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Energy Harvesting Cognitive Radio Networking for IoT-enabled Smart Grid

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Abstract The Internet of Things (IoT) provides connectivity to the objects that monitor and sense the environment to integrate physical world with digital world. If IoT is enabled in the Smart Grid (SG), it can benefit from advantages of the IoT such as interoperability, connectivity, etc. By combining the IoT with energy harvesting (EH) and cognitive radio (CR) techniques, the problems of SG, such as harsh channel conditions and limited battery power, may be resolved. Hence, incorporation of EH and CR reveals a new networking paradigm for IoT-enabled SG. To this end, we first introduce CR usage in the IoT-enabled SG, and explain the advantages and challenges of CRs. Furthermore, we propose EH approaches for the resource constraint of wireless devices in the IoT-enabled SG. Operation and node architecture of energy harvesting cognitive radios, and network architecture of the IoT-enabled SG are described to explain details of our networking paradigm. Open issues and future research directions are discussed to enable this new paradigm.

Keywords Energy Harvesting, Cognitive Radio, Internet of Things, Smart Grids.

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1 Introduction

The IoT paradigm provides connectivity to objects for information exchange from one remote place to another via the Internet [1, 2]. These objects sense the physical world and harvest information about it, and send the harvested data to remote users via the Internet. It provides the accessibility of information from anywhere in anytime. These objects form interconnected networks that are self-configurable and intelligent. Hence, the IoT is utilized in a number of applications such as e-health monitoring, transportation, environment monitoring, and logistic management [3].

As the IoT extends the wireless communication by providing connectivity among the objects, SG supports evolution of electrical power system by the utilization of next generation communication systems [4, 5]. It paves the road for more agile grid with increased efficiency, reliability and security. The energy demand, aging infrastructure of the electric grid and varying energy production due to renewable energy resources are some challenges of the SG. Furthermore, it provides real-time remote monitoring of the SG equipments for power provisioning, estimating failures, capacity limitations and blackouts [4], [6]. This provides an effective monitoring of the electric grid and control for safe, reliable and efficient power delivery in the SG [7]. Wireless sensor networks are main components of the IoT, and they form a digital skin the observed system. From this point of view, enabling the IoT in the SG is fundamental step towards the realization of it.

The SG can benefit from the application of the IoT technology since the IoT enables smart monitoring of the environment, which is the main goal of the SG. Utilization of the IoT provides efficient management of resources by smart meters, home gateways, smart

