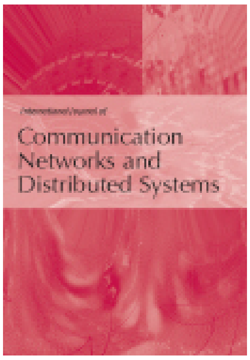

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An investigation on teletraffic attributes for channel selection of IoT objects in cognitive radio internet of things networks towards 5G

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Abstract: This paper investigates multiple attributes and related comparative issues regarding channel selection of IoT objects for cognitive radio IoT networks towards 5G. CU or SU as IoT nodes may intelligently manage their activity in a licensed spectrum by accessing vacant spectrum through dynamic spectrum access methodology. Therefore, that IoT is a booming developing concern to organise digital accessories. It will also provide the fastest data connections through sensor nodes by producing more data than any other emerging technology. With the continuous evolution in CRN and cognition capability, the IoT objects may think, learn, and make decisions by perceiving outside worlds. To frame the IoT with CR-based architecture in the coming future, some attributes such as intracell/intrapool handoff latency, intercell/interpool handoff latency, link continuation probability, link failure probability, switching cost, awaited number of spectrum handoff, non-execution probability, blocking probability, dropping probability, and throughput, are needed to learn the overall network attributes.

Keywords: IoT; CRN towards 5G; CRIoT; DSA; handoff; channel selection attributes.

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1 Introduction

Several digital accessories within the home area and working environment connected to the internet ensuring the security of the digital movement of the IoT is turning into a big rising concern. Using smart devices associated with the broader openings or cloud networking platforms, the IoT may also provide the speediest data connections among sensor nodes by producing a more remarkable volume of data than any other evolving technology. The intelligent tracking system in shipping, public safety, manufacturing wireless automation, individual health monitoring, and health application for the aged society are examples of IoT, IIoT, and edge computing that is developing at a wildly fast pace and has become an indispensable part of our everyday lives. The possibility is infinite. As per the report on IoT in IDC (2020), the worldwide investment in 2021 on IoT will achieve double-digit growth, with a CAGR of 11.3%. As all the sectors like smart sensor nodes to smart factories, from smart home digital accessories to connected healthcare devices, everything is productive. The IoT entities can be managed just like any other internet-enabled device because those are connected with the web. Making business with such a high level of IoT objects connectivity through the web may bring into the job can create a remarkable risk of data security. Several types of national security alerts like shutting down IoT gadgets by web hackers and firewall-security attacks against enterprise infrastructure, electrical grids, dams, etc. also came into the picture along with home or enterprise data security (DSCI, 2021). The evolution of IoT in India has drawn the industrial transformation to the next level, representing Industry 4.0. IoT plays a prime role in developing the IoT trade and technology in India and naming as the new ‘Digital India’. A program launched by the Government of India. The funding for IoT was around to USD 5Bn in 2019 in India, according to a recently released report by Zinnov in June 2020 (TechSagar, 2020), and which will be projected to increase up to USD 15Bn in 2021. The basic concept of IoT is unfolding rapidly to reach most of our daily life. To deal with the packets which is delivered from the IoT networks are important and requires a spectrum access. The idea of IoT is amalgamated with the cognitive radio networks (CRNs), named as cognitive radio internet of thing (CRIoT), to provide sufficient spectrum to spread as required for the IoT (Tarek et al., 2020b).

This paper is structured in a following manner; Section 2 gives the basic concept of IoT, the idea of spectrum resources used in CRN towards 5G is discussed in Section 3, Section 4 presents a short review on CRIoT, system model and analysis with respect to various attributes for IoT objects’ spectrum utilisation in CRIoT are discussed in Section 5, Section 6 represents results including discussion and the conclusion has been drawn in Section 7.

