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A REVIEW OF INTEGRATED RADIO FREQUENCY ENERGY HARVESTING AND COGNITIVE RADIO FOR THE INTERNET OF THINGS

EDWAR MUALLIM[1,2]*, MD RABIUL AWAL[1] AND AHMAD ZAKI ANNUAR[1]

[1]*Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia.* [2]*Faculty of Engineering, Universitas Pamulang, Indonesia.*

**Corresponding author: p4780@pps.umt.edu.my*

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Abstract: In recent decades, there has been significant growth in interconnected communication devices, with the Internet of Things (IoT) being one of the most intensively developed wireless communication appliances. This concept can be implemented in several areas, including smart cities, transportation, telemedicine, agriculture, and wearable applications. However, this increase in connectivity demand can lead to spectrum shortages in the future. In addition, in the development of future green communications, it is crucial to incorporate self-powered systems using energy harvesting technologies. In this review, it is shown that the integration of cognitive radio and radio frequency energy harvesting into IoT development can address the spectrum shortages and energy issues mentioned earlier. The findings indicate that the operating model works based on the slotted approach and state consideration, and the system's performance metric can be optimised by adjusting parameters such as harvesting time, sensing time, transmit time, transmission power, interference level, and others. This review provides a comparative summary of several focus domains, such as RF harvesting, spectrum sensing and utilisation, operating models, and some open research issues for further work.

Keywords: Internet of Things, RF Energy Harvesting, Cognitive Radio

Introduction

The Internet of Things (IoT) is a visible manifestation of the new digital platform era, where each object can be connected and can communicate with each other. The simplest concept of IoT consists of three components (Mohamed, 2019), namely "Thing" (object to be connected, such as a device or machine), "Connectivity" (the type of connectivity that can connect the objects to the internet), and "Intelligent Capability" (which allows objects to process information and ensure interoperability between systems, generally consisting of sensors, actuators, storage, computing, protocols, and applications).

IoT has been implemented in various fields, such as industrial manufacturing, healthcare and telemedicine, transportation, agriculture, smart cities, home utilities, and others. With such diverse applications of IoT, the number of connected devices is projected to increase significantly in the coming years (as seen in Figure 1),.It is estimated that by 2025, there will be approximately 21.5 billion IoT devices, representing a growth of about 190% compared with 2020 (Prasetya *et al*., 2020).

These increasing telecommunication demands will inevitably lead to an increase in spectrum demand, potentially resulting spectrum scarcity in the future. To address this issue, one potential solution is the implementation of a cognitive radio (CR) system. According to the International Telecommunication Union (ITU) document SM.2152, the CR system is designed to gather and analyse information from internal conditions, the environment, and policies, and then adjust its modulation, encoding, transmission power, or other parameters to operate under expected conditions (ITU, 2009). In this way, network providers or operators with limited spectrum can utilise spectrum holes owned by other providers or operators to accommodate their traffic, thus improving overall spectrum utility.

One primary concern for future communication technology is the implementation

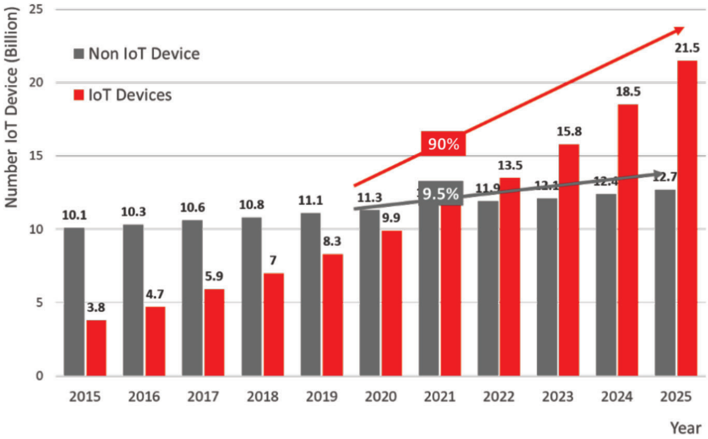


Figure 1: Projected growth of IoT devices

of the green energy concept, in which the system is expected to achieve high energy efficiency and reduce its dependencies on the existing power grid supply. This can be accomplished by developing an IoT device that can operate entirely on self-generated power through a harvesting mechanism from ambient energy (T. Huang *et al*., 2019), also known as energy harvesting (EH).

Several survey papers on EH and CR have been published. Mohjazi *et al*. (2015) conducted a survey on the classification of radio frequency EH (RF-EH) and the technical challenges of CR systems powered by RF-EH. X. Huang *et* al. (2015) presented a survey on spectrum sensing, sharing, and management, as well as CR energy efficiency. Singla *et al*. (2018), meanwhile, carried out a survey on the EH architecture model for CR. Liang *et al*. (2019) undertook a survey on RF-EH scenarios through simultaneous wireless information and power transfer in 5G environments, particularly mmWave networks. Similarly, Perera *et al*. (2017) surveyed simultaneous wireless information and power transfer that addressed several emerging technologies.

Several survey papers have also been published with the aim of providing insights into IoT and its characteristics. For example, Sabry *et al*. (2019) presented a survey on the classification of IoT architecture and its energy consumption. Shirvanimoghaddam *et al*. (2019) conducted a survey of literature on EH techniques that can be used in IoT. Raza *et al*. (2018), meanwhile, explored different energy harvesting techniques for industrial wireless sensor networks.

Based on the limited topic coverage of the survey papers, there are several aspects that require further discussion. These include exploring communication technology options for IoT, conducting experiments on architecture and circuits for RF-EH, comparing the characteristics of spectrum sharing mechanisms, and developing an operating model for the integration of CR and RF-EH into IoT. To complement the research gap that was not been covered in previously published survey papers, this paper will focus on several domains, such as RF-EH, the sensing and utilisation of spectrum, performance metric, and operating models.

A comparison summary of the research domains covered by previous survey papers is provided in Table 1.

The organisation of this paper was arranged as follows: The first section provides a brief introduction to IoT, its growing demand and its relation to the concepts of CR and EH. The second section discussed several IoT standards and their characteristics. The third section focuses on EH techniques specifically related to RF-EH. The fourth section presents the CR mechanism. The fifth section discusses the mechanism of the integrated concept of CR and

Table 1: Comparison of several existing reviews

Topic Exploration	Related Paper Label								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**This paper**
IoT framework exposure	○	○	○	○	○	●	●	●	●
IoT technology classification	○	○	○	○	○	●	●	●	●
EH source classification	●	○	●	●	○	○	●	●	●
RF-EH architecture	○	◎	◎	●	●	○	●	◎	●
Spectrum sensing for CR	●	●	○	○	○	○	○	○	●
Spectrum sharing for CR	◎	●	○	○	○	○	○	◎	●
Integrated concept of CR and RF-EH	◎	◎	◎	○	◎	○	◎	○	●

Notes :
○ : Not Covered
◎ : Partially Covered
● : Covered
A : (Mohjazi *et al*., 2015)
B : (X. Huang *et al*., 2015)
C : (Singla *et al*., 2018)
D : (Liang *et al*., 2019)
E : (Perera *et al*., 2017)
F : (Sabry *et al*., 2019)
G : (Shirvanimoghaddam *et al*., 2019)
H : (Raza *et al*., 2018)

RF-EH that is applicable for IoT. Finally, in the last section, research issues that require further investigation are discussed.

Internet of Things

The IoT concept builds upon the advancements of machine-to-machine (M2M), computing and telephony concepts that originated in the 1980s and continued through the 1990s. This was highlighted by the emergence of the SCADA and M2M for cellular systems, which were defined by Siemens in 1995.

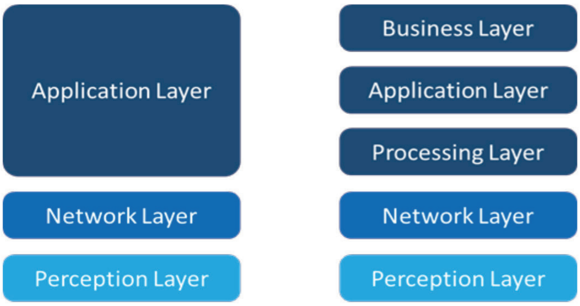
According to Recommendation Y.2060, IoT is defined as a global infrastructure for the information society that enables advanced services by interconnecting physical and virtual things using existing and evolving interoperable information and communication technologies.

Framework

The simplest IoT architecture model consists of three layers (Benkhelifa *et al*., 2018; Jamali *et al*., 2020), namely the application, network, and perception layers (as shown in Figure 2a). The application layer is responsible for providing services to users through IoT applications, such as smart cities, intelligent transportation and smart health; the network layer connects devices to the network; and, the perception layer consists of a physical layer equipped with sensors that receive and send information from and to the environment.

Another model presents the IoT architecture in five layers (Patil & Rhee, 2017; Wu *et al*., 2010), which are the business, application, processing, network, and perception layers (as shown in Figure 2.b). This model has two additional layers, which are the business and processing layers. The business layer serves as a management system related to business and profit models, and workflows, while the processing layer is responsible for processing information, including database storage, and data analysis and computing.

The International Telecommunication Union, meanwhile, has developed a four-layer IoT architecture model (Figure 3a) in its ITU-T Y.2060 recommendation, which consists of the application, service support and application support, network, and device layers (ITU, 2012). The four layers are facilitated by management



(a) (b)

Figure 2: (a) The three-layer Internet of Things model, and (b) The five-layer model

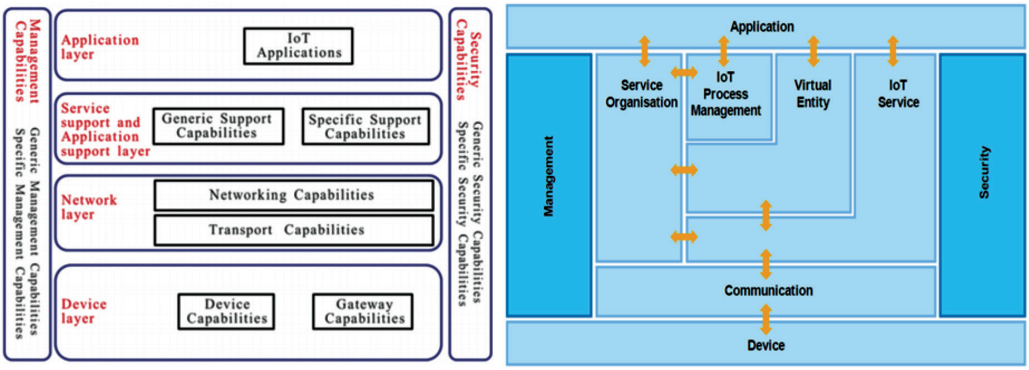
and security capabilities. The application layer provides services to users. The service support and application support layer performs general functions of data processing and data storage, has and this layer has specific functions to support a wide range of IoT applications. The network layer provides the configuration settings for network access connectivity and transport network, resource settings, and mobility management, among other things. The device layer performs several functions, such as receiving and sending information (from and to communication networks) and regulating the sleeping and wake-up mechanisms to conserve energy.