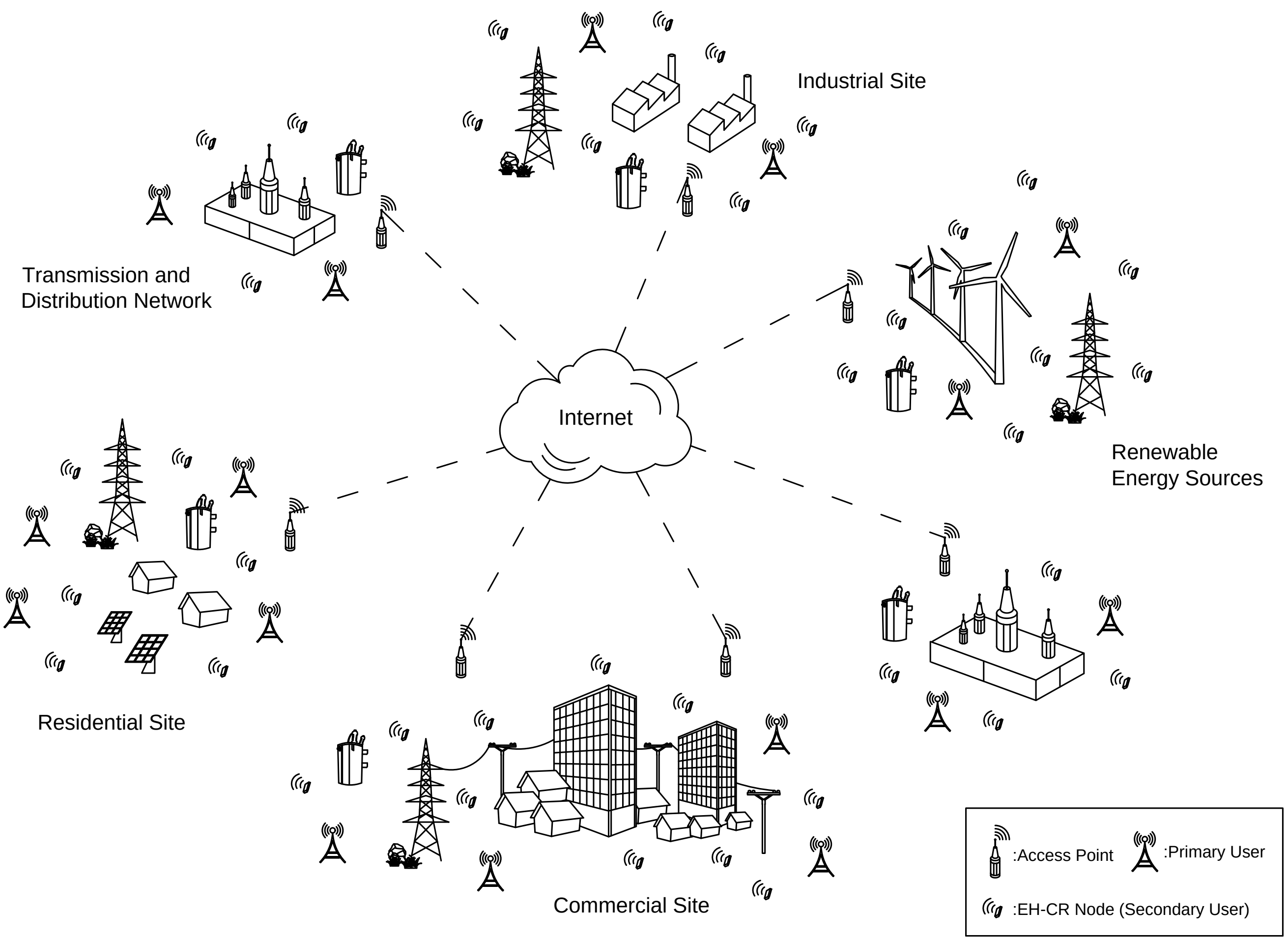

Fig. 1 IoT-enabled SG Architecture.

plugs and connected appliances via the Internet since it ensures efficient communication between consumers and utility providers, which provides efficiency in energy production and consumption [8]. Satisfaction of consumers' requirements and energy production from alternative resources cause a very dynamic environment and require efficient management of the electric grid. Autonomous monitoring, diagnosis and control, and efficient operation of the power equipments for the power generation, and distribution require monitoring and actuating devices [9]. Hence, the inclusion of the IoT in the SG is important. This will increase the utilization of information and communication technologies in the SG and provide effective management of power grid system [10]. Empowering the SG with the IoT technology will lead a new paradigm, i.e., IoT-enabled SG. An IoT-enabled SG architecture can be seen in Fig. 1, which shows that the elements of the SG communicate over the Internet. The nodes, which are named as energy harvesting cognitive radios (EH-CR) in sequel, are our IoT wireless devices, and they access the Internet via access point. The condition of power grid elements, their energy production, the consumption of the energy are observed and measured via the IoT devices. The observations and measurements are sent over multiple hops to reach the Internet gateway, i.e., access point, to send them to remote areas for necessary actions to be taken in the IoT-enabled SG. Power consumption in industrial, commercial and residential sites can be monitored, and the power generated by renewable energy resources can be observed in real time via the Internet. For this architecture, SG benefits from the advantages of IoT, which are support for the communication of heterogeneous wireless devices, flexibility and context-awareness. This provides also better management of the grid with the Internet connection between SG components, which increases accessibility.

Enabling wireless technologies for the communication across the Internet are Wi-Fi, 3G, 4G, and satellite [11]. On the other hand, the standards used in the IoT environments are IEEE 802.11 and IEEE 802.15.4 for local areas. Hence, IoT devices to realize the SG operate mostly on ISM bands. However, these bands are heavily utilized. The over-utilization decreases the communication quality and increases the energy consumption of the resource-constrained wireless devices in the SG due to collisions. Furthermore, communication links have high packet error rates and variable link capacity due to the SG specific challenges such as electromagnetic interferences and equipment noise [9], [12], [13]. Hence, the channel conditions are generally harsh in the SG environment [14], which results in a dynamic delay and capacity variations in the SG networks. To overcome these challenges, CR technology can be utilized in the SG applications [15] so that the IoT nodes in the SG can access bands, which have better channel characteristics, in a dynamic manner. CR has special functionalities, which enables it to utilize licensed bands opportunistically, are spectrum sensing, spectrum decision and spectrum hand-off [16]. With the spectrum sensing, idle licensed channels are determined. Afterwards, CR can resolve the problems of spatio-temporal variation on the channel characteristics, reliability, latency, harsh propagation conditions and collisions due to excessive use of certain channels by utilizing idle licensed channels [9].

Wireless nodes in the IoT-enabled SG are resource constrained. In spite of the recent advancements in ultra-low power transceiver and processor technologies, a conventional battery tends to deplete less than a year. This issue necessitates periodic replenishment and maintenance, however, the excessive numbers of the deployed elements, the tasks that are being fulfilled and the randomness of depletion times make this option impractical. Therefore, the need for a self-sustaining mechanism becomes more apparent to overcome limited power supply difficulty of IoT nodes. Although an auxiliary and/or a totally distinct source can contribute this aim sufficiently, energy harvesting methods come to the forefront as the energy that can be provided by these techniques is theoretically unlimited. As there are numerous potential alternatives, i.e, environmental and non-environmental, to gather energy, temperature and motion variations; electromagnetic fields, radio frequency signals; and light propagations can be regarded as the well-studied ones of these techniques. EH eases the problem of limited supply for IoT-enabled SG.

There are two fundamental problems in the domain of IoT, which are spectrum scarcity and resource constraint. They are intensified if the IoT is utilized in the SG since wireless channel conditions and environment in the SG are harsher than those of any other IoT domain. In this paper, we propose a new networking paradigm, energy harvesting cognitive radio networking (EH-CRN) for IoT-enabled SG, which utilizes two important techniques, namely energy harvesting and cognitive radio. The contributions of this paper are to provide a framework to merge these techniques to eliminate the problems of IoT-enabled SG and to introduce challenges, the potential advantages of this new paradigm, and to present network and node architectures. To this end, we first explain the usage of CR in the IoT-enabled SG. Afterwards, we outline the existing energy harvesting techniques and how they can contribute to the realization of IoT-enabled SG. We overview the operation of the energy harvesting cognitive radios (EH-CRs), and explain their node and network architectures. We also state open issues and future research directions to realize EH-CRN for IoT-enabled SG.