2 Internet of things

2.1 Overview

The next-generation communication system came into the picture to survive with the emerging extension of the mobile data traffic, gigantic connection for devices with the uninterrupted development of new technology, and various application situations for the future. The generation is named 5G, and IoT with mobile internet will be the significant steering force for expanding this generation. Soon, 5G will achieve the multiple requirements of human being in several sectors like accommodation, jobs, leisure, and transportation. It fulfils the spectrum allocation need of IoT as well. It also meets the numerous professional domains to realise the actual interrelation of all things such as transportation, industry, medical, and other enterprises (Agiwal et al., 2016). Human beings are trying to gather information and assistance from the internet every time, everywhere, and even during the relocation in the rapid growth of broadband access of wireless channel and mobile terminology (Gupta and Jha, 2015). IoT devices are economical and typically have moderate power, average battery health, low bitrate, economical range, and processing. For the academic and industrial circles, the IoT is increasingly receiving more and more recognition as an emerging technology (Gubbi et al., 2013; Gazis, 2016) and is nominated as one of the most powerful technologies that may escort to the growth of the future network (Ghanbari et al., 2017; Hortelano et al., 2017). IoT is defined in the following ways.

2.2 Definition

"IoT is a seamlessly connected network of embedded objects/devices, with identifiers, in which M2M communication without any human intervention is possible using standard and interoperable communication protocols" – tablets, phones, and computers belong to part of IoT (Liu et al., 2019). IoT is a network where objects are interconnected, based on standard communication protocols. It is uniquely addressable preferably using any path/network and any facility (Khan et al., 2017).

2.3 IoT structure

The structure of IoT (Liu et al., 2019; Antao et al., 2018; Gaitan et al., 2015) consists of five layers which are depicted in Figure 1.

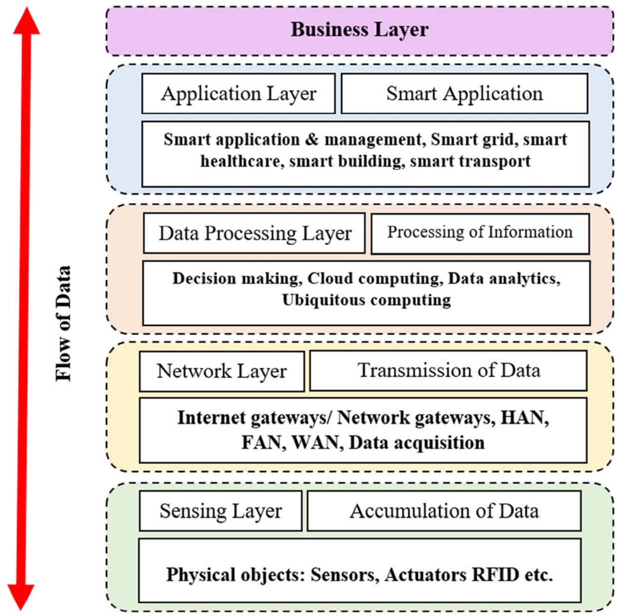
2.3.1 Sensing layer

It is also called data accumulation or recognition layer. The primary job of this layer is to accumulate the purposeful information and transform it into corresponding data. Just like conversion of the control signal into order by actuators. It represents physical objects like sensors, actuators RFID, etc.

2.3.2 Network layer

It is also called transmission layer. The primary role of this layer is to pass on the data which is collected by the sensing layer to the data processing layer. The control signals which are transferred from the middleware layer are accumulated in it using networking technologies.

Figure 1 IoT architecture: five stages of layer (see online version for colours)



2.3.3 Data processing layer

This is a kind of software layer. The accepted data which are accumulated from previous layer will be analysed and corresponding decisions would be taken based on that analysis.

2.3.4 Application layer

The responsibility of this layer is defined for IoT applications. By the help of this layer the assistance has been provided to an end-subscriber according to the modified data such as smart application and management, smart grid, smart healthcare, smart building, smart transport, etc.

2.3.5 Business layer

Beyond the above four layers, another layer has been considered hypothetically. It is termed the business layer that permits the system administrator to command the whole IoT networks' functionality. It may shape numerous trading prototypes.

It promotes world-wide partnerships of industry and research bodies to promote IoT technologies exhibited in the country by creating a committee of national experts for IoT standards development. The expert committee is contained of industry experts/organisations. They participate in standards committees of ITU, IEEE, and other relevant global forums for standards making in IoT (https://www.meity.gov.in, 2021). The fields are contained with research technology like development of open framework for IoT, communication technology like ultra-low power chipsets, platform interoperability, on-chip antennas, network technology like self-organising networks, storage and energy networks, hybrid networking technologies, algorithms with software like next-generation IoT based social application, application for enterprises, power and energy storage technologies.