Finally, The European Commission, under the Seventh Framework Programme (Bauer *et al*., 2013), has formulated an IoT architecture model that consists of seven functional groups (Figure 3b), which are organised into four layers: the device, communication, service (combined service function organisations, IoT process management, virtual entity, and IoT service), and application layers. The model also incorporates transversal functionality, which comprise management and security capabilities.

Technology Classification

IoT technology can be categorised into two groups based on the scale of application, which are industrial and consumer IoT. Industrial IoT involves a large and extensive network coverage compared with consumer IoT. Examples of industrial IoT applications are smart farming (Farooq *et al*., 2019) and smart transportation (J. Zhang *et al*., 2021), and an example of consumer IoT applications is smart homes (Gaikwad *et al*., 2015).

IoT technology includes several types of devices, such as sensors, actuators, and radio frequency identification (RFID). Sensors are devices that collect data from the environment,



(a) (b)

Figure 3: (a) Architecture Model ITU-T Y.2060, (b) Architecture Model EU IoT-A

typically in the form of physical or analog inputs, and convert them into electrical output. Common types of sensors include temperature sensors, speed sensors, level sensors, image sensors, and proximity sensors. Actuators are devices that initiate an action in a system. Examples of actuators include pneumatic, hydraulic, and electrical actuators. RFID, meanwhile, is a device that provides identity information in the form of tags for objects connected to an IoT system.

IoT devices can be categorised into three groups based on their capabilities (Bansal & Kumar, 2020), namely low-end, mid-end, and high-end devices. Low-end devices are those with limited storage, computing, and communication capabilities that have only basic components, such as sensors and actuators. Mid-end devices, on the other hand, have a basic microcontroller and support multiple communication types, providing more adequate features than low-end devices. High-end devices have increasingly complex capabilities, equipped with a CPU, RAM, and an operating system, and support almost all types of communication protocols.

In terms of platforms, IoT can be classified into three groups (Kaňuch *et al*., 2020), namely firmware-based, operating system-based, and cloud-based devices. Firmware-based devices are equipped with only the embedded elementary operations on a basic microcontroller (such as Atmega TinkeringTech, ESP32/8266, or MediaTek Linkit One). Operating system-based devices have more complex capabilities as they are equipped with an operating system (such as Arduino, Nanopi, Raspberry Pi, and Beagleboard). Finally, cloud-based devices are those that are operationally connected with servers or clouds provided by the manufacturers (such as Particle and Konekt).

When it comes to connectivity, IoT technology can be classified into two groups, namely short-range and long-range IoT. Examples of short-range IoT are Zigbee, Bluetooth-LE, and WiFi, while examples of long-range IoT include LTE-M, NB-IoT, SigFox, and Lora.

A comparison of several communication technologies in IoT can be seen in Table 2 (Ray, 2018; Raza *et al*., 2018; Sabry *et al*., 2019; Shirvanimoghaddam *et al*., 2019; Khalifeh *et al*., 2019; Zeadally *et al*., 2020; Kaňuch *et al*., 2020; Onumanyi *et al*., 2020).

Radio Frequency Energy Harvesting

EH is an essential technique for IoT devices operating in remote locations with limited or no access to conventional power sources or auxiliary power storage sources, such as batteries. This technique enables devices to operate using a self-powered mechanism, utilising existing energy sources in their environment. In this section, the classification of EH sources that can be implemented by IoT devices will be briefly described. Later, the discussion will focus on the EH technique that uses RF source energy.

Energy Harvesting Source

In general, EH sources can be classified into four groups, namely kinetic energy, thermal energy, bioenergy, and radiant energy. A summary of the characteristics each energy source is presented in Table 3 (Akan *et al*., 2018; H. Sharma *et al*., 2018; Sun *et al*., 2018; Shirvanimoghaddam *et al*., 2019; Choudhary *et al*., 2020; Sandhu *et al*., 2020).

The harvesting of kinetic energy utilises the vibration or motion of objects, and some of the techniques for doing so include the use of piezoelectric materials, as well as the principles of electromagnetic and electrostatic induction. The harvesting of thermal energy utilises the differences and changes in an object's temperature, and the principles used for this include thermoelectricity and pyroelectricity. Bioenergy harvesting mechanism utilises biomechanics or the biochemical processes of living organisms to produce electrical energy. Finally, the harvesting of radiant energy includes various techniques, such as using solar or light energy, RF signals (AM, FM, TV, Cellular), and acoustic signals.

Table 2: Comparison of several IoT communication technologies

Aspects	ZigBee	BLE	WiFi	Cellular	LTE-M	NB-IoT	SigFox	LoRa
Coverage	Short Range	Short Range	Short Range	Long Range	Long Range	Long Range	Long Range	Long Range
Range	10-100 m	10-100 m	20-100 m	Cell Area	10-50 km	1.5-40 km	10-50 km	2-50 km
Channel access	CSMA /CA	FHSS, CSMA /CA	CSMA /CA	TDMA, CDMA, OFDMA	OFDMA	OFDMA	UNB	FHSS, CDMA, ALOHA
Modulation	BPSK	GFSK	DSSC	GMSK, BPSK, QPSK, QAM. OFDM	16 QAM, OFDM	GFSK, BPSK	GFSK	CSS
Data rate	<250 kbps	1 Mbps	1-54 Mbps	2G: 5-100 kbps, 3G: 200 kbps. 4G: 0.1-1 Gbps	100-150 kbps	<200 kbps	<100 kbps	20-50 kbps
Frequency	868/915 MHz, 2.4 GHz	2.4 GHz	2.4 GHz, 5 GHz	GSM/ UMTS/LTE Band	LTE In-Band	LTE In-Band, LTE Guard-Band, Standalone/ outside LTE	868/915/433 MHz	868/915/433 MHz
Spectrum	Un-licensed	Un-licensed	Un-licensed	Licensed	Licensed	Licensed	Un-licensed	Un-licensed
Channel bandwidth	2 MHz	2 MHz	20-40 MHz	2G: 200 KHz, 3G: 5MHz, 4G: 1.4-20 MHZ	1.4-20 MHz	200 KHz	100-600 Hz	125-500 kHz
Latency	Low <100ms	Low <100ms	Low <100ms	Low <10ms	Low <50 ms	High 1.5 – 10 sec	High 10 sec	High 1 sec
CR support	-	-	-	-	-	-	Yes	Yes
Power consumption	10-100mW	10-100mW	0.5-0.8W	0.5-1W	0.5-1W	0.5-1W	0.1-0.5W	0.1-0.5W

Radio Frequency Energy Harvesting Architecture

In general, the construction of an EH architecture with a RF source consists of matching circuits, RF-DC converters (rectifier and multiplier circuits), and storage. There are two types of operating modes as shown in Figure 4, namely harvest-then-use mode and harvest-store-then-use mode (Sudevalayam & Kulkarni, 2011).

The matching circuit of a RF-EH module ensures the maximum transfer of power from the antenna to the load. This circuit can be formed using the L or T configuration, or transformers (Figure 5).

The L configuration is the simplest configuration, using L and C components. It is easy to implement, especially in small circuit boards. The T configuration consists of a combination of two inductors and one capacitor, or two capacitors and one inductor. This configuration is suitable for coupling with an antenna that has a small impedance. Another option is to use transformers; which is suitable for coupling with an antenna that has a large impedance.

Table 3: Comparison of energy harvesting sources

	Power Density	Efficiency	Complexity	Pros	Cons
Kinetic					
Piezoelectric	0.4 mW/cm3	1-10%	High	Compact configuration	High output variance
Electromagnetic	800 µW/cm3	1-10%	Low	Easy to integrate	Needs perpetual flow
Electrostatic	0.1 mW/cm3	1-10%	Low	Easy to integrate	Has mechanical constraints
Wind	4-50µW/cm3	1-10%	High	Widely available	Area dependency
Thermal					
Thermoelectric	100µW/cm2	1-10%	Mid	Low maintenance	Needs high gradient
Pyroelectric	50µW/cm2	1-10%	Mid	Utilises waste heat	conversion efficiency dependency
Bio					
Biochemical	300µW	-	-	Low maintenance	Needs chemical extraction cost
Biomechanical	13µW	-	-	Suitable for wearable devices	Limited by user motion or vibration
Radiant					
Solar	15-100 mW/cm2	5-30%	Mid	High power density	Daytime dependency
Light	10-100 µW/cm2	15%	Mid	Mature and predictable	Costly
RF	1-10µW/cm2	50%	Mid	Can deliver information simultaneously	Distance dependency
Acoustic	6µW/cm3	35%	-	Clean	High loss

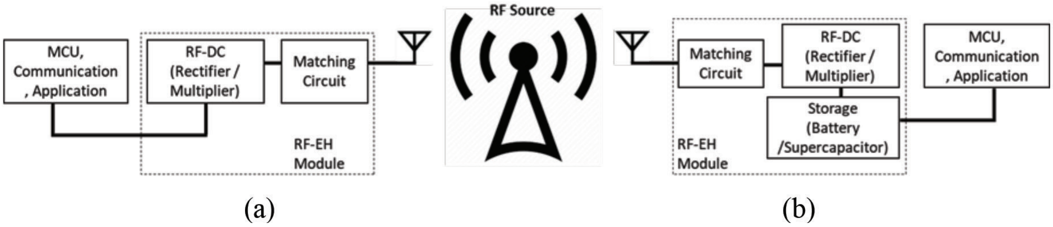


Figure 4: (a) Harvest-then-Use, (b) Harvest-Store-then-Use

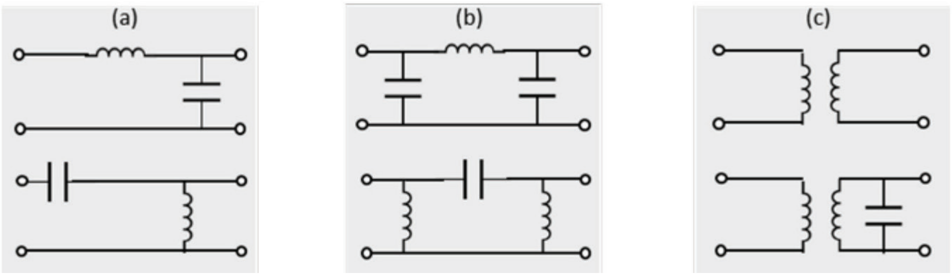


Figure 5: Examples of matching circuits using the (a) L configuration, (b) T configuration, and (c) transformers

The rectifier and multiplier circuits convert RF signals to DC signals. A simple form of the rectifier circuit can be constructed with two basic components, a diode and a capacitor. Two common configurations are the half-wave and full-wave configurations, as shown in Figure 6 (a) and (b). The multiplier cicrcuit, meanwhile, can generally be implemented using the Dickson or Villard configurations, as shown in Figure 6 (c) and (d).