The paper is organized as follows. CR usage in IoT-enabled SG is explained in Section II. Energy harvesting techniques for IoT-enabled SG are outlined in Section III. The node and network architectures, their operation, and open research issues are discussed in Section IV. Finally, Section V concludes the paper.

2 Cognitive Radios in IoT-enabled Smart Grid

The centralized management of the electric grid has experienced a paradigm shift towards the SG. It enables the two way communication, which connects the consumer side and the utility companies [5]. This paradigm provides an efficient management and control of the grid in a better way. SG brings the capability of monitoring of demand and supply in real time. Hence, SG adds new services to the customers, in which they can adjust their energy consumption according to the demand and supply balance.

To enable the concept of the SG, it should be integrated with the next-generation information and communication technologies having the ability of sensing and broadband wireless communication, supporting ubiquitous computing and adaptive control [17]. This will increase the stability of the electric grid, decrease unnecessary power consumption, predict communication blackouts, and provide security of the grid and power provisioning.

According to [17], sensing, transmission and control are the basic functionalities that are being offered by the SG infrastructure. Smart meters and sensors are the key components for sensing operations. Depending on the transmission scheme, sensed data reach to the controller or centralized coordinator/gateway via multiple hops. The SG covers a large geographical area, which makes the communication infeasible due to the harsh environmental conditions and the increased distance between communicating parties. Hence, the communication architecture of the SG is divided into three main groups, which are home/building area networks (HANs/BANs), neighborhood area networks (NANs), and wide area networks (WANs) [18], [19], [15], [17]. The sensors in homes are essential parts of HAN. They send their readings to the local access points. HANs in a neighborhood constitutes a NAN, and a NAN connects the grid to the core utility systems [15]. SG's WAN is the network that covers the core network and the backhaul network [15]. For the connection of these networks wireless communication is utilized. When we look at the overall SG network, there is a hierarchical communication infrastructure [19].

Sensor nodes may be deployed in different parts of the electrical power system, which make them vital components of the SG. The deployment of the sensor nodes on the grid realizes the efficient and reliable power flow from the generation units to the end users [14]. These sensors provide monitoring of the power systems and diagnosing failures, which prevent the outages, and increase the reliability and efficiency of the electric grid [14], [21]. The SG benefits from the advantages of wireless sensor networks (WSNs), which are easy deployment, collaborative effort for sensing, support for increased coverage, flexible operation and low cost. This provides low-cost monitoring and diagnostic system for the SG [22].

The use of wireless sensor nodes poses some challenges in the SG. These challenges can be summarized as harsh channel conditions, reliability and latency requirements, bit error rate and channel capacity variation, and the limited power capability of the sensor nodes [14]. Conditions in SG may deteriorate the wireless channel by high humidity, dirt, dust and vibrations [23]. These environment-related parameters are also harmful for the sensor nodes. Furthermore, different SG applications would have various quality of service (QoS) requirements. For instance, monitoring a transformer vault demands a strict delay requirement to decrease the repair time by reporting the failure within a restricted time. Hence, the deployed sensor nodes should satisfy different levels of QoS. Also, the electrical systems in the SG cause variation in the noise level and interference in these environments may be high. These situations result in variation of the signal-to-interference-plus-noise ratio (SINR), which causes deviations in the channel capacity. Furthermore, limited battery power and processing capability require highly energy-efficient protocols. The most important challenge is the collisions and resulting redundant energy consumption due to over-utilization of the unlicensed bands.

Although there are some studies to increase the context awareness of the SG, few of them consider the spectrum-awareness of the devices deployed in the SG [24]. These studies provide recognition in the spectrum usage. CR technology is proposed to support spectrum-awareness in wireless communications. The motivations behind this technology are to overcome the spectrum scarcity challenge and to dynamically use the underutilized licensed spectrum bands [25].

CR technology provides sharing licensed spectrum bands with primary users (PUs), which are the owners of these bands. In order to utilize these bands while the PUs are not active, CRs can change their transmitting parameters to operate on the vacant channel [26]. There are two main characteristics of CRs, which are cognitive capability and reconfigurability [25], [26]. With the cognitive capability, the idle spectrum bands are detected, and the best channel among these idle channels is selected for the communication without any interference to the PUs. With reconfigurability, CR can operate in different frequencies and reconfigure its parameters for the best performance. The use of the idle licensed spectrum bands increases spectrum utilization and decreases the traffic in ISM bands. Hence, collisions due to the excessive utilization of the unlicensed spectrum bands are decreased, which provides efficient spectrum usage and energy-efficiency.

The cognitive capability of the nodes is possible with cognitive functionalities. They are spectrum sensing, spectrum decision and spectrum hand-off. Spectrum sensing gives the ability of revealing the radio spectrum band usage in the licensed bands. Spectrum decision is the process that the band for the transmission is decided. Furthermore, a radio with CR capability must vacate the licensed channel if this channel become occupied. This process is performed by the spectrum hand-off functionality. Using these features, nodes with CR capability can coexist with the licensed users, which are the license holders of that spectrum band. Although CR provides advantages for the wireless communication, it poses challenges such as dynamic radio environment. If CR technology is utilized in the SG, it also intensifies the challenges posed by the SG itself.