Table 1 Physical layer parameters of various IoT protocols: a summary

Technology	*Modulation type (UNB/NB/SS/OFDM/UWB)*	*Frequency bands*	*Channel bandwidth (MHz/GHz)*
5G	OFDM	< 100	mmWave, GHz
ANT+	NB	1	GHz
BLE mesh	NB	1	GHz
LTE-M	OFDM	1.08,1.4	Sub-GHz and GHz
MiWi	NB	0.040, 0.250	Sub-GHz and GHz
NB-IoT	NB, OFDM	0.18	Sub-GHz and GHz
RFID	NB	0.2	Sub-GHz and GHz
Sigfox	UNB	0.2	Sub-GHz
Telensa	NB	0.1	Sub-GHz
Thread	NB	5	GHz
Dash7	NB	0.025, 0.200	Sub-GHz
EC-GSM-IOT	NB	0.2	Sub-GHz
EnOcean	NB	0.0625	Sub-GHz
Ingenu	SS	1	Sub-GHz and GHz
ISA101.11a	SS	5	GHz
LoRa	SS	0.125, 0.50	Sub-GHz
Wirepas	NB	0.126, 0.5	Sub-GHz and GHz
WiSUN	NB, SS and OFDM	0.2–1.2	Sub-GHz and GHz
ZigBee	SS	0.6, 1.2, 2	Sub-GHz and GHz
ZigBee-NaN	SS	0.6, 1.2, 2	Sub-GHz
Z-Wave	NB	0.2	Sub-GHz
Weightless-N	UNB	0.2	Sub-GHz
Weightless-P	NB	0.0125	Sub-GHz
Weightless-W	SS	5	Sub-GHz
WirelessHART	SS	0.25	GHz
WiFi802.11af	OFDM	8	sub-GHz
WiFi802.11ah	OFDM	1,2,4,8,16	sub-GHz
WiFi802.11az	OFDM	20, 40, 60, 80, 160	GHz, mmWave
WiFi802.11p	OFDM	10	GHz

It defines each technologies' strategic physical characteristics, like channel bandwidth, frequency bands and modulation type (Figueiredo e Silva et al., 2018).

3 Spectrum resources towards 5G

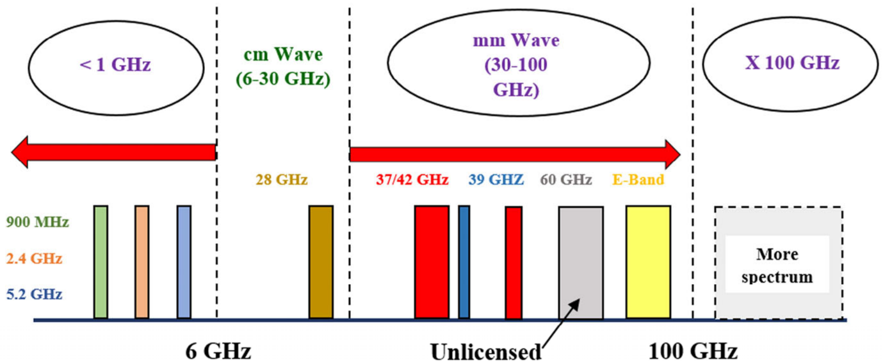
Different countries manage the radio frequency spectrum resources by their spectrum management departments. The fixed allocation principle is endorsed by the spectrum allocation method (Zhou et al., 2017), and the spectrums are split into several parts. Each and individual part is allocated to various licensed subscribers, and there is no freedom to access it by other subscribers. The allocated spectrum is called the licensed band, and the allocated subscriber is called the licensed subscriber or user. In Spectrum Policy Task Force Report (2002), FCC's survey report showed that several resources of spectrum band at different levels of inactiveness in dimensions like time and space due to the FSA, even in any congested bands. In contrast, only a small part of the spectrum is used repeatedly. Therefore, different multiplexing technologies came into the picture like FDMA, TDMA, CDMA, and MIMO to enhance the use of licensed spectrum utmost. These techniques are useful to assist more number of subscribers on inadequate spectrum resources (Wang and Liu, 2010).

