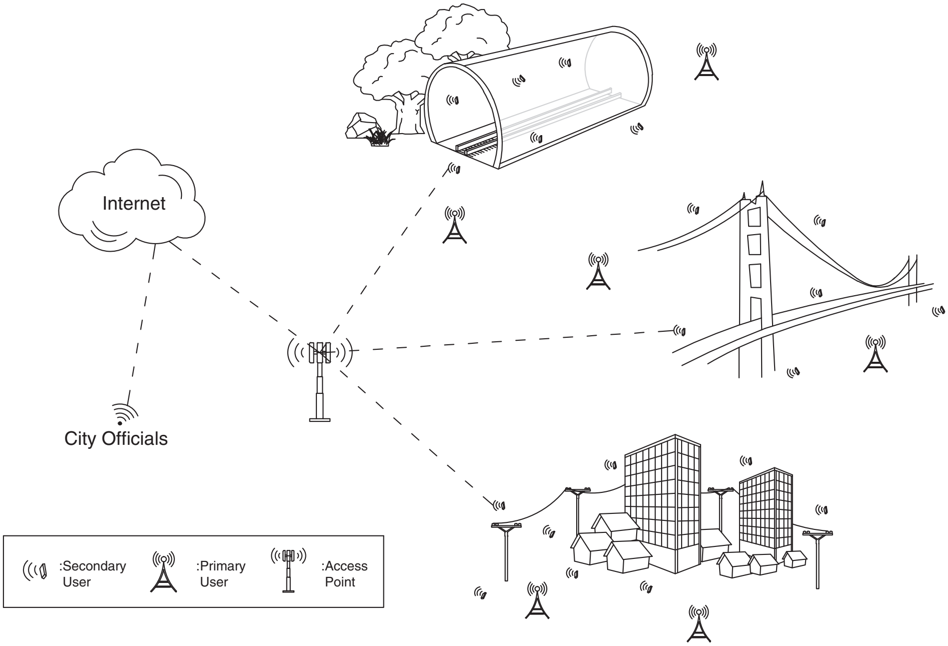

Figure 1.5.1 Operation overview of EH-CR in the smart city.

in the technical side of the smart city. First of all, due to excessive increase in wireless communications, there are some challenges. The smart city concept requires to sense the systems of the city and to report the application-specific data to the city officials. This causes an enormous amount of data transfer from different part of the city, which also increases wireless traffic in the city. Hence, new communication paradigms should be utilized. To this end, CR is an efficient solution to overcome the excessive wireless traffic in the city by opportunistic spectrum access. Secondly, wireless devices deployed in the smart city are resource constrained. The reporting about the systems in the city causes energy depletion of the wireless nodes. Since the maintenance of these nodes is a difficult task, EH methods are perfect candidates to extend the lifetime of these nodes. To this end, the concept of EH-CRs becomes very important to address the technical challenges for enabling the smart city.

From the holistic point of view, operation overview of EH-CRs in the Smart Cities can be explained as in Figure 1.5.1. The EH-CR nodes deployed in the systems of the city report their sensing results to the city officials thanks to the approaches enabling integration of EH-CRs with the Internet. By using the spectrum opportunistically, they send their information in a more reliable manner. With the adoption of EH, they do not face the shortages in battery power. They increase the communication efficiency and power efficiency of the smart city.

1.5.2 Node Architecture

The node architecture of an EH-CR node in the smart city contains four main units (Figure 1.5.2), which are antenna unit, ultra-low power communication unit, ultra-low