The IoT paradigm has a goal to connect every electronic device to the Internet [1], [2]. It leads to the integration of different technologies and communication techniques. Hence, the devices within the IoT should communicate with different types of communication devices. The IoT is regarded as a union of wireless devices via the Internet to observe and sense the environment, and to monitor the surrounding. This paradigm has been evolving the way we communicate, most importantly, the standards of living since it finds many application areas such as transportation manufacturing, logistics, management of cities etc. [2].

With the emergence of the IoT, the Internet has been evolved in such a way that Network of Interconnected objects senses the environment and actuates accordingly by using Internet services for communication, data transfer and analysis of the sensed data [1]. From this point of view, the SG has the same characteristics since it covers the electrical grid to sense for providing intelligence on demand and supply side. Furthermore, the sensing from houses to the generation side provides less energy loss, immediate response to the grid failures and easy adaptation to new systems [27]. Hence, integration of the SG with the IoT helps better monitoring and management of the electrical grid. This integration will also provide IoT services such as broad connectivity, privacy, interoperability between the heterogeneous wireless devices and access to the cloud computing systems.

Internet connection of the SG and addressing the sensing and actuator devices in the Internet domain provide flexibility, reliability, efficiency and adaptation. Hence, SG can adopt the services provided by the IoT. However, the Internet connection via wireless links and the communication between the sensing and actuator devices in the SG suffers from the harsh channel conditions such as high path loss exponent and shadowing deviation [14] and changing spectrum characteristics over time and space [7]. Hence, CR may also be solution to overcome these challenges to provide unique reliability and requirements by dynamic spectrum access and decrease the energy consumption of the wireless devices by avoiding the collisions with adapting its operating frequency according to the spectrum sensing.

2.1 Advantages of CR in IoT-enabled SG

Cognitive cycle operations provides awareness in frequency usage. Dynamic adaption to the frequency bands and opportunistic usage of the licensed channels increase the spectrum utilization and communication efficiency. The advantages of CR in IoT-enabled SG can be outlined as follows [7].

- *Adaptation to the environmental conditions:* The harsh conditions of a band can be eliminated by changing the operating frequency to channels with less noise level.
- *Accessing to underutilized licensed spectrum:* With the spectrum sensing, idle channels are utilized, efficiency of these bands is increased.
- *Resistance to the varying link capacity:* Due to varying channel conditions, CR can dynamically hop to the frequency bands with higher link capacity.
- *The ability of existence with different type of networks:* Due to the CR capability, they can coexist with different type of networks since they can opportunistically access to the spectrum. This advantage supports operation with different technologies due to IoT feature in SG.

2.2 Challenges of Cognitive Radio capable IoT-enabled SG

The challenges for the realization of the SG are empowered by inclusion in the IoT paradigm and the utilization of CR. The IoT requires scalable, energy efficient and flexible solutions. Furthermore, the solutions must support spectrum-awareness if CR is utilized. Hence, the challenges of CR capable IoT-enabled SG can be outlined as follows [14].

- *Excessive overall data transfer:* Since there is a large number of wireless devices in the IoT-enabled SG, the overall sensing data conveyed to the control center may result in huge amount. Opportunistic wireless transfer of this data will pose a great challenge without any excessive interference to PUs.
- *Balancing the energy resources:* Due to the variations between the demand and supply, balancing the energy resources and the determination of their share is a difficult task. Spectrum-aware communication between the demand and supply side with the harsh environmental condition of the IoT-enabled SG poses a challenge.
- *Dynamic licensed user activity:* Interference to the licensed users should be less than a certain threshold.
- *Variation in the traffic:* Due to the activities on the user side, the traffic flowing from the user side to the supply side varies.
- *Satisfying different levels of QoS:* SG can have a wide variety of QoS level due to diverse SG applications. Satisfaction of all the users in SG is a challenging task.

3 Existing Methods of Energy Harvesting

Existing techniques of energy scavenging is broadly categorized into two groups as Harvest-Use and Harvest-Store- Use, where these can be further sub-categorized as controllable and uncontrollable [28]. By regarding this separation and the frequency of preference some leading EH methods are discussed below, and a detailed comparison is presented in Table 1.

3.1 Energy Harvesting from Light Sources

Power extraction from light sources is a well-known technique of energy harvesting in which the energy carried by photons is converted into utilizable electrical power with respect to a chemical phenomenon, namely photo-voltaic (PV) effect [28], [29].

In outdoor, solar energy is efficiently exploited to power various systems and applications, thanks to its sufficient power rating, and implementation flexibility. One of the most well-established applications of sunlight EH, in terms of wireless networking, can be regarded as intelligent surveillance and advanced control of grid assets over the Internet since the electrical power grid related elements are in widespread. This aspect also contributes to the realization of SG and Smart City visions. However, as a corollary of being environmental, the energy that can be gathered by sunlight illumination is highly affected by ambient factors. For indoor applications, more specialized PV materials, which are better suited for diffused lights, are being developed for profiting from any kind of light propagation to build HANs/BANs [28]. Although the period of harvesting is much longer on the contrary of sunlight's daytime constraint, the energy that can be gathered by artificial lights is roughly one third of sunlight energy.