The mobile data demand due to the rise of mobile devices and varied data traffic applications will increase ten-fold between 2014 and 2019 (Cisco, 2015). But due to the fixed allocation policy, they fundamentally failed to solve spectrum resources deficiency. This booming demand for mobile data affects numerous challenges, bringing the research objectives to 5G networks (Chen and Zhao, 2014). 5G networks are considered to provide pointedly high data rate access and assured QoS. Therefore, the demand for spectrum resources is expected to increase considerably in 5G networks. It needs wireless system designers to suggest suitable spectrum management schemes. Several views on 5G architecture are explained in Iwamura (2015), Droste et al. (2015) and Agyapong et al. (2014) with crucial technologies like massive MIMO, visible light communication, energy-efficient communications, CR, small cells, etc. It can meet the demand of high capacity and consist of network densification over space and frequency in 5G heterogeneous networks (Bhushan et al., 2014). DSA has appeared as the solution for spectrum sharing, ensuring the coverage of 5G heterogeneous networks everywhere and always opportunistically. Employing DSA into a radio network to coexist with a licensed network is named CRN (Ejaz et al., 2013). 5G will meet higher data transfer rates and more affluent business conditions due to the very congested frequency bands below 6 GHz. The inactive licensed bands are known as 'spectrum holes.' It is difficult to find an ample amount of spectrum to reach the growing spectrum need. It is practically simple to find out the spectrum above 6 GHz and provide a constant wide band. To increase the system capacity and high data rate transmission support, the spectrum band will be further enlarged into the entire spectrum era, likely from 1 GHz to 100 GHz in 5G, as shown in Figure 2.

The solution to establish spectrum allocation is to compose dynamic algorithms and protocols for spectrum allocation, to improve spectrum utilisation performance in a conflict-free manner, relatively as near to the optimal point as possible (Hu et al., 2018). Traditionally 802.11, microwave, Bluetooth and other applications occupy short-distance wireless communication spectrum (such as 2.4 GHz, 5 GHz band). Again, communication technology is used to achieve a higher spectrum utilisation in increased complexity. Like the Europe and USA, several countries have segregated the 60 GHz band for general use (Yong and Chong, 2007). The 60 GHz band is divided into 5 GHz–7 GHz unlicensed continuous spectrum resources. The WiFi is compatible with 60 GHz IEEE 802.11ad with MAC architecture. As the signal direction of wireless 60

GHz is powerful, the interference of communication signals in various directions is minimum and valuable to the space division multiplexing (Kobayashi et al., 2016).

Figure 2 Spectrum utilisation towards 5G (see online version for colours)



3.1 White space

The ultra-high frequency band is generally used in television and broadcasting. It is positioned in an identical frequency band and has high-grade propagation characteristics. According to the research outcome in Van de Beek et al. (2011) explained, the popular UHF band is very ineffective, with an ordinary utilisation rate 17.4% in Chicago and 4.54% in Singapore. For the effective use of reliable spectrum resources, the inactive frequency bands are used for analogue broadcasting for television are called 'TV White Spaces.' It is essential to obtain fast internet access in rural areas like topographical blind regions due to the unavailability of the wireless network while the television signal is available. The TV White spaces are used for data transmission in the USA to promote superWiFi (Wang et al., 2016), which is not WiFi in the true sense.

4 Cognitive radio internet of things

DSA capability allows a CR user to adopt different network requirements. PU may get insured protection while a CR user can use this spectrum. It is visualised that CR-based IoT frameworks will be compulsory to develop CRNs and IoT soon. The IoT objects are provided with cognition capability to think, learn, and make decisions by learning physical and social, i.e., real worlds (Khan et al., 2017). Due to the following reasons, CR-based IoT would be a predictable requirement soon.

- The primary motive arrives in force from spectrum allocation for IoT objects. It is anticipated to expand IoT objects in massive numbers. So that spectrum assignment for such a massive number of objects may make unneeded investments due to FSA, which needs spectrum purchase. CRNs may help in all of these situations.
- The interference is reduced in CR-based IoT framework among all users by scanning for interference-free channels through DSA.
- IoT objects can achieve consistent connectivity equipped with cognitive capability.

- It is anticipated that CR-based IoT objects will automatically explore in a self-governed manner for available storage places in cloud servers to support a gigantic number of data generation by the process named spectrum sensing.
- The single wireless mechanism may unavailable everywhere to provide continuous connectivity to these objects. The OTG platform can provide connectivity to smart objects with cognitive capability.