Storage in a RF-EH system can be implemented using a rechargeable battery or supercapacitor. Rechargeable batteries are currently the most commonly used option, as this technology is quite mature and has a high energy density. However, batteries have limited recharge cycles. Another technique for energy storage is the use of supercapacitors. While they are simpler to implement and have unlimited recharge cycles in theory, they have a higher level of self-discharge compared with batteries.

Sample and Smith (2019) conducted a study on RF-EH using a four-stage multiplier. The experiment was tested at a frequency range of 674-680 MHz, with a distance of 4 km, and it produced an output power of 60 µW. Rehman *et al*. (2017) studied RF-EH using two voltage multipliers formed into a Greinacher rectifier. The system was tested on the source of an FM transmitter with a frequency range of 88-108MHz at a distance of 10 m, and it produced an output power of 12.77 µW with a conversion efficiency of 33.6% at an input of -14.2dBm.

Stoopman *et al*. (2014) used a five-stage multiplier equipped with a module control loop for impedance tuning. The experiment was carried out at a frequency of 868 MHz with a distance of 27 m, resulting in a conversion efficiency of 40% at an input of -17dBm. Munir *et al*. (2016), developed a RF-EH system using a four-stage multiplier. The system was tested on WLAN frequencies of 2.4 GHz and 5.8 GHz, and it produced an output of 1.3mW at a distance of 1 m, with a 40% conversion efficiency for the 2.4 GHz frequency and 22% for 5.8 GHz, at an input of 5dBm. Vyas *et al*. (2013) was built a RF-EH system using a five-stage multiplier. The

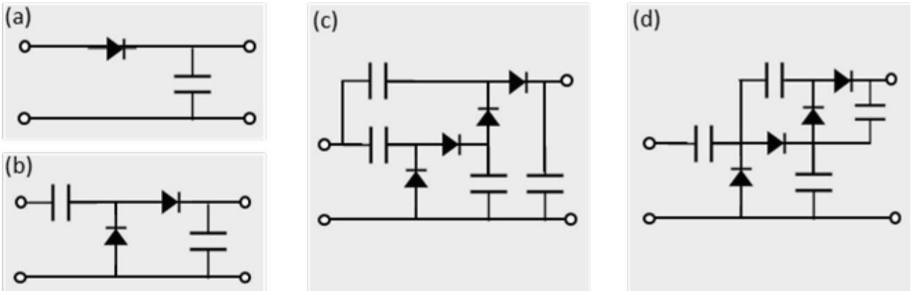


Figure 6: Examples of rectifier and multiplier circuits in the (a) half-wave, (b) full-wave, (c) Dickson , and (d) Villard configurations

system was tested on digital TV frequencies of 512-566 MHz at a distance of 6.3 km, and the output power produced was rated at 15-17 mW.

Agrawal *et al*. (2014) studied RF-EH using a seven-stage multiplier, and the experiment was carried out at a frequency 900 MHz with a conversion efficiency of 75% at an input if -10dBm. Otsuka and Nakashima (2014), meanwhile, built a rectenna, which has a full-bridge rectifier series, The experiment was carried out with a 1278 kHz transmitter (AM frequency) at a distance of 50 m, and it produced an output of 2.39 mW.

Shen *et al.* (2021) designed a RF-EH system using four single-series diode rectifiers with combined parallel DC. The experiment was carried out at a frequency 1800 MHz with a conversion efficiency of 75% and an input of -10dBm. Aboulsaad *et al.* (2022) presented the design of an RF-EH circuit using a 30-stage Dickson rectifier that operates using a frequency of 900 MHz. The system achieved a conversion efficiency of 36%-45% at an input of 0dBm. Mouapi *et al.* (2020) used a three-stages Villard multiplier design that also operates using a frequency of 900 MHz. The system had a conversion efficiency of 40.74% and an RF input 4 dBm.

Khan *et al.* (2021) designed a RF-EH system for use with frequencies of 5.8 GHz, 900 MHz, and 2.4 GHz. It uses six parallel Dickson structures for the 5.8 GHz frequency and two Dickson structures for the dual-band 900 MHz/2.4 GHz. The RF-DC conversion efficiency was 76% at an input of 30 dBm for 5.8 GHz, 73% at an input of 0 dBm for 900 MHz, and 71.9% at an input of 0 dBm for 2.4 GHz. Finally, Song *et al.* (2021) designed a RF-EH system using two sub-rectifiers, with each structure using a three-stage Dickson circuit, connected to a hybrid coupler. The system works using a frequency of 915 MHz, and has a conversion efficiency 60% at inputs -2 dBm to 15 dBm (with the peak efficiency being 74.2% at an input of 10 dBm).

Table 4 provides a comparison summary of some of the implementations of RF-EH as described above.

Table 4: Comparison of several implementations of RF-EH

Source	Frequency	Distance	Eff.	Output	Related Paper
UHF TV	674-680 MHz	4 km	NA	60 µW	(Sample & Smith, 2019)
FM	88-108 MHz	10 m	33.6%@-14.2 dBm	12.77 µW	(Rehman *et al*., 2017)
Isotropic	868 MHz	27 m	40%@-17dBm	8 µW	(Stoopman *et al*., 2014)
WLAN	2.4 Ghz & 5.8 Mhz	1 m	22%-40%@5dBm	0.7-1.3 mW	(Munir *et al*., 2016)
Digital TV	512-566 MHz	6.3 km	26.2%–29.7%	15-17 mW	(Vyas *et al*., 2013)
GSM	900 MHz	NA	75%@-10 dBm	75 µW	(Agrawal *et al*., 2014)
AM	1278 kHz	50 m	NA	2.39 mW	(Otsuka & Nakashima, 2014)
GSM	1800 MHz	NA	51.3%@-10dBm	51 µW	(Shen *et al*., 2021)
NA	900 MHz	NA	36%-45%@0dBm	0.3-0.4 mW	(Aboulsaad *et al.* 2022)
NA	900 MHz	NA	40.74%@4dBm	1 mW	(Mouapi *et al.* 2020)
Hybrid	5.8 GHz 900 MHz 2.4 GHz	NA	76% @ 30 dBm 73% @ 0 dBm 71.9% @ 0 dBm	760 mW 0.73 mW 0.72 mW	(Khan *et al.* 2021)
NA	915 MHz	NA	60%@-2 to 15 dBm	0.3-18 mW	(Song *et al.* 2021)

EH technology utilising ambient RF waves can potentially produce output power at the scale range of μW to mW. However, it still limited to the commercial industry (A. Sharma & Sharma, 2021). That power range is sufficient for some IoT applications, such as watches or calculators (1 μW), RFID tags (10 μW), sensors and remotes (100 μW), wireless sensors and hearing aids (1 mW), and Bluetooth transceivers (10 mW). But, for other IoT applications, more power is needed since IoT applications require 0.1 μW to 1W (Unlu *et al*., 2018). Furthermore, the energy supply from the ambient environment may not always align with the energy demand of an IoT equipment, necessitating the use of multiple RF-DC circuits with boost converters to achieve a higher and stable output. This harvested energy is then typically stored in batteries or supercapacitors (Olgun *et al*., 2011; Piñuela *et al*., 2013; Kuhn *et al*., 2015; Milanezi *et al*., 2017; Abbasizadeh *et al*., 2019).

Cognitive Radio for IoT

The widespread implementation of IoT applications and sensor networks may lead to a higher demand for spectrum usage, which could potentially cause a spectrum scarcity in the near future. One concept that could address this challenge is cognitive radio, which was first introduced by Mitola (2000), and later developed by Haykin (2005).

According to ITU (2009), ithe concept of cognitive radio refers to a system with the ability to collect and analyse information related to its internal conditions, environment, and policy. Those mechanisms are followed by adjustments in the system, such as modulation, encoding, transmission power, so that the system can operate in expected conditions.

Through cognitive radio, the primary user (PU) as the owner of a licensed spectrum can share their spectrum with a secondary user (SU). In this case, the SU can utilise the primary user's spectrum opportunistically by not creating performance degradation for PUs. This mechanism is carried out in real-time to bring reliable communication with a more efficient spectrum utility (the illustration of spectrum utilisation in a cognitive radio network is seen in Figure 7).

The main functional blocks of cognitive radio are illustrated in Figure 8. There are two important mechanisms that directly interact with the radio environment, namely spectrum sensing and sharing (Mahmood & Matin, 2020).

The spectrum sensing mechanism detects the presence of PUs and determine the availability of spectrum hole or white spectrum that can be utilised by the SUs. Spectrum sharing is a mechanism that allocates spectrum and organises access for SUs. Spectrum management, meanwhile, maintains the quality of service (QoS), security, energy efficiency and regulates the handoff spectrum if it detects the presence of PUs.