3.2 Thermal Energy Harvesting

Thermal EH is based on a physical phenomenon, i.e., Seeback Effect, which occurs between conductor pairs. In brief, due to a thermal difference the junction expands in a certain direction that results in utilizable electrical power. The attainable energy can be easily adjusted by changing connection of the pairs as series and/or parallel [28]. Thermo-electric generation (TEG) can be regarded as an innate method for SG communications, where the temperature gradients between the grid assets and the environment are being utilized for providing energy to the wireless devices attached [30]. In small scale, mostly peltiers and/or thermocouples are preferred for low-power requiring time-uncritical consumer electronics solutions. It is also possible to energize the circuitries that are obliged to monitor the human bodies or any body-attached control systems by using the very same approach. As the devices are more likely to operate self-sustainably, they may suffer from the quite low power extraction efficiency of the TEG process [28], [31].

3.3 Kinetic Energy Harvesting

As the name suggest, kinetic energy conversion (KEC) means profiting from any mechanical stress and/or vibration resultant motion variation to gather power for wireless devices. KEC includes electrostatic, piezoelectric and electromagnetic methods to extract energy from mostly uncontrollable but somehow predictable environmental sources, as well as partly-controllable and mostly unpredictable man-made actions [29]. Airflow EH, in particular, can be considered as one of the well-established power provision methods for SG applications, in which the wireless autonomous devices destined to surveil the grid are powered by KEC-capable anemometer like mechanisms. As these systems provide longevity and maintenance-free operation for the networks to be built, the available power is highly threatened by many factors, such as daytime and weather conditions. Although the vibrations alternate the wind power in SG communications, they require specialized harvesters as the frequency of each vibrating element differs. For indoor applications, piezoelectric materials are mostly preferred to operate HANs and BANs intermittently [28], [31].

3.4 Radio Frequency (RF) Energy Harvesting

With the unprecedented grow in wireless technologies in recent years, electromagnetic (EM) waves become more attractive for especially EH applications [28], [29]. Because of the nature of wireless communication, EM signals have the characteristics of being easily attainable and efficiently utilizable, which open up the potential of building battery-less WSNs that profit from ambient and underutilized RF waves. For urban areas, RF energy is about to unseat the conventional methods of EH that are destined to run remote services of Smart Cities. For indoor, EM waves emitted from modems, routers, smart phones, and laptops are first collected, then converted into AC and DC by using power receiving antennae, transducers, and rectifiers, respectively. Although the RF EH provides quite satisfying solutions regardless of the environmental parameters, being distortive for the communication; having strict deployment requirements; depending highly on an unpredictable source compel its utilization in mission-critical applications [31].

3.5 Energy Harvesting from Electromagnetic Fields

In addition to above-mentioned harvesting techniques, low-power operative wireless devices can be also pow-

Table 1 Comparison of the existing EH techniques [31].

	Type	Characteristics	Power Density	Advantages	Disadvantages
Light	Solar	Uncontrollable, Predictable	15 – 100 mW/cm^2	Environmental, Independent of grid, High output voltage	Not always available, Sensitive structure, Deployment constraints
	Artificial	Partly-controllable, Predictable	10 – 100 $\mu W/cm^2$	Abundant in indoor, Easy to implement	Low power density, Sensitive structure
Temperature gradient	-	Uncontrollable, Unpredictable	$\simeq 50$ $\mu W/cm^2$	Environmental, Low maintenance, Scalable	Not always available, Requires eff. heat sinking Low power density
Motion	Airflow	Uncontrollable, Unpredictable	100 mW/cm^2	Environmental, Independent of grid, Available day and night	Big in size, Hard to implement, Requires construction
	Human-based	Controllable, Partly-predictable	200 $\mu W/cm^3$	No ext. power source, Compact configuration, Light in weight	Charge leakage, Brittle materials, Highly variable output
EM Waves	-	Partly-controllable, Partly-predictable	1 – 10 $\mu W/cm^2$	Abundant in urban lands, Allows mobility	Scarce in rural areas, Low power density, Distance dependent
EM Fields	M-field	Controllable, Predictable	150 $\mu W/cm^3$	No ext. power source, Easy to implement, Non-complex structure	Requires high and perpetual current flow, Safety vulnerabilities
	E-field	Controllable, Predictable	N.A.	No need of current flow, Easy to implement, Always available	Being capacitive, Mechanical constraints

ered by exploiting electromagnetic fields around the conductive materials energized at any level. Magnetic field (M-field) EH, in particular, is based on coupling the surrounding field flow of AC current carrying conductors by clamping them with current transformers [29], [30], [31]. This power transfer-based technique provides acceptable rate of stable power as long as there exist sufficient current flow on the conductor that is being utilized. Being bulky and requiring additional safety procedures due to the mechanical contact are the factors that restrict its employment in certain applications. However, for online condition monitoring of overhead power lines and environmental sensing around grid assets, it is the most efficient solution in contrast with the ambient sources such as sunlight and airflow.

Electric field (E-field), in similar, exploits the electric charges induced on a conductive material due to a voltage difference. The field that is being emitted is obstructed by again a conductive material, where a displacement current starts to drain. The charges conveyed are first converted into DC and then accumulated in a storage element after regulated. As the source of this gathered energy is the ambient field, this method can be termed as E-Field EH (EFEH) [30], [31]. EFEH depends only on the existence of voltage potential. Since the voltage and the frequency are firmly regulated and exactingly maintained, the E-field is stable and also predictable in its behavior. Therefore, it can be referred as the most promising way of composing long-term and self-operable communication services notwithstanding the environmental parameters.