Two type of approaches are essential for IoT related to cognitive-communication. The first one is the INTRACC approach. The next is the INTERCC approach. In INTRACC approach, the same cognitive capabilities are allotted to IoT objects, while in INTERCC approach, the object has unlike cognitive abilities (Tervonen et al., 2014). IoT spectrum deficiency problem may overcome using CRN as an inexpensive and effective solution to establish the IoT intelligent network. The IoT framework is amalgamated with CR technology named CRIoT. These technologies should meet several network attributes like intracell/intrapool handoff latency, intercell/interpool handoff latency, channel availability, link continuation probability, allocation delay, end-to-end delay, link failure probability, switching cost, high throughput, energy efficiency, reliability, etc. The IoT networks should perform all the different functions intelligently. It will have to sense the interference-free channels, detect the holes by evaluating the quality of service. CRIoT provides constant communication by changing the working channel, either at appearance of a PU or its movement. Ultimately, it manages the spectrum access of licensed band for the massive number of IoT objects including little interference.

Figure 3 CRIoT design factors (see online version for colours)

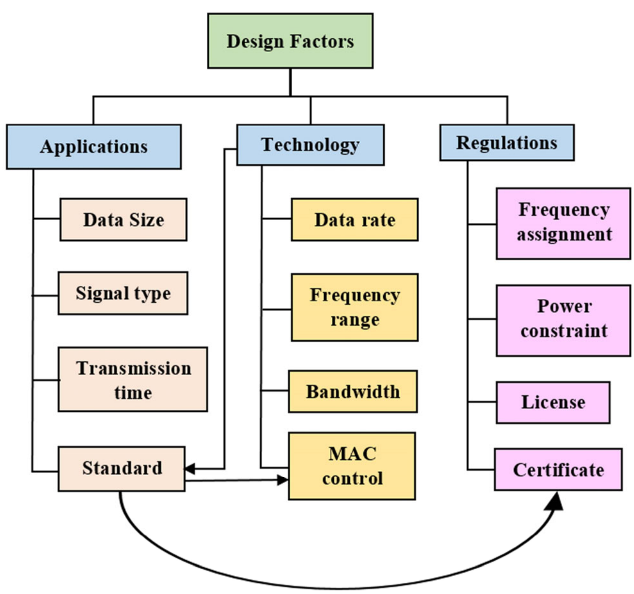


Figure 3 shows the factors which are considered to design a CR-based IoT system. Furthermore, the figure actually represents the connection among the design factors (Awin et al., 2019). Three different kind of key parameters like applications, technology and regulations are structured. Where data size, signal type, transmission time define the applications, again the standard is maintained through the technology involves a special data rate, frequency range, bandwidth and MAC control mechanism. The regulations imply a proper frequency assignment, power constraint and licensing.

4.1 Spectrum handoff

Spectrum handoff is a fundamental process of the secondary user which assures seamless and healthy services to maintain the QoS of the CRN. Liu et al. (2008) obtained a standard form of probability of spectrum handoff for a stationary SU with exponential traffic parameter distribution. The outcome of general service time distributions has been presented on the possibility of spectrum handoff for a stationary SU in a CR network (Hoque et al., 2014, 2018). Yao et al. (2012) supposed that the inter-handoff CUs have a higher priority than the new CUs to access a spectrum band to enhance the blocking probability. Pan et al. (2015) introduced a spectrum handoff scheme based on analysis and matching for higher traffic networks to reduce handoffs. Tran et al. (2015) proposed a new spectrum handoff scheme to improve the spectrum utilisation in an industrial CR network. Yawada and Dong (2019) and Yawada et al. (2019) explained various handoff algorithms to illustrate and enhance spectrum handoff mechanisms for the better performance of a CR network. Tair et al. (2019) developed a seamless spectrum handoff strategy to minimise the occurrence of the same in CR networks. The authors proposed a secure handoff mechanism in Rathee et al. (2020), introducing cognitive user emulation attack for the better performance of CR network. Hoque et al. (2020) proposed a cell-based spectrum handoff model in a CR cellular network. They analysed the performance of a mobile SU for link maintenance probability and service completion probability.

In this article, we have discussed various teletraffic attributes to analyse the system model performance for a non-stationary CRIoT object considering the service time of CRIoT as SU also termed as CU. The system model is discussed in Section 5 along with the theoretical analysis.