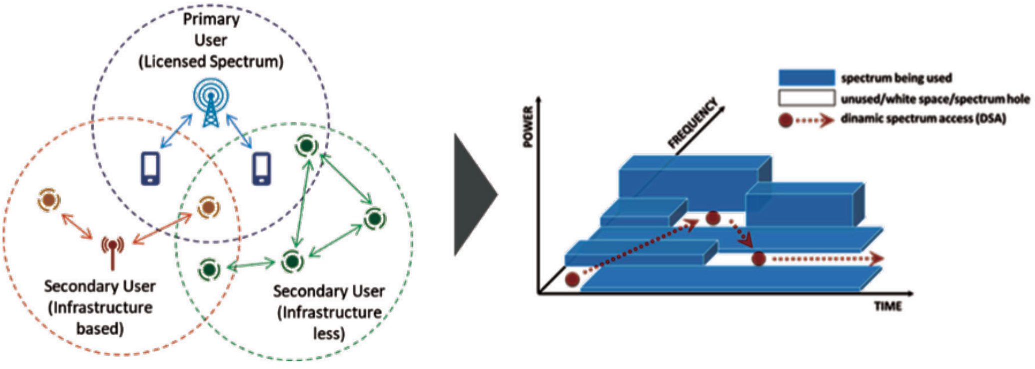


Figure 7: Spectrum utilisation in a cognitive radio network

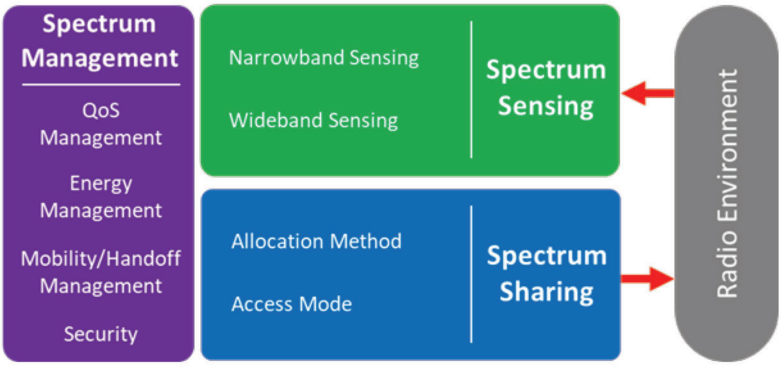


Figure 8: The main functional blocks of cognitive radio

Spectrum Sensing

Technically, there are two spectrum sensing methods, namely narrow-band sensing and wide-band sensing. The characteristics of each technique are described in Table 5.

To improve the accuracy of spectrum sensing, cooperative sensing mechanism can be used. The SUs will detect a spectrum hole or white spectrum, and their results will be shared with each other as comparison information. The cooperative sensing mechanism can be performed in two ways, namely centralized cooperation and distributed cooperation. In the centralized cooperative mechanism, any information obtained by each SU will be sent to the central entity (e.g., secondary base station or fusion centre), which will calculate and define the unutilised channel. This information is then shared with all SUs. Meanwhile, in distributed cooperative mechanisms, each SU will share information on the unutilised channel with other SUs and the information is compared as the basis for their decision to define the unutilised channel.

Tripta *et al.* (2020) proposed a sensing method for in-band full-duplex CR with a single-input-multi-output (SIMO) channel. It is FFT-based, using the two-dimensional averaging method and least square technique. The proposed formulation aimed to improve detection performance. Eze *et al.* (2018) presented an analysis and simulation of CR-IoT

Table 5: Comparison of several spectrum sensing techniques

	Characteristic
Narrow-band sensing	
Energy detection	Easy to implement; Detection misses in low SNR conditions; No need for prior knowledge of PUs; Low sensing time
Matched-filter detection	Medium complexity; Detection can be done in low SNR conditions; Need prior knowledge of primary users; Low sensing time
Cyclo-stationary features detection	Complicated to implement; Detection can be done in low SNR conditions; Need prior knowledge of primary users; Need longer sensing time
Wide-Band Sensing	
FFT-based detection	Medium complexity; Need high sampling rate
Wavelet-based detection	Complicated to implement; Detection has high accuracy; Sub-bands have known in uniform width
Compressive sensing	More complicated to implement; Detection has high accuracy; Sensitive to signal noise

for vehicular communication that senses PU channels along road locations. It used energy detection sensing mechanism with a distributed cooperative mode. The proposed model aimed to improve opportunistic spectrum usage for current and future SU locations. Roncancio *et al.* (2018) studied CR-IoT operating with the SigFox frequency band using the cyclo-stationary detection sensing method. The proposed model characterised the unlicensed frequency band for IoT (particularly ISM band) used by SigFox. Saeedzarandi and Azmi (2013) proposed a multi-band joint detection, which used energy detection in a centralised cooperative mode. The proposed method aimed to maximise the throughput.

X. Zhang *et al.* (2018) investigated a sensing method for wideband spectrum using compressive sensing with a centralised cooperative mode. The method produced outputs in terms of reducing sampling, processing complexity, and energy consumption. Hattab and Cabric (2019) studied sensing mechanisms for IoT objects and base stations that coexist with the incumbent network. It used energy detection with a distributed cooperative mode. The method aimed to identify more sepcial spectra with lower detection misses. Salahdine *et al.* (2015), meanwhile, simulated the sensing method for QPSK signals. It used a matched filter with a dynamic threshold. The method increased the efficiency of the detection.

Singh *et al.* (2018) presented a sensing method based on the wavelet technique, which was simulated on 16 channels (100 kHz for each channel). The proposed design improved sensing speed and reduced complexity. Long *et al.* (2021) studied a cooperative sensing method that simulates multiple CR-IoT. It used an energy detection technique with a fusion centre and aimed to improve the throughput by optimising spectrum sensing time and sensor selection. Alijani and Osman (2020) investigated the use of an energy detection technique with an optimum threshold. The proposed design improved detection probability and reduced collision probability.

Martian *et al.* (2020) studied the sensing method of using an energy detection technique with an adaptive threshold. Their model aimed to minimise the decision error probability. Bala *et al.* (2022) presented a sensing method that works under low signal-to-noise ratio (SNR). It used energy detection technique with an adaptive threshold and improved throughput with a satisfying sensing performance (detection probability and false alarm probability). Hossain *et al.* (2021) proposed an energy-efficient sequential sensing approach for multi-CR-IoT, which used an energy detection technique with centralised cooperation. The approach enhanced sensing performance, and improved energy and spectral efficiency. Table 6 summarises several studies on the applications of spectrum sensing techniques.

Spectrum Sharing

After conducting spectrum sensing to detect spectrum occupancy or spectrum holes, Sus will use a fair and efficient spectrum allocation mechanism that takes into account the presence of primary users and other secondary users. Thus, optimum spectrum utilisation can be achieved by maintaining performance and minimising potential conflict or interference between PUs and Sus.

Spectrum allocation can be implemented either through a cooperative mode or non-cooperative mode. In the cooperative mode, every entity will coordinate with one another. However, in the non-cooperative mode, each entity will define the spectrum allocation in a self-interested manner without coordination with others. There are three spectrum access modes for occupying a spectrum, which are the interweave, overlay, and underlay modes. In the interweave mode the SU will occupy the spectrum not occupied by the PU. In the overlay mode, the SU will use a portion of its transmission power as a relay for the primary signal (the SU will forward the primary signal together with its own signal). Lastly, in underlay mode, the SU and PU occupy the spectrum simultaneously. However, the SU must operate

Table 6: A summary on related papers on spectrum sensing

Related paper	Model entity	Output	Sensing technique	Interaction behaviour
Tripta *et al*. (2020)	Sensing for SIMO channel using in-band full-duplex	Improving detection performance	FFT-based Detection	Non-cooperative
Eze *et al*. (2018)	CR-IoT for vehicular communication that senses PU channels along road location	Improving spectrum opportunistic usage for current and future SU locations	Energy detection	Distributed cooperation
Roncancio *et al*. (2018)	CR-IoT within SigFox's frequency band	Characterising unlicensed frequency band for IoT	Cyclo-stationary detection	Non-cooperative
Saeedzarandi amd Azmi (2013)	Sensing PUs with multiple sub-bands	Maximising throughput	Energy detection	Centralised cooperation
X. Zhang *et al*. (2018)	Sensing wide-band spectrum from PU signals	Reducing sampling, processing complexity, and energy consumption	Compressive sensing	Centralised cooperation
Hattab and Cabric (2019)	IoT objects and base stations share spectrum with the incumbent network	Identifying more spatial spectrum blocks with lower detection misses	Energy detection	Distributed cooperation
Salahdine *et al*. (2015)	Sensing Pus with QPSK signals	Increasing the efficiency of sensing detection with a dynamic threshold	Matched filter detection	Non-cooperative
Singh *et al*. (2018)	Sensing PU signals with 16 channels	Improving sensing speed and reducing complexity	Wavelet-based detection	Non-cooperative
Long *et al*. (2021)	One PU shares spectrum with multi-CR-IoT with Fusion Center	Improving the throughput of CR-IoT	Energy detection	Centralised cooperation
Alijani and Osman (2020)	Sensing PU with optimum threshold	Improving detection probability and reducing collision probability	Energy detection	Non-cooperative
Martian *et al*. (2020)	Sensing PU with adaptive threshold	Minimising decision error probability	Energy detection	Non-cooperative
Bala *et al*. (2022)	Sensing PU under low SNR	Improving throughput with satisfying sensing performance	Energy detection	Non-cooperative
Hossain *et al*. *(*2021)	Pus share spectrum with multi-CR-IoT with a fusion centre	Enhance sensing performance, energy and spectral efficiency	Energy detection	Centralised cooperation

with low power to minimise the interference and maintain the performance of the PU.

Sharing control between entities can be done through a centralised or distributed mechanism. In centralised mechanism, a central entity, such as a base station or cluster head, is needed, and the spectrum access and allocation decisions are made by the central entity. In distributed mechanism, spectrum access and allocation decisions are made by local entities. The characteristics of each technique is described in Table 7.

Karaca (2020) proposed a centralised cooperative spectrum sharing system between multiple PUs and multiple SUs with a central server. The SUs may transmit in either an overlay or underlay mode. The main objective of the framework is to improve channel distribution fairness for multi-channel allocation scenarios. Amjad *et al.* (2016) introduced a sharing mode between multiple SUs that coexist with PUs, which has multi-channels. The selfish behaviour of SUs in acquiring vacant frequencies was formulated as an evolutionary non-cooperative game. The framework aimed to provide fairness among Sus. Zhang *et al.* (2013) designed a cooperative spectrum sharing system between one PU and multiple Sus. The PU acts as a central point, where the SU negotiates and cooperates according to the channel or bandwidth usage. The proposed framework utilises bargaining game theory and aimed to achieve a fair rate-reward under QoS constraints. Jing *et al.* (2018) addressed the cooperation between PUs and Sus, where the latter acts as a relay for PU signals. The proposed model used an overlay access mode and aimed to maximise SU throughput.