4 Energy Harvesting Cognitive Radios in IoT-enabled Smart Grid

We separately investigate the usage of CR and EH in the IoT-enabled SG in prior sections. This section explains how the nodes operate by utilizing these technologies in the IoT-enabled SG. Spectrum-aware communication and energy harvesting capabilities of these nodes are the key elements for successful operation of the IoT-enabled SG. Hence, the wireless devices in an IoT-enabled SG are named as energy harvesting-cognitive radios (EH-CRs). As EH-CRs have additional capabilities, their node architecture would be different from conventional wireless nodes in the IoT-enabled SG. Furthermore, these capabilities require considering the network architectures of the IoT-enabled SG. Hence, we overview operation of EH-CRs, their node architecture, and the architectures of the network consisting of these nodes.

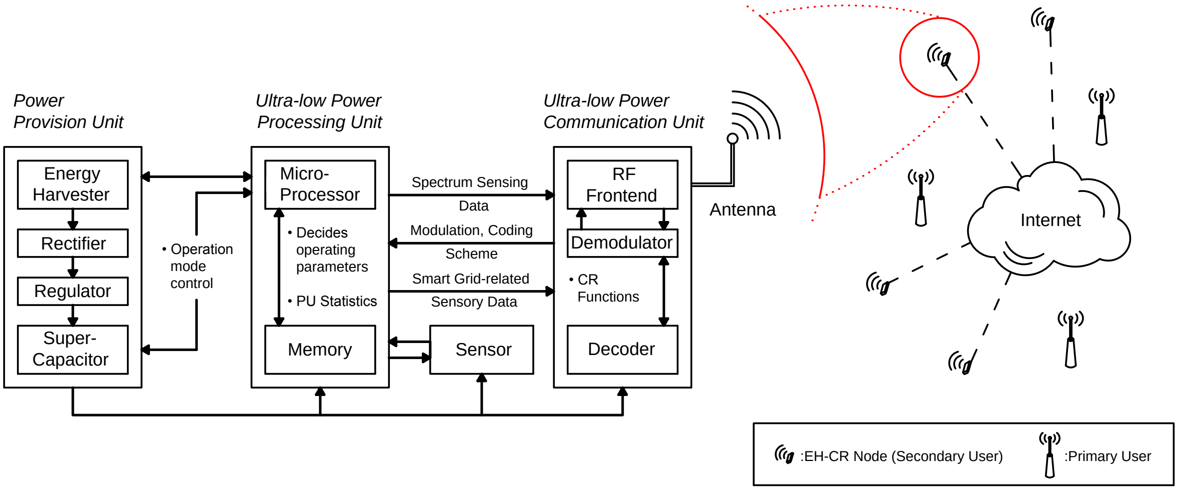

Fig. 2 Node Architecture of EH-CRs.

4.1 Operation of EH-CRs

Overcoming the spectrum scarcity challenges with CR and solving the limited energy supply problem with the EH techniques provide significant benefits in the SG domain. Furthermore, including the SG in the IoT results in very diverse application areas. This fact necessitates a clear understanding of operation of the IoT-enabled EH-CRs.

The SG is a visionary concept that connects the demand and supply sides by enabling two way communication. These connection is provided by the deployment of wireless sensing devices and actuators. Hence, the proper operation of these devices is quite important. In the IoT-enabled SG, there are different operation schemes for the wireless devices. The deployed devices in homes may access directly to their gateways or they may reach their Internet gateways through multiple hops.

During the operation, EH-CRs use spectrum-aware communication techniques for the transmission, and EH methods to energize the device. Depending on the subnetwork architectures, the packet generated by sensing are conveyed in one or multiple hops in dynamic radio environment to reach the Internet for realizing IoT-enabled SG. They utilize the licensed spectrum bands since they coexist with PUs. Furthermore, they scavenge energy by utilizing EH techniques.

4.2 Node Architecture of EH-CRs

We propose a node architecture for IoT-enabled EH-CRs that supports energy harvesting and spectrum aware communications. In this architecture, we include three main units, which are ultra-low power (ULP) communication, ULP processing, and power provision units. A detailed structure is depicted in Fig. 2. The ULP communication unit performs channel switching, channel sensing, modulation and power control duties at the expense of miliwatts. Furthermore, sensory operations are performed in the sensor unit, which is controlled by the ULP processing unit. The sensed information is processed in ULP, and it is transferred to the ultra-low power communication unit.

The power provision unit includes energy harvester, rectifier, regulator and energy buffer, i.e., super-capacitor, sub-units. As the name suggest, this unit is responsible for providing utilizable energy to the each part of the sensor node. In other words, profitable sources are captured, converted (if necessary), regulated and stored to be distributed to the rest of the system. The processing unit mainly decides on operating parameters and manages every process carried out by the sensor node. The ULP communication unit has an Internet-capable RF front-end, demodulator and decoder to provide the communication with CR functionalities. This node architecture is designed to support energy harvesting and spectrum-aware communications in the IoT-enabled SG.