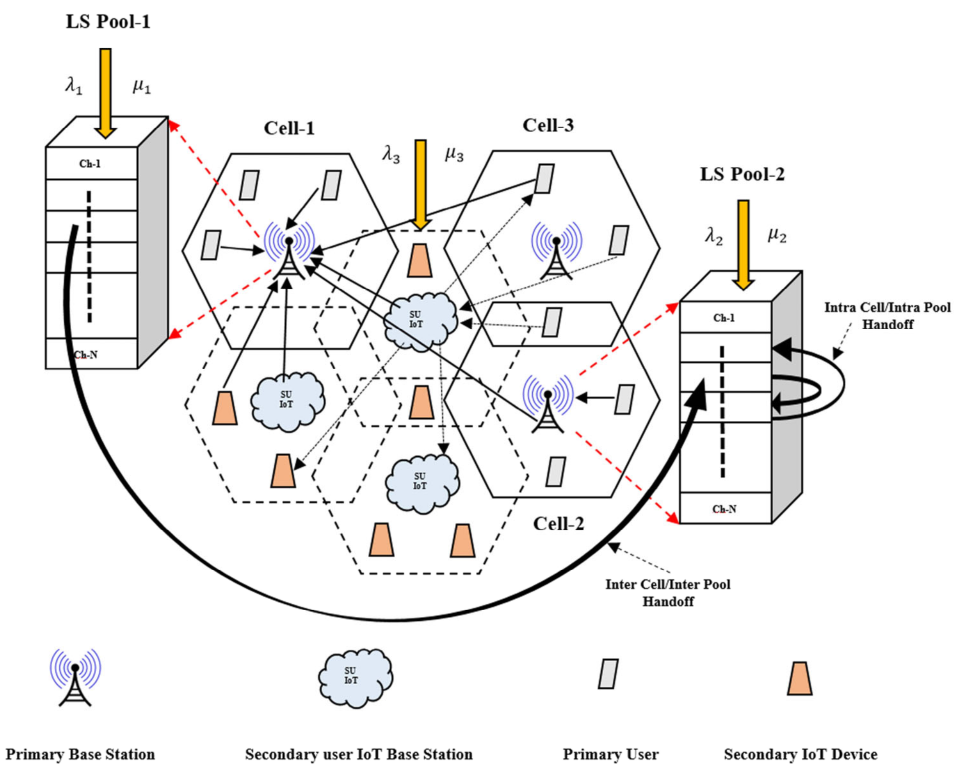
5 System model and analysis

We have assumed that the IoT objects as SU completes its service within two cells of the CRIoT network. For simplicity, we call those objects as SUIoT. In our proposed model, we consider two identical cells:

1. cell 1 as source cell where an SUIoT starts its service
2. cell 2 as target cell where the SUIoT completes or ends its service.

Figure 4 shows the proposed spectrum handoff mechanism of a mobile SUIoT along with the PUs activity model. The grey, orange boxes in Figure 4, indicate the PU and SUIoT objects respectively. The sky coloured cloud based architecture is represented for SUIoT base station whereas PU base station has been defined by different symbol in the Figure 4. We have assumed that the non-stationary SUIoT object operates in the vacant licensed channel of cell 1 of LSP1 to begin its service. If the ongoing communication of the SUIoT is interrupted in cell 1 before it crosses the cell boundary, the SUIoT object requires to switch its service to another spectrum holes of the source cell to continue its service. This process is known as intracell/intrapool spectrum handoff of a newly arrived SUIoT object similarly if the SUIoT object moves out from the cell 1 to cell 2 during the ongoing communication, the SUIoT requires to perform spectrum handoff to maintain the seamless and unbroken communication. This type of handoff is known as traditional or intercell/interpool spectrum handoff which is indicated by black thick line in Figure 4. After performing the intercell spectrum handoff, the SUIoT object service may interrupt due to the arrival of PUs in cell 2. Hence, the SUIoT object may require to perform spectrum handoff within cell 2 to continue its ongoing communication. This process of handoff is known as intracell/intrapool spectrum handoff of a post intercell/interpool handoff SUIoT object which is shown by black coloured thick arrow within cell 2 of Figure 4. The IoT objects are represented in CRN, therefore SUIoT object is termed as CRIoT object. In the next section, we have discussed some of the major teletraffic attributes (Kundu et al., 2020) which may affect the CRIoT network.