Table 7: Characteristics of spectrum sharing techniques

	Characteristics
Non-cooperative	• Constraints of other entities are not considered • Focuses on local optimal performance • No need for intensive interaction between entities, thus reducing power consumption
Cooperative	• Constraints of all entities are considered • Focuses on overall entity performance (high fairness) • Need intensive interaction between entity
Interweave access	• Require information on spectrum holes (time, frequency, and space) • SUs will occupy the spectrum hole opportunistically when it is not used by PUs • Interference may happen if there is false detection at the sensing phase • Applicable in TDMA, FDMA, and OFDM systems
Overlay access	• SUs and PUs occupy the spectrum simultaneously • SUs will use a portion of their transmission power as a relay of the PU signal • Need cooperation between PUs and SUs • Interference may happen if there is false detection at the sensing phase
Underlay access	• SUs and PUs occupy the spectrum simultaneously • Interference limit of PUs is needed • SUs transmit in limited power to minimise interference for PU • Applicable in CDMA systems
Centralised	• Requires a central entity, such as a base station or cluster head • Spectrum access and allocation decisions are made by a central entity • Optimal performance for the overall system can be maintained by the central entity (high fairness)
Distributed	• Central entity not required • Spectrum access and allocation decisions are made by a local entity • Optimal performance maintained by local entity (and its neighbour) • More flexible and fast

Khaledi and Abouzeid (2013) studied spectrum sharing between multiple SUs and a primary spectrum owner with multiple idle channels. In that model, each SU bids for vacant channels in an auction-based mechanism with the objective of maximising SU valuation (channel capacity). Wen *et al.* (2018) investigated spectrum sharing between multiples Sus and multiple PUs in a distributed scheme. The optimal operating channel and location for SUs were formulated through particle swarm optimisation and the proposed model aimed to maximise SU capacity. Jagannathan *et al.* (2012) presented a non-cooperative spectrum sharing system between one PU or multiple PUs and multiple SUs that utilised a dedicated or spectrum hole option. That model was formulated as a non-cooperative game and aimed to maximise revenue. Kanadje *et al.* (2019) studied cooperative underlay spectrum allocation between a pair of SUs in the presence of a pair of PUs and a relay. Game theory was applied to the model and it aimed to reach Nash equilibrium with a transmission power strategy.

Ngo and Le-Ngoc (2010) designed a distributed spectrum allocation between multiple SUs and multiple PUs that has a vacant orthogonal frequency-division multiplexing (OFDM) subchannel. The proposed framework aimed to maximise throughput while being fair in its allocation. Etim and Lota (2016) addressed underlay spectrum sharing between a pair of PUs with multiple SUs across different environments. The framework was modelled as a non-cooperative game and aimed to optimise transmission power with QoS constraints. Moon (2017) introduced centralised spectrum sharing between PUs and SUs that coexist in two overlapped channel bands. It involved a spectrum broker to manage the spectrum allocation. The model was formulated using the matrix geometric approach and aimed to maximise spectrum capacity.

Khalifa *et al.* (2020) proposed a spectrum sharing model between multiple Pus and multiple SUs that are coordinated by a cognitive base station. That model was formulated using knapsack optimisation to maximise the fairness based on cooperative behaviour. Khan *et al.* (2020) presented spectrum sharing that involves multiple PUs and multiple SUs with a base station controller to allocate the channels. The model was formulated using a continuous-time Markov chain and multi-attribute-based fairness-driven algorithm to reach fairness among SUs and enhance spectrum utilisation efficiency. Moayedian *et al.* (2020) studied cooperative spectrum sharing between a pair of PUs and multiple SUs with an access point, and the spectrum access was performed through an overlay and underlay. The model was formulated using quadratic transformation and aimed to reach fair resource allocation.

Lu *et al.* (2020) investigated the cooperative spectrum between PUs and SUs, with the SU relaying PU signal through an OFDM subcarrier. Joint optimisation of power and subcarrier allocation was formulated to maximise the achievable rate. Khan *et al.* (2021) presented spectrum sharing between multiple PUs and multiple SUs with two group priorities. Underlay amd interweave access modes were used for the model. The framework using by Markov chain modelling and aimed to enhance spectrum utilisation efficiency. Agrawal and Asawa (2022) proposed a non-cooperative spectrum sharing model for multi-channel scenarios between multiple SUs and multiple PUs. The model was formulated with a multi-armed bandit and aimed to minimise regret through best channel selection. Table 8 lists summaries of several papers on the applications of spectrum sensing techniques.

Spectrum Management

Spectrum management is part of the cognitive system that ensures the system works with the specified performance and policy, such as QoS management, energy efficiency management, mobility or handoff management, and security management.

Due to CR-IoT utilising a spectrum hole from the PU, the resource opportunities for CR-IoT are limited. For this reason, effective QoS

Table 8: Summary Related Paper on Spectrum Sharing

Related paper	**Model entity**	**Output**	**Access mode**	**Interaction behaviour**
Karaca (2020)	Multi-PU and Multi-SU with central server	Improve channel distribution fairness for multi-channel allocation	Underlay and overlay	Centralized & Cooperative
Amjad *et al.* (2016)	Multi-SU with selfish mode and PU which has multi-channel	Fairness among SUs	Interweave	Non-Cooperative
Zhang *et al.* (2013)	One PU and multi-SU with QoS constraint	Fairness rate-reward with QoS constraints	Interweave	Centralized & Cooperative
Jing *et al.* (2018)	One PU and one SU that relay PU signal	Maximise SU throughput	Overlay	Cooperative
Khaledi and Abouzeid (2013)	Multiple SUs and a primary spectrum owner with multi-idle channels	Maximise SU valuation (channel capacity)	Interweave	Non-Cooperative
Wen *et al.* (2018)	Multiple PUs and multiple SUs with optimal location and channel selection	Maximise SU capacity	Interweave	Distributed & Cooperative
Jagannathan *et al.* (2012)	One or multiple PUs with multiple SUs with a dedicated or spectrum hole option	Maximise revenue	Interweave	Non-cooperative
Kanadje *et al.* (2019)	A pair of SUs coexist with a pair of PUs and a relay	Transmission power strategy to reach Nash equilibrium	Underlay	Cooperative
Ngo and Le-Ngoc (2010)	Multiple SUs and Multi-PU with vacant OFDM subchannel	Maximise throughput with fairness allocation	Interweave	Distributed and cooperative
Etim and Lota (2016)	A pair of PUs with multiple SUs across different environments	Optimise transmission power with QoS constraints	Underlay	Non-cooperative
Moon (2017)	PUs and SUs coexist in two overlapped channel bands	Maximise spectrum capacity	Interweave	Centralised and cooperative
Khalifa *et al.* (2020)	Multiple PUs and multiple SUs with a cognitive base station	Maximise fairness based on cooperative behaviour	Interweave	Centralized and cooperative
Khan *et al.* (2020)	Multiple PUs and multiple SUs with a base station controller	Fairness among SUs and enhance spectrum utilisation efficiency	Underlay and interweave	Centralised and cooperative
Moayedian *et al.* (2020)	A pair of PUs and multiple SUs with an access point	Fair resource allocation	Overlay and underlay	Centralised and cooperative
Lu *et al.* (2020)	PU and SU that relay PU signal by OFDM subcarrier	Maximise achievable rate	Interweave	Cooperative

Khan *et al.* (2021)	Multi-PU and Multi-SU with two group priority	Enhancing spectrum utilisation efficiency	Underlay and interweave	Centralized and cooperative
Agrawal and Asawa (2022)	Multi-SU and Multi-PU share across Multi Channel	Minimise regret by selecting the best channel	Interweave	Non-cooperative

management is crucial for CR-IoT. The QoS management mechanism regulates the allocation and method of resource use so that it can deliver the applications and traffic according to the expected level of service. The metrics used to measure QoS include bandwidth, throughput, delay, availability, and packet loss.

Ali *et al.* (2020) proposed a QoS provisioning system for cognitive IoT, in which the admission and channel allocations were based on traffic awareness and priority class. The QoS metrics used in the study are blocking probability, dropping probability, channel utilisation, and throughput. Hassan *et al.* (2017) investigate the usage of TV white space spectrum of cognitive IoT, and the QoS metrics evaluated are delay and data quality. Li *et al.* (2019) investigated cognitive IoT that used a shared spectrum with uncertain availability. The QoS metric used in the study is probabilistic link capacity, which corresponds to the achievable rate. Qian *et al.* (2021) proposed cognitive IoT that coexists with the multiple mobile network operators, with the QoS metric involved being the transmission rate.

Energy consumption is very critical in the implementation of CR-IoT as the CR mechanism requires energy for spectrum sening and sharing. However, IoT has a limited energy capacity, generally using batteries as a source of energy). For this reason, energy management in CR-IoT is crucial.

According to Awin *et al.* (2016), cognitive networks were formulated to maximise energy efficiency by optimising the duration of the sensing and transmission phases. Lee and Wolf (2008) put forward an energy-efficient method for spectrum sensing inr cognitive radio. Two scenarios are presented, the first is based on confidence voting and the second on the cluster-collect-forward scenario. Qureshi *et al.* (2017) demonstrated an energy-efficient medium access control scheme for cognitive IoT. In that study, the energy efficiency scheme was achieved through three factors: reducing the handshake mechanism, minimising the control frame size, and reducing retransmission. Yu *et al.*, 2010 investigated energy-efficient spectrum allocation in cognitive networks. The framework was formulated by optimising power and channel assignment to simultaneously maximise capacity and minimise power consumption.

SUs in CR-IoT cannot always occupy the spectrum hole, as when the PU becomes active again, the SU must immediately leave the spectrum hole so it does not interfere with the primary user. The SU must then search and occupy the other spectrum hole. For this reason, mobility and handoff management is necessary for the implementation of CR-IoT. Through this mechanism, SU systems can perform the handoff spectrum quickly and smoothly with minimal performance degradation.