4.3 Network Architecture of IoT-enabled SG

Using the node architecture of EH-CRs, we establish a network architecture for the IoT-enabled SG. Furthermore, we also utilize the general SG network architecture while establishing it for the IoT-enabled SG. The general SG network architecture has a multi-layer architecture and spread over a very geographical region, which poses challenges and limitations in wireless communications. Furthermore, this network architecture in-

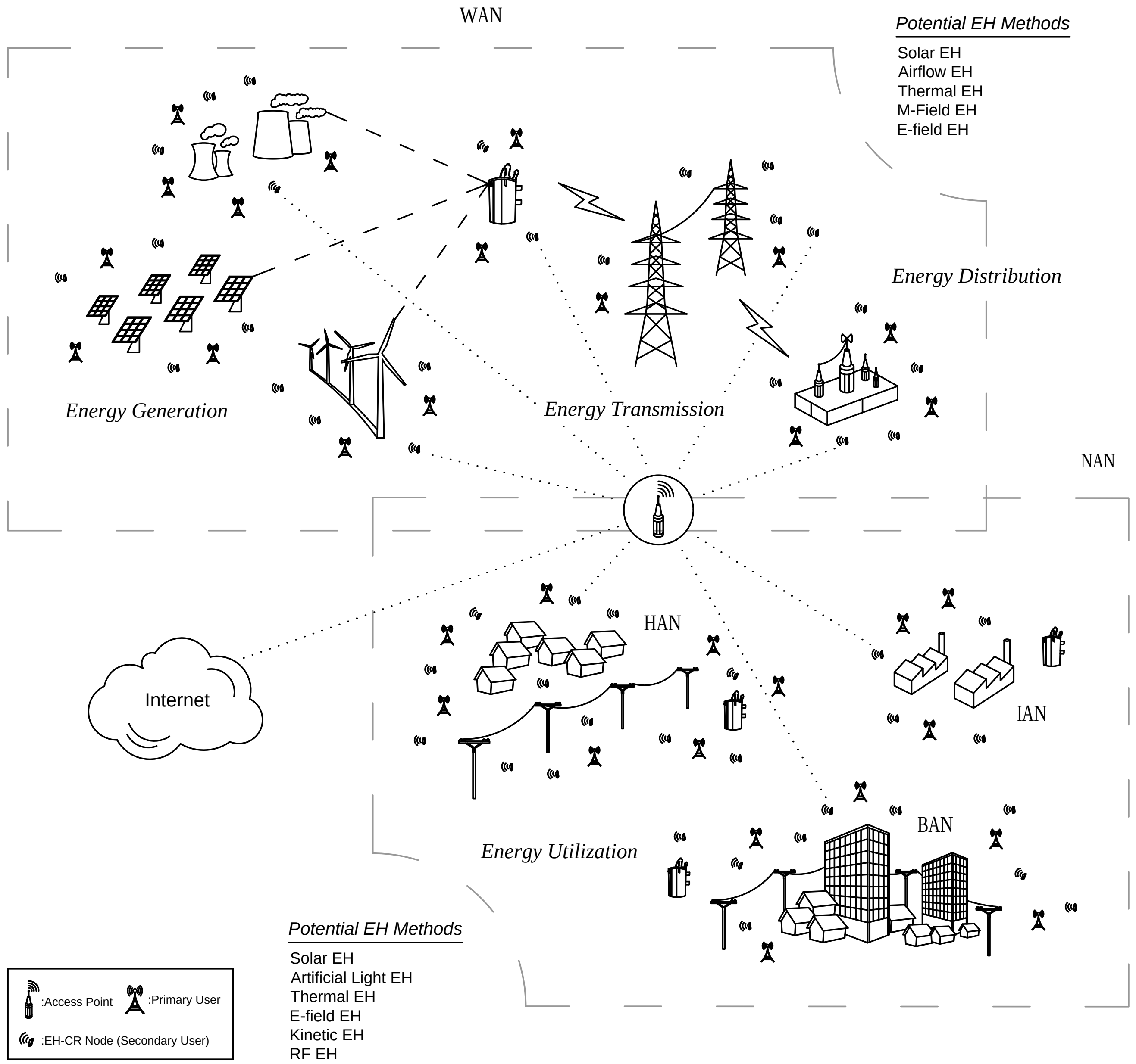

Fig. 3 Network Architecture of IoT-enabled SG.

cludes a number of sub-networks that have different QoS and other communication requirements.

There are three main components for the SG network architectures, namely, HAN, NAN and WAN as seen in Fig.3 [18], [19]. IAN in Fig. 3 refers to industrial area network, which is a sub-network of NAN located at industrial sites. BAN in Fig. 3 refers to building area network, which is again a sub-network of NAN consisting of wireless nodes located in buildings. In our architecture, we split the IoT-enabled SG network like in the conventional SG networks. However, we consider the capabilities of EH-CRs while proposing our network architecture. We investigate the sub-networks of the IoT-enabled SG in the following subsections.

4.3.1 Home Area Networks

HANs cover houses and buildings. They provide real time monitoring for adjustment of energy consumption. Furthermore, they have the capability of control, managing and track of the devices at homes and buildings [32]. These networks bring intelligence to the houses, i.e., Smart Homes (SHs) [33]. Remote control and tracking, management of heat and light, and health-care monitoring are some of the applications of SHs. Home is the smallest part of the grid and provides context-aware services to the HAN users.

The most important elements in HANs are smart meters, which have the capability of measuring the energy consumptions of the nodes [34]. WSNs are the key components to realize the SG in HANs that can be used home applications related to demand and energy management [35]. The collaborative nature of WSNs helps to exchange of the sensory information from the home appliances and systems, and makes this information accessible via the Internet with the inclusion of IoT.