Figure 4 Spectrum pool-based CRIoT architecture (see online version for colours)



5.1 Teletraffic attributes for CRIoT network

5.1.1 Intracell/intrapool handoff latency

This is known as scheme-1 and may be given as

$$L_1 = l_{prep} + l_{syn}^{sen} + l_{sen} + l_{dec} + l_{syn}^{tx} \tag{1}$$

It may occur when the spectrum identifies the PU. Hence, it has been executed reactively. Here, (l_{prep}) is the preparation time. It is required to specify the type of handoff. CRIoT objects must await (l_{syn}^{sen}) the sensing time for synchronisation, where they check spectrum bands in the pool (l_{sen}). After identification by CRIoT, a suitable spectrum decision latency (l_{dec}) will be included. The scheduled transmission with synchronisation on that spectrum is (l_{syn}^{tx}).

5.1.2 Intercell/interpool handoff latency

This is known as scheme-2 and written as

$$L_2 = l_{recfg} + l_{syn}^{sen} + l_{sen} + l_{dec} + l_{sych}^{tx} \tag{2}$$

Like intracell/interpool handoff, this scheme requires L_3 handoff latency, where handoff preparation time (l_{prep}).

$$L_3 = l_{prep} + l_{recfg} + l_{syn}^{sen} + l_{sen} + l_{dec} + l_{syn}^{tx} \tag{3}$$

Again, the control channel is monitored by CRIoT objects for a particular time (l_{lis}) for every reconfiguration. This type of latency may define as scheme-3 is expressed as follows. In this case switching latency performed worse due to multiple reconfigurations. Where γ is randomly chosen, and hence it is considered as $\frac{(f+1)}{2}$ on average. Where f = frequency reuse factor.

$$L_4 = l_{prep} + \gamma\left(l_{recfg} + l_{lis}\right) + l_{syn}^{sen} + l_{sen} + l_{dec} + l_{syn}^{tx} \tag{4}$$

An extended neighbour cell that uses the same spectrum pool is called new target cell. Therefore, reconfiguration is not at all necessary. The intercell/intrapool handoff latency is expressed as follows. This scheme is known as scheme-4.

$$L_5 = l_{syn}^{sen} + l_{sen} + l_{dec} + l_{syn}^{tx} \tag{5}$$

5.1.3 Link continuation probability

Let q_{s1} is the link continuation probability for the CRIoT. It migrates its service from one LC to another free LC in the same licensed spectrum pool LSP1, and defines intrapool spectrum handoff. It derives the link continuation probability of the CRIoT as

$$q_{s1} = \Pr_v\left[\left(1 - \Pr_{b1}\right) + \Pr_{b1}\Pr_{b2}\Pr\left(T_{LC} < D_{th}\right)\right] \tag{6}$$

where T_{LC} is the delay in LSP1 during intrapool spectrum handoff and is represents as,

$$T_{LC} = \min\left(T_{(pu,1)}^{r}, T_{(pu,2)}^{r}, T_{(pu,3)}^{r} \ldots\ldots T_{(pu,C_1-1)}^{r}, T_{(pu,C_1)}^{r}\right) \tag{7}$$

where $T_{(pu,i)}^{r}$ is PU's residual service time for i^{th} licensed channel. The expression $\Pr(T_{LC} < D_{th})$ which is expressed in equation (6) is calculated from (Hoque and Arif, 2019)

$$\Pr\left(T_{LC} < D_{th}\right) = 1 - \beta^{(C_1-1)}\gamma \tag{8}$$

where

$$\beta = 1 - F_{(T_s r_{pu})}(D_{th}) \tag{9}$$

And,

$$\gamma = 1 - F_{T_{s_{pu}}}(D_{th}) \tag{10}$$

Similarly, the interpool spectrum handoff occurred while the LCs become full. So that link continuation probability q_{s2} of CRIoT is

$$q_{s2} = \mathrm{Pr}_v\, \mathrm{Pr}_{b1}\left[(1-\mathrm{Pr}_{b2})\,\mathrm{Pr}(T_{SD} < D_{th}) + \mathrm{Pr}_{b2}\,\mathrm{Pr}(T_{HD} < D_{th})\right] \tag{11}$$

where switching delay is $T_{SD} = \min(t_{SD.1}, t_{SD.2}, t_{SD.3}, \ldots\ldots\ldots\ldots, t_{SD.C_2})$ and intrapool spectrum handoff delay is

$$T_{HD} = \min\left(t^r_{s_{cu*1}} + t_{SD.1}, t^r_{s_{cu*2}} + t_{SD.2}, \ldots\ldots, t^r_{s_{cu*C_2}} + t_{SD.C_2}\right).$$

Here, $t_{SD.j}$ is switching delay and $t^r_{s_{cu*j}} + t_{SD.j}$ denote the handoff delay during interpool spectrum handoff, and CRIoT migrate its service to j^{th} UC from LCs.