Prasad and Jaya (2020) proposed a spectrum handoff decision method for cognitive network using weighting and order preference techniques. This framed involves several parameters, which are power consumption, traffic density, jitter, delay, packet loss ratio, bandwidth, and price. Christian *et al.* (2012) analysed different spectrum handoff mechanisms, namely those using proactive, reactive, and hybrid strategies, and they were evaluated based on the handoff latency parameter. Wu *et al.* (2015) addressed the spectrum handoff method for cognitive network by optimising the channel sensing sequence. The framework was formulated using dynamic programming and aimed to maximise throughput and minimise energy consumption. Zhao *et al.* (2020) investigated the spectrum handoff strategy between the original SU and

Table 9: A summary of related papers on spectrum management

	Function scope	**Related paper**
QoS management	Resource allocation Traffic classification Prioritisation and scheduling	Ali *et al*. (2020), Hassan *et al*. (2017), Li *et al*. (2019) and Qian *et al*. (2021)
Energy management	Sensing and active time allocation Transmission power allocation Energy reservation	Awin *et al*. (2016), Lee and Wolf (2008), Qureshi *et al*. (2017) and L. Yu *et al*. (2010)
Handoff management	User mobility handoff User activity handoff Handoff delay management	Prasad and Jaya (2020), Christian *et al*. (2012), Wu *et al*. (2015), and Zhao *et al.* (2020)
Security management	Channel robustness Confidentiality management Authentication management	Hossain and Xie (2020), Chaczko *et al*. (2018), Lin *et al.* (2017), Basak and Acharya (2020)

newly arrived SU. The framework utilised a Q table through reinforcement learning to improve the spectrum strategy of the newly arrived SU.

The increasing deployment of IoT devices and data exchange between them will indirectly increase the potential security risks of security from malicious parties in the communication system. Due to the lack of human supervision and the autonomous nature of IoT devices, security management is crucial during implementation. Some of the main aspects are confidentiality (ensuring data is available and can be decoded only for authorised users or nodes), authentication (ensuring only legitimate users or nodes have access to the network or data), data integrity (ensuring data accuracy by eliminating corrupted or false data), and channel robustness (ensuring the channel is reliable and resilient to attacks, such as jamming).

Hossain and Xie (2020) focused on hidden terminal attacks on cognitive IoT networks, and proposed a context-aware detection method that utilises a Markov model to capture the behaviour of such attacks. Chaczko *et al.* (2018) studied the potential of jamming attacks on cognitive IoT networks and proposed a protection method that adapts the multi-arm bandit game. Lin *et al.* (2017) introduced a security protocol for cognitive IoT application. The framework was formulated using a two-tier device-based authentication protocol to ward off primary user emulation attacks. Basak and Acharya (2020) investigated the physical layer security of multi-hop cognitive radio device-to-device communication, such as in IoT. The study considered confidential packet transmissions that could be compromised by multiple eavesdroppers. The secure routing method was proposed by using the Bellman-Ford approach, with the objective of maximising secrecy energy efficiency.

Table 9 shows a summary of several works related to spectrum management in the CR system.

Integrated Concept

The implementation of CR and EH concepts is essential for the future of IoT technology, as the application of these concepts can increase both spectrum and energy efficiency. This will allow the implementation of IoT in massive quantities by optimising the use of spectrums and energy for IoT devices, which often operates with a limited battery capacity and may be located in remote areas, where conventional power sources are difficult to obtain.

The Architecture of CR-IoT with RF-EH

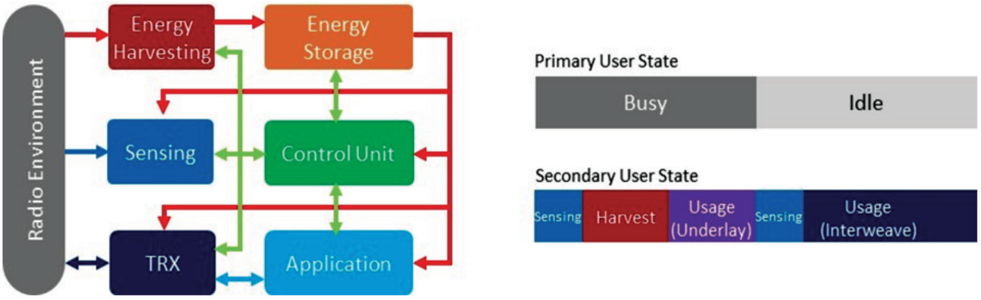
The integration of RF-EH and CR-IoT is be illustrated in Figure 9. The coexistence of SUs and PUs can be achieved using a slotted and state approach. When the PU is occupying the channel (busy), the SU can perform EH on the primary signal or use the channel in the underlay mode to avoid interference with the PU. When the PU is not using the channel (idle), the SU can use that channel in the interweave mode.

The presence of PUs can be detected through a spectrum-sensing mechanism. If the sensing output does not detect the presence of the PU, the SU can occupy the channel (spectrum access or sharing). In this case, the control unit will activate the transceiver and application modules to carry out the communication process in optimal way by considering the amount of energy available in storage, the number of data queues to be sent, transmission power, and the residual energy adequacy for the next cycle.

In order to implement CR, IoT devices require power to operate and run the spectrum sensing and spectrum sharing/access mechanisms. Thus, the trade-off between sensing parameters, sharing/access, energy storage, and service performance (e.g., spectrum utilisation, usage fairness, throughput, and energy efficiency) must be considered so that RF-EH for CR-IoT can be impelemented.

Liu and Zhang (2020) proposed a model comparising a single PU, multiple SUs, and a central entity. The SU may operate in the overlay and underlay modes. In the overlay mode, the SU will sense and harvest energy at each of the beginning frame, and the rest of frame period will be used for data transmission when the PU is detected to be idle. In the underlay mode, the SU may harvest and transmit in whole frames. However, the SU needs to consider the interference impact on the PU. The framework was formulated to maximise the throughput by considering parameters such as sensing time, energy supplied, and total power. Shetkar and Ronghe (2019) developed a model that consists of multiple PUs, multiple SUs, and a central entity, with the involvement of multiple channels. The central entity generates a channel allocation matrix based on the idle state probability of each channel. Channels with a high idle probability may be used by the SU for data transmission, while channels with a low idle probability may be used by the SU for EH. The framework considered parameters such as transmission count and the SU's residual energy. It aimed to achieve bandwidth utilisation efficiency and fairness among SUs.

Hooshiary *et al.* (2018) proposed a model composed of multiple PUs, multiple SUs and multple -channels. The SU could harvest energy and transmit simultaneously by selecting best channels for EH and transmission. The



(a) (b)

Figure 9: (a) General architecture of CR-IoT with RF-EH and (b) the basic operating model

framework aimed to maximise the throughput by considering parameters such as transmission power and residual energy. Pathak and Andrish (2016) presented a model consisting of a pair of PUs and a pair of SUs. In each time slot, the SU works in two phases, EH phase and information transfer phase. The framework aimed to maximise the throughput by considering parameters such as harvesting time, transmission time, and transmission power.

Lee *et al.* (2018) investigated a model comprising a pair of PUs and a pair of SUs, where the SU can harvest energy from the PU during sensing time and transmit data if the PU is detected to be in an idle state. Some of the parameters considered are sensing time, power allocation, and signal-to-interference-plus-noise ratio (SINR) to achieve energy efficiency. Yan *et al.* (2019) proposed a model that assembled of a pair of PUs and a pair of SUs, where the SU acts as a relay for th PU signal. The framework operates in three phases. In the first phase, the PU transmitter sends its signal to the PU receiver and the SU transmitter. In second phase, the SU transmitter acts as a relay, decoding and forwarding the PU signal to the PU receiver, while also sharing energy with the PU. In last phase, the SU transmitter sends its information to the SU receiver, while also sharing energy with the PU. The proposed framework aimed to achieve energy efficiency by considering parameters such as residual energy, transmission time, transmission power, and the PU's QoS. Basharat *et al.* (2016) constructed a model with a single PU, multiple Sus, a central entity, and multiple sub-bands. In this model, some SUs may experience energy deficits and the other SUs need to perform the sensing and data transmission. The central entity will allocate sub-bands according to the SUs' requirements. The framework was formulated to maximise the throughput by examining parameters such as residual energy, sensing time, transmission power, and the amount of SUs.

Jing *et al.* (2018) presented a model that consisting of a pair of PUs and a pair of SUs, where the SU acts as a relay for the PU signal. The SU may perform EH when the PU is detected in the active mode. The SU may operate cooperative data transmission in three phases: in the first phase, the SU transmitter receives the signal from the PU transmitter; in the second phase, the SU transmitter forwards the PU signal to the PU receiver; and, in the last phase, the SU sends its signal to the SU receiver. This framework considered parameters such as sensing time, transmission power, and residual energy, and was formulated to maximise the throughput. Alzahrani and Ejaz (2018) created a model with multiple PUs, multiple SUs and a central entity that were grouped in clusters. The SU will send the local sensing results to the central entity and request an allocation of channel for data transmission, or request EH if its residual energy is insufficient. The framework was formulated to maximise the throughput by considering parameters such as sensing time, transmission power, and residual energy. Guo *et al.* (2018) presented a model that consists of a single PU and a single SU. The SU works in two regions, namely the harvesting nd sensing region. The framework aimed to maximise energy efficiency and considered parameters such as sensing time and transmission power.

Yan *et al.* (2018) studied a model that composed of a single PU and a single SU. The SU will occupy the channel whenever the PU is idle, and at beginning of the time slot, the SU needs to decide whether to sense or harvest energy. The parameters considered are sensing time, transmission power, and residual energy. The proposed framework aimed to maximise the throughput. Tian *et al*. (2020) investigated a model that consists of a single PU and a single SU. The SU occupies the channel in the underlay mode, and in every beginning frame, the SU will harvest energy over a certain duration and the rest of frame will be used for data transmission. The framework aimed to achieve energy efficiency by examining parameters such as residual energy, transmission time, transmission power, and the SU's QoS. Liu *et al.* (2020) composed a model with a single PU, multiple SUs, and a central entity. In the beginning of each frame, the SU will sense or harvest energy over a certain duration and in the rest of the frame, the SU will transmit tits signal. The multiple SUs were divided into two groups, in which the first group senses channel availability (PU activity) and the second group harvests energy, with both groups being coordinated by the central entity. The proposed model was formulated to maximise energy efficiency by considering parameters such as sensing time, transmission power, and the amount of SUs.