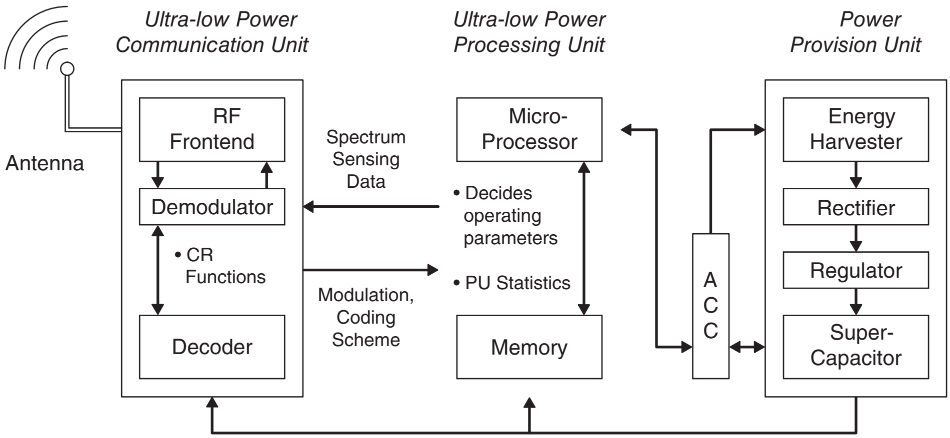

Figure 1.5.2 Node architecture of EH-CR node.

power processing, and power-provisioning unit. The ultra-low power communication unit provides the capability of channel switching, channel sensing, modulation, and power control. The power-provisioning unit has an energy harvester, a rectifier, a regulator and a supercapacitor. It provides energy to the antenna unit, communication unit, and power processing unit. The aim of this unit is to convert an available resource into utilizable electrical power to operate the nodes. The processing unit decides the operating parameters, which consist of a microprocessor and memory. The communication unit has RF frontend, demodulator, and decoder to provide the communication with CR functionalities.

The block stated as ACC in Figure 1.5.2, i.e., autonomous connection circuit, needs to be employed to switch between harvesting and nodal operation stages. This circuit simultaneously observes the voltage level on the storage element, i.e., the supercapacitor, and accordingly enables charge transfer when the harvested energy is sufficient enough for sensory operations and disengages the supercapacitor from the circuit to turn back the harvesting period when the voltage level descends below a certain threshold. This operation, held under the control of the processing unit, not only prevents undesired discharge of the supercapacitor but also allows more frequent transmission cycles by shortening the time exerted for harvesting processes (Cetinkaya and Oktay, 2017b).

1.5.3 Network Architecture

The networks consisting of EH-CRs have ad hoc and cluster-based architectures. The centralized architecture would not be feasible due to limited harvestable energy. The harvestable energy cannot support the energy required for the transmission and the reception of the control data with the central entity regulating the communication.

In ad hoc networks, each EH-CR node detects the vacant channels with the spectrum sensing. The sensing results are exchanged in the neighborhood to decide on which channel to operate for communication. This may lead to high power consumption for the nodes due to failures in the exchange of control data and false spectrum sensing results. Hence, cooperation between nodes is required to increase the reliability of the

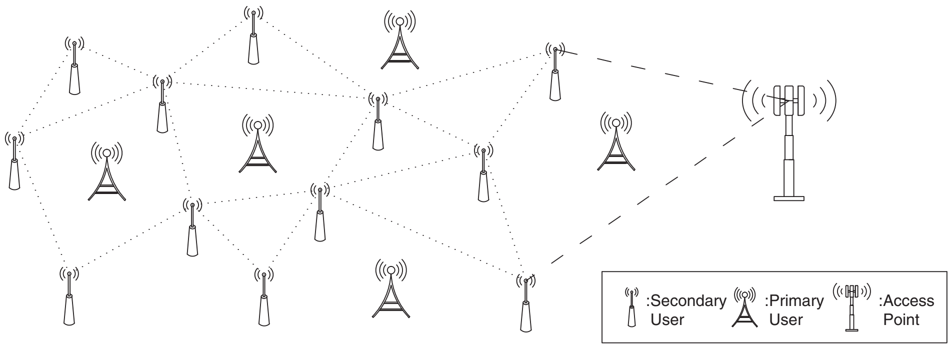

Figure 1.5.3 Ad hoc network architecture of EH-CR in the smart city.

spectrum-aware communications; however, it may increase the amount of the control data. Ad hoc network architecture can be seen in Figure 1.5.3.