The development of the SG have increased the usage of HANs, which utilizes protocols such as ZigBee, Wi-Fi, and 6LoWPAN. However, they use ISM (Industrial, Scientific, Medical) bands, which are highly utilized and become insufficient for the transmission. This also increases the collision and deteriorates the network performance. Hence, CR plays a key role to eliminate these problems in HANs. CR is also being utilized in the SG domain to manage high volume of data and to satisfy different QoS levels [36]. In our network architecture, the nodes in home communicates with the access point by dynamic spectrum access techniques to overcome the difficulties in the SG. This scenario is seen in Fig. 3 with exploitation of different EH methods such as harvesting from solar and thermal energy. The EH methods extend the lifetime of EH-CRs in HANs.

4.3.2 Neighborhood Area Networks

Neighborhood Area Networks (NANs) provide the connection between HANs. These networks are also named as field area networks (FANs) due to their connection of field devices such as advanced metering infrastructures (AMI) and intelligent electronic devices (IEDs) [18]. NANs gather the energy consumption information from the homes in a neighborhood and sends it to utility companies via wide area networks (WANs) [36].

NANs also connect SHs and the utility companies. It provides real-time communication for pricing and control. Furthermore, main fields of NAN applications can be named as distribution automation, load management and so on. Depending on the application, the network radius of NANs may be up to 10 km with a rate of $0.1 - 10$ Mbps [19]. Multi-hop capable wireless nodes may be utilized such as ZigBee and Wi-Fi nodes [20]. Wireless sensor nodes may be utilized for this purpose. However, they may face the spectrum scarcity challenge in addition to the SG challenges such as harsh channel environment. CR again stands as a solution for these problems. In our networking paradigm, the nodes in NANs also access the licensed spectrum opportunistically. Gateway nodes are with cognitive radio capability. Their energy is supplied by the EH methods, which depend on the available energy resources in that neighborhood. Fig. 3 shows a NAN that gateway node is connected to the different sub-networks such as HAN, IAN and BAN. Furthermore, nodes in NANs need more energy since they communicate with the nodes in HANs. Hence, efficient EH techniques should be employed.

4.3.3 Wide Area Networks

WANs cover large areas and connects much smaller networks to form the communication backbone [37]. NANs forms WANs, the NANs communicates with the utility center via the Internet through WANs [36]. The observations and the real-time measurements of the substations and end users are conveyed to the control center traversing WANs, where the data from control centers is transmitted in the same manner [37].

IEDs are the sensor and actuator nodes, which are deployed in critical parts of the electrical grid such as transformers, circuit breakers, etc. [38]. The communication between the nodes of WANs requires high bandwidth and low delay due to the accumulated data from HANs and NANs. For instance, 5 Mbps data rate and 100 milliseconds delay is required for seamless communication [39]. The current WSN solutions may not satisfy these requirements due to inherent. CR provides the use of the licensed channels with high bandwidth to support the demands. If gateway noes can not access base stations in WANs, they reach them in multiple hops by utilizing idle licensed bands.

4.4 Open Issues and Future Research Directions

In this paper, we have proposed a new networking paradigm, namely energy harvesting cognitive radio networking in IoT-enabled Smart Grid. The nodes have two capabilities, which are energy scavenging and spectrum-aware communications. Furthermore, these nodes operate in a very harsh domain, which is IoT-enabled Smart Grid. To enable EH-CR networking in IoT-enabled SG, we have explained the operation of EH-CRs, the node architecture and their network operation in a IoT-enabled SG. This new paradigm yields some open issues and future research directions, which are outlined as follows.

- Spectrum management frameworks must be designed according to the networking architecture of the IoT-enabled SG and the CR capability of the nodes. Furthermore, EH aspects of these nodes should be considered to enable efficient power consumption to support battery free operation.

- Energy harvesting and the energy consumption due to the cognitive cycle operations should be considered to balance the energy expenditure for perpetual lifetime. Furthermore, the spectrum-aware communication challenges such as arrival of PU during opportunistic communication should be considered in IoT-enabled SG with the intrinsic harsh channel conditions.
- Coverage and connectivity of the IoT-enabled SG should be studied according to the spectrum-awareness and energy harvesting points of view. New power control method can be utilized considering the harvested energy in IoT-enabled SG. Furthermore, the connectivity of IoT-enabled SG should be investigated in such a setup.
- The heterogeneity of IoT-enabled devices should be handled since these devices use different communication technologies. The compatibility with EH-CRs and the other IoT devices deployed in SG must be investigated in terms of communication.
- Spectrum-aware routing protocols should be designed to enhance the lifetime of the nodes with EH techniques. The routing techniques should also consider the different network architectures of SG such as HAN, WAN, NAN.
- Application specific EH methods should be offered to support battery free operations of EH-CRs. Furthermore, hybrid energy harvesting approach may be proposed to exploit different EH methods in EH-CR nodes.
- EH methods must be utilized in accordance with required operation in different parts of the IoT-enabled SG since different nodes in different subnetworks of the IoT-enabled SG uses different amount of energy for the communication due to different transmission ranges.

5 Conclusion

In this paper, we propose a totally new networking architecture, namely, Energy Harvesting Cognitive Radio Networking for Internet of Things-enabled Smart Grid. EH techniques are planned to be utilized for increasing the lifetime of wireless devices deployed in IoT-enabled SG. Furthermore, as the SG has harsh channel conditions and spectrum scarcity problems in its network architecture, we propose to use CR to overcome these issues. This new networking paradigm is investigated in terms of general operation, node and network architecture aspects. Open issues and future research directions are presented to realize EH-CR networking in the IoT-enabled SG.

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