Table 10: A summary of related papers on CR for RF-EH

Related paper	**Model entity**	**Access mode**	**Interaction behaviour**	**Performance metric**	**Parameter involved**
Liu and Zhang (2020)	Single PU, multiple SUs, central entity	Underlay, overlay	Cooperative	Throughput	Sensing time, energy supplied & total power
Shetkar and Ronghe (2019)	Multiple PUs, Multiple SUs, central node, multiple channels	Interweave	Cooperative	Bandwidth utilisation efficiency, fairness	Transmission count & residual energy
Hooshiary *et al.* (2018)	Multiple PUs, Multiple SUs, multiple channels	Interweave	Non-cooperative	Throughput	tTansmission power & residual energy
Pathak and Andrish (2016)	Single PU, single SU	Underlay	Non-cooperative	Throughput	Harvesting time, transmission time, transmission power
Lee *et al.* (2018)	Single PU, single SU	Interweave	Non-cooperative	Energy efficiency	Sensing time, power allocation, SINR
Yan *et al.* (2019)	Single PU, single SU as a relay for PU signal	Overlay	Cooperative	Energy efficiency	Residual energy, transmission time, transmission power, PU's QoS
Basharat *et al.* (2016)	Single PU, multiple SUs, central entity	Interweave	Cooperative	Throughput	Residual energy, sensing time, transmission power, SU number
Jing *et al.* (2018)	Single PU, single SU	Overlay	Cooperative	Throughput	Sensing time, transmission power, residual energy
Alzahrani and Ejaz (2018)	Multiple PUs, multiple Sus, central entity in cluster groups	Interweave	Cooperative	Throughput	Sensing time, transmission power, residual energy
Guo *et al.* (2018)	Single PU, single SU	Interweave	Non-cooperative	Energy efficiency	Sensing time, transmission power

Yan *et al.* (2018)	Single PU, single SU	Interweave	Non-cooperative	Throughput	Sensing Time, transmission power, residual energy
Tian *et al.* (2020)	Single PU, single SU	Underlay	Non-cooperative	Energy efficiency	Residual energy, transmission time & power
Liu *et al*. (2020)	Single PU, multiple SUs, central entity	Interweave	Cooperative	Energy efficiency	Sensing Time, transmission power, SU number
Zheng *et al*. (2020)	Single PU, single SU	Underlay, interweave	Non-cooperative	Throughput	Residual energy, Sensing time, transmission power, collision
Karaca (2020)	Multiple PUs, multiple SUs, central entity	Underlay, overlay	Cooperative	Fairness distribution	Residual energy, Sensing time, transmission power, SINR
Halima and Boujemâa (2020)	Single PU, single SU	Underlay	Non-cooperative	Throughput	Harvesting time, transmission time

Zheng *et al.* (2020) presented a model that contains a single PU and a single SU, where the SU activity was mapped into three areas, namely the harvesting, overlay (where the SU may transmit in an opportunistic mode), and joint areas (where the SU may transmit in the underlay or opportunistic modes). The proposed framework was formulated to maximise the throughput, and as the parameters involved were residual energy, sensing time, transmission power, and collision probability. Karaca (2020) proposed a model that consists of multiple PUs, multiple SUs, and a central entity that organises the spectrum allocation. It has four areas of operation, namely the harvesting, guard, underlay, and overlay areas. The framework was formulated to achieve a fair distribution by considering parameters such as residual energy, sensing time, transmission power, and SINR.

Halima and Boujemâa (2020) investigated a model composed of a single PU and a single SU. The SU is equipped with multiple antennas on both the transmitter and receiver sides. The SU operates in two phases. The first phase was used to harvest the energy and the second phase was used for data transmission. However, SU needed to adjust its transmission power to minimise interference with the PU. The framework was formulated to maximise throughput by examining parameters such as sensing time, energy supplied and total power. The summary of each paper on RF-EH and CR-IoT is provided in Table 10.

Various Operating Models

The application of wireless power transfers, especially using RF signals as a source of EH, can be used in communication systems, especially in devices that have low power consumption, such as IoT or wireless sensors. The communication devices, combined with RF-EH and the cognitive concept, led to the emergence of several alternative operating models, such as CR-wireless-powered backscattered communication (CR-WPBC), and CR-simultaneous wireless information and power transfer (CR-SWIPT).

In the CR-WPBC model, the terminal node receives a signal sent by the primary base station. The signal can be reflected and modulated directly by the node before its information is sent to another secondary entity (e.g., a secondary access point or secondary cluster head). The primary signal can also be harvested to gather energy, and if the energy collected is sufficient, then the accumulated energy will be utilised by the node to transmit its information. The secondary node can transmit its signal in the interweave mode (if the primary user is detected in an idle state) or the underlay mode (if the primary user is detected to be in a busy state). An illustration of the CR-WPBC operating model can be seen in Figure 10.

Tran and Le (2019) proposed a model that consists of a single PU and multiple Sus. The PU always occupies the channel, thus the SU will access the channel in the underlay mode. Each SU operates either through backscattering, harvesting, or underlay transmission, and they are scheduled in a time-fraction scheme. The framework aimed to maximise the throughput, and the parameters considered were backscattering time, harvesting time, transmission time, and transmission power. Kishore *et al.* (2019) presented a model that contains a single PU and a single SU. The SU operates in two stages. In the first stage, the SU needs to sense the availability of the PU, and when the PU is present, the SU will allocate a time slot duration for the backscattering mode and the rest of the time slot duration for the harvesting mode. In the next stage, the SU may transmit its signal when the PU is absent by utilising the harvested energy from the previous stage. The framework was formulated to maximise energy efficiency by considering parameters such as sensing time, transmission time, harvesting time, and detection threshold.

Kim *et al.* (2022) studied a model that encompasses a single PU, multiple SU transmitters, a power beacon, and one SU receiver. The PU's activity was sensed by the power beacon, and when the PU is active, the SU may transmit its signal in the backscattered mode (the SU modulates its data by utilising the PU signal). Alternatively, if the PU is idle, the power beacon will generate the RF signal, thus the SU may transmit its signal in the backscattered mode, but now the SU modulates its data through utilising the RF signal from the power beacon. Parameters considered in the model are decision threshold, primary activation probability, and SNR. The framework was made to evaluate bit error rate and throughput.

Li (2022) proposed a model that accommodates a single PU, multiple SU transmitters, and one SU receiver. The SU works in two phases. In the first phase, all of the SU transmitters harvest energy from the PU signal. In the second phase, each SU takes

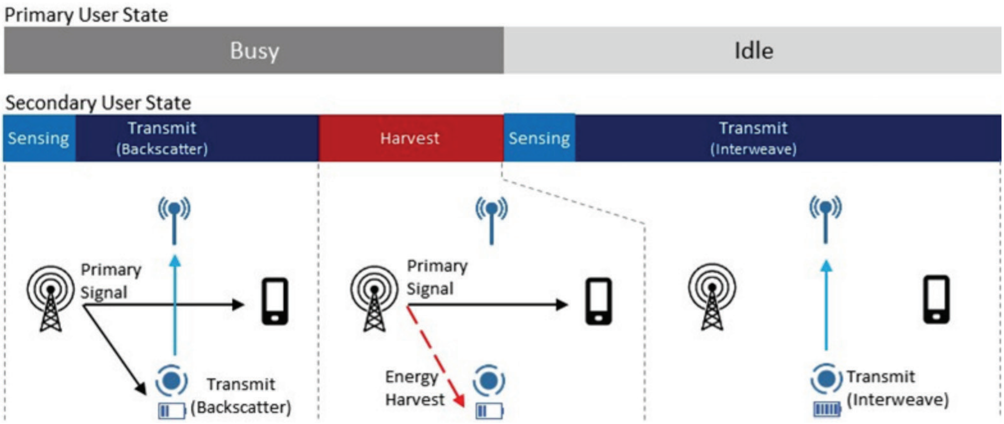


Figure 10: An illustration of the CR-WPBC operating model

Table 11: A summary of related poapers on CR-WPBC

Related paper	**Model entity**	**Access mode**	**Performance metric**	**Parameter involved**
Tran and Le (2019)	Single PU, multiple SU	Backscatter, underlay	Throughput	Backscattering time, harvesting time, transmission time, transmission power
Kishore *et al*. (2019)	Single PU, single SU	Backscatter, interweave	Energy efficiency	Sensing time, transmission time, harvesting time, detection threshold
Kim *et al.* (2022)	Single PU, multiple SU transmitters, one SU receiver, power beacon	Backscatter	BER, Throughput	Decision threshold, primary activation probability, SNR
Li (2022)	Single PU, multiple SU transmitters, one SU receiver	Backscatter	Throughput	Backscattering time, harvesting time, transmission time, transmission power
Fu *et al.* (2022)	Single PU, multiple PUs	Backscatter, interweave	Throughput	Backscattering time, harvesting time, transmission time, transmission power

turn to transmit signal in the backscattered mode. The framework was formulated to maximise the throughput with parameters such as backscattering time, harvesting time, transmission time, and transmission power.

Fu *et al.* (2022) presented a model with a single PU and multiple SUs. The SU operates in three modes, which are harvesting and backscattered modes (performed while the PU is present), as well as active mode (performed while the PU is idle). The framework was formulated to maximise the throughput by considering parameters such as backscattering time, harvesting time, transmission time, and transmission power.

Table 11 provides a summary of several works related to CR-WPBC. The basic concept of simultaneous wireless information and power transfer (SWIPT) was introduced by Varshney (2008). Generally, there are three approaches for the implementation of simultaneous wireless information and power transfer, which are antenna separation, time switching, and power splitting (Figure 11).

In the antenna separation approach (Figure 11a), the destination is equipped with two separated antennas; the first antenna to receive the information, and the second antenna to harvest the energy. In the time-switching approach (Figure 11b), the destination is equipped with one antenna only, and the device's EH and information receiving functions are controlled by time switcher. A similar antenna structure was applied for the power splitting approach (Figure 11.c). However, the EH and information receiving functions is controlled by a power splitter. Combinations of these approaches have also been investigated, such as the model that combines the antenna separation and time-switching approaches as developed by Ropokis and Bithas (2022), and the model that combines the power splitting with time-switching approaches as studied by Prathima *et al.* (2020).