The cluster-based architecture supports cooperation in the network by enabling more local coordinators in the network. These local coordinators are called cluster heads, where the spectrum sensing results of the cluster members are gathered for determining the operating frequency among the cluster members. This increases the reliability since the nodes in a neighborhood reach an agreement on the parameters of the spectrum-aware communications.

However, the cluster heads require more power since they are the most active nodes in their corresponding cluster. These issues make the cluster head selection procedure important. The cluster heads should have the highest number of available channels, since they should communicate with as many neighbors as possible to increase their connectivity. Furthermore, the node exchanges information with its members, which increases the power consumption of the cluster heads in comparison to the ordinary nodes. Hence, the selection of the cluster heads in the network should depend on the harvested energy as well as the number of available idle channels. This architecture is illustrated in Figure 1.5.4.

1.5.4 Application Areas

The main application areas of the networks consisting of EH-CRs are the systems of cities. These application areas can be outlined as follows (Hernandez-Munoz et al., 2011).

- *Transport systems*: Provisioning of traffic data by dynamic mapping, monitoring of parking lots, pollution detection in different parts of the city, and monitoring of the transportation network.
- *Hospitals*: Monitoring of hospital conditions such as temperature of vaccines and people with disabilities.
- *Alert Services*: Deployment of EH-CRs in different parts of the city for alerting services such as traffic control and communication services to alert citizen about critical situations.
- *Energy systems*: Decreasing the outages and failures and monitoring of water and gas consumption by smart metering systems.

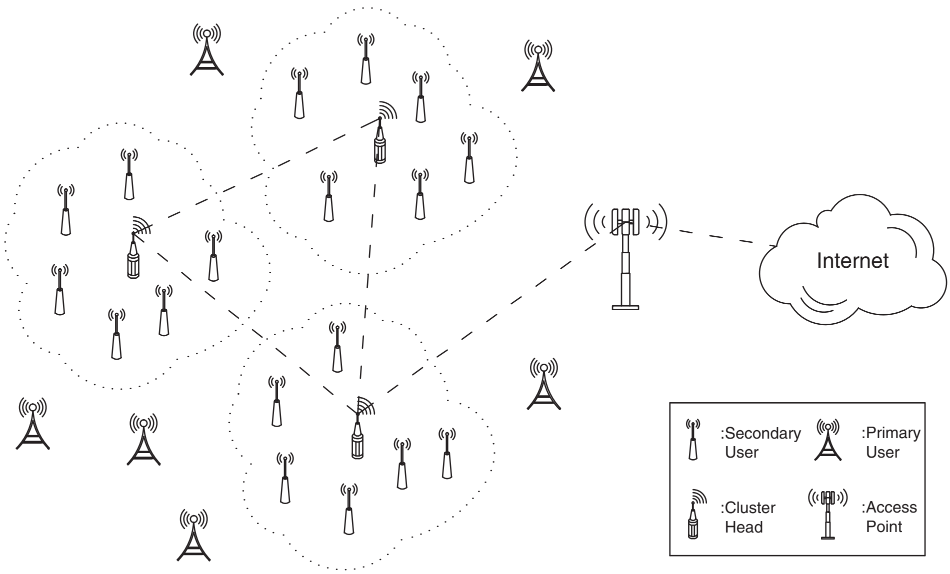

Figure 1.5.4 Clustered network architecture of EH-CR in the smart city.

1.6 Conclusion

In this chapter, we overview the joint use of two important techniques for the realization of the smart city concept, which are CR and EH techniques. We discuss these techniques and their use in the smart city. We explain the motivations for spectrum-aware and self-sustaining communications. The challenges posed by utilization of these techniques in the smart city are studied, and IoT networks with CR and EH capabilities are discussed. According to these discussions, a general framework for EH-CRs is explained for the smart city concept.

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