The integration of CR and SWIPT (CR-SWIPT) can be applied to relay primary information and power the SU, benefiting both PUs and SUs. The CR-SWIPT operating model is illustrated in Figure 12.

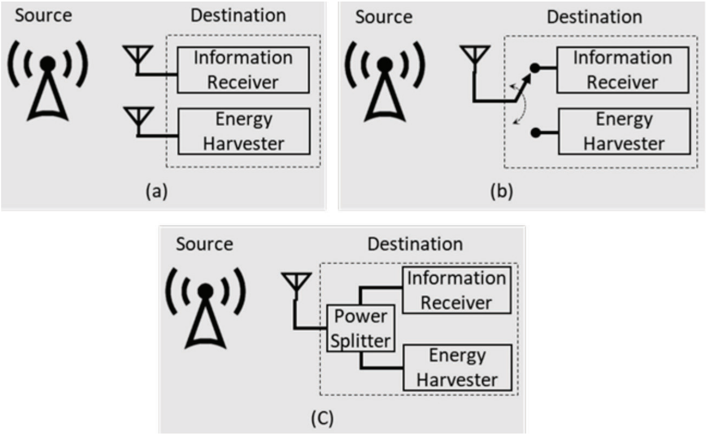


Figure 11: (a) Antenna separation, (b) time switching, and (c) power splitting

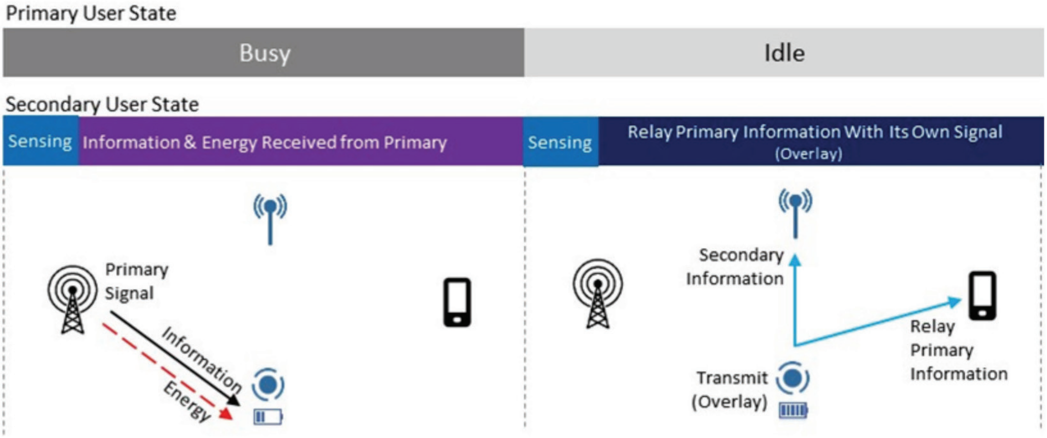


Figure 12: An illustration of the CR-SWIPT operating model to relay primary information

In this model, the secondary node receives a signal from the primary base station. Here, EH can be carried out to power the secondary node, and, at the same time, the received signal also carries information that will be forwarded to primary node (the secondary node acts as a relay for primary information). Thus, whenever the secondary nodes send their own information to another secondary entity (e.g., secondary access point/secondary cluster head), the secondary node will also relay primary information to the primary nodes in the overlay mode.

Ghosh *et al.* (2020) presented a model comprising multiple PUs and multiple SUs. The model operates in two stages. In the first stage, each SU harvests the energy and receives the information from the PU. In the second stage, each SU takes turn to relay the PU signal and transmit its own information. The proposed approach aimed to characterise the outage probability through parameters such as harvesting time, power splitting and sharing factor. Salama *et al.* (2019) investigated a model that consists of a single PU and multiple SUs. Each SU operates in three ways., harvesting energy from the PU signal, relaying the PU signal, and transmitting its own signal. The SUs are divided into two groups. Some SUs transmit their own data and relay the PU signal, while the others harvest the energy from the PU signal. The framework was formulated to achieve optimal throughput and fairness by considering parameters such as transmission power and the number of SUs.

Li *et al.* (2019) developed a model that involves a single PU and a single SU. The proposed model works in two phases. The first phase sees the SU receiving information and harvesting energy from the PU signal through the power-splitting approach. The second phase, meanwhile, sees the SU relaying the PU signal and transmiting its own signal. The framework was formulated to characterise the outage probability and throughput by considering parameters such as the power allocation factor and the number of retransmissions. Gurjar *et al.* (2019) proposed a model with multiple PUs and multiple SUs. The model operates in two stages. In the first stage, each SU harvests the energy from all the PUs. In the next stage, each SU either receives information from all the PUs, or takes turn to transmit its own signal and relay the PU signal. The framework was formulated to characterise the outage probability, throughput, end-to-end transmission time through parameters such as time-switching factor and power -splitting factor.

Prathima *et al.* (2020) studied a model constructed of multiple PUs and multiple SUs. The model works in three steps, where in the first step, each SU harvests energy only from the PU signal. In the second step, each SU harvests energy and receives information from the PU. In the final stage, each SU takes turn to relay the PU signal and transmit its own information. The framework was formulated to maximise throughput and energy efficiency by examining parameters such as harvesting time, power splitting and sharing factor. Lu *et al.* (2020) presented a model comprising a single PU and a single SU. The model operates in two phases. The first phase involves the PU transmitting its signal within multiple subcarriers, followed by the SU using some subcarriers to transmit its own signal and relay the PU signal in the second phase. The framework was formulated to achieve energy and spectrum efficiency by considering parameters such as transmission power, number of subcarriers, and the power-splitting factor.

Mi *et al.* (2021) investigated a model that has a single PU and a single SU. The model operates in three steps. In the first step, the SU senses and harvests the PU activity through the power-splitting approach. In the second step, the SU receives the information signal from the PU. And, in the last step, the SU transmits its own signal and relays the PU signal. The framework was formulated to maximise energy efficiency by dealing with parameters such as sensing time, power-splitting factor, and transmission power. Talukdar *et al.*, (2020) discussed a model composed of a single PU and a single SU. The model operates in two phases. The first phase involves the SU harvesting and receiving information from the PU through the time-switch approach. Then, in the second phase, the SU acts to relay the PU signal and transmits its own signal. The framework was formulated to characterise the output probability and throughput by examining parameters, such as the power-splitting factor and time-switching ratio.

Table 12 provides a summary of several works related to the CR-SWIPT operating model as described above.

Further Research Challenges

Several emerging technologies are expected to be used for next-generation communication systems (5G, 6G and beyond), such as mmWave, massive multiple input multi output, non-orthogonal multiple access, and FD communications. However, integrating these mechanisms with RF-EH and CR-IoT may lead to potential research challenges, such as hardware complexity, and there are still few works that involve studies into the implementation of or testbed investigations for the concept integrations. Therefore, more research efforts are needed to explore the proof of concept to determine whether the analytical model of these emerging technologies integrated with RF-EH and CR-IoT will meet the actual implementation requirements.

Besides the emerging technologies discussed above, RF-EH and CR-IoT have

Table 12: A summary of related papers on CR-SWIPTA

Related Paper	Model Entity	Access Mode	SWIPT Approach	Performance Metric	Parameter Involved
Ghosh *et al.* (2020)	Multiple PUs, multiple Sus	Overlay	Power splitting	Outage probability	Harvesting time, power splitting, sharing factor
Salama *et al.* (2019)	Single PU, multiple SUs	Interweave	Time switching	Throughput, fairness	Transmission power, SU number
Li *et al.* (2019)	Single PU, single SU	Overlay	Power splitting	Outage probability, throughput	Power allocation factor, number of retransmissions
Gurjar *et al.* (2019)	Multiple PUs, multiple SUs	Overlay	Time switching	Outage probability, throughput, end-to-end transmission time	Time switching factor, power-splitting factor
Prathima *et al.* (2020)	Multiple PUs, multiple SUs	Overlay	Time switching, power splitting	Throughput, energy efficiency	Harvesting time, power splitting, sharing factor
Lu *et al.* (2020)	Single PU, single SU	Interweave	Power splitting	Energy and spectrum efficiency	Transmission power, number of subcarriers, power-splitting factor
Mi *et al.* (2021)	Single PU, single SU	Overlay	Time switching	Energy efficiency	Sensing time, transmission power, power-splitting factor
Talukdar *et al.* (2020)	Single PU, single SU	Overlay	Time switching	Outage probability, throughput	Power-splitting factor, time-Sswitching ratio

been applied in specific environments, such as industrial IoT and body sensor networks, as well as vehicular environments, such as vehicle-to-everything. However, these applications pose research challenges such as data continuity, mobility, seamless connectivity, interoperability, and secure and robust communication.

To address the coverage constraint of IoT devices, multi-hop communication is needed to deliver information from the source device to the destination device. Thus, further research efforts are needed to explore the application of RF-EH and CR-IoT in muti-hop networks. This includes scenarios for reducing the number of hops, minimising end-to-end time delivery, optimising power and resource allocation, using multi-path routing approaches, and implementing duplexing mechanisms.

The application of artificial intelligence or machine learning into RF-EH and CR-IoT is also an interesting avenue for further research. These methods have be the potential to serve as a decision support and system optimisation frameworks (e.g., determining optimal sensing, harvesting, and transmit parameters to achieve maximum performance). In addition, there are potential research challenges related to the economic aspects, such as business models, energy trading, and spectrum monetisation, that warrant further investigation.

Conclusion

This paper presents a literature review on the integration of RF energy harvesting with cognitive radio IoT, which has become increasingly important for sustainable and reliable IoT networks. The review highlights the potential of this integration to address spectrum and energy issues, with the operating model based on the slotted approach and state consideration, and performance metrics optimized through system parameters such as harvesting time, sensing time, transmit time, transmit power, and interference level. While there has been significant research on this topic, there are still open questions and potential areas for further exploration, including integrating the system with emerging technologies for next-generation communication systems, implementing it in specific application environments, incorporating artificial intelligence or machine learning frameworks, and exploring economic aspects such as business models, energy trading, and spectrum monetization.

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