Hence, the q_s, link continuation probability for CRIoT in OSB is calculated from (Hoque and Arif, 2019)

$$q_s = \mathrm{Pr}_v\left[(1-\mathrm{Pr}_{b1}) + \mathrm{Pr}_{b1}(1-\mathrm{Pr}_{b2})(1-\alpha^{C_2}) + \mathrm{Pr}_{b1}\,\mathrm{Pr}_{b2}\left(1-\beta^{(C_1-1)}\gamma\xi^{C_2}\right)\right] \tag{12}$$

where

$$\alpha = 1 - F_{T_{SD}}(D_{th}) \tag{13}$$

And,

$$\xi = 1 - F_{T_{HD}}(D_{th}) \tag{14}$$

5.1.4 *Link failure probability*

Within the limited threshold period, i.e., D_{th}, the continuation of link will be terminated if there is no available channel. Therefore, the link failure probability in OSB for the interrupted CRIoT objects is written as

$$\begin{aligned} q_f &= \mathrm{Pr}_v\,\mathrm{Pr}_{b1}\,\mathrm{Pr}_{b2}\,\mathrm{Pr}\Big(\min\Big(T^r_{s_{pu,1}}, T^r_{s_{pu,2}}, T^r_{s_{pu,3}} \ldots\ldots T^r_{s_{pu,C_1-1}}, T^r_{s_{pu,C_1}}, t^r_{s_{cu*1}} \\ &\quad + t_{SD.1}, t^r_{s_{cu*2}} + t_{SD.2}, \ldots\ldots., t^r_{s_{cu*C_2}} + t_{SD.C_2}\Big) > D_{th}\Big) \\ &= \mathrm{Pr}_v\,\mathrm{Pr}_{b1}\,\mathrm{Pr}_{b2}\,\beta^{C_1-1}\gamma\xi^{C_2} \end{aligned} \tag{15}$$

where D^{th} is the threshold period, Pr_{b1}, Pr_{b2} = blocking probability, $T^r_{(pu,i)}$ = PU's residual service time for licensed channel and $\xi = 1 - F_{T_{HD}}(D_{th})$.

5.1.5 Switching cost

The estimated switching cost is defined as the sum of two types of delay. These are instantaneous switching delay and the estimated switching delay. It is caused due to overload in the neighbouring cell because CRIoT objects move to neighbouring cell

$$T_{ESC_{BA}} = L_2 + L_1 . \left(\frac{T_m}{T_{off,i} + L_1} \right) + \mathrm{Pr}_{B,i}^{hover}(R).L_3 \tag{16}$$

where $T_{ESC_{BA}}$ is base area (BA) intracell/intrapool handoff and $\left(\frac{T_m}{T_{off,i} + \mathrm{L}_1} \right)$ is the intracell/intrapool handoff's average value, and $T_{off,i}$ is the inactive duration on average for the spectrum within the cell i.

5.1.6 Awaited number of spectrum handoff

It is defined by $E(H)$. CRIoT experienced the required number of spectrum handoffs during its whole service time. It harms the performance of the delay in handoff, service execution, and link continuation of CRIoTN. For absolute complete and incomplete service of the CRIoT in a distinct diverse spectrum environment under HetSE the $E(H)$ is written as

$$\begin{aligned} E(H) &= \sum_{n=0}^{\infty} n \,\mathrm{Pr}(H = n) = \sum_{n=0}^{\infty} n \frac{\left(-\lambda_{pu} q_{s1}\right)^{(n-1)} \lambda_{pu}}{(n-1)!} \\ &\cdot \left[\frac{q_{s1} f_{T_{scu}}^{*(n)} \left(\lambda_{pu} \mathrm{Pr}_v\right)}{n} + \left(q_{s2} + q_f\right) F_{T_{scu}}^{*(n-1)} \left(\lambda_{pu} \mathrm{Pr}_v\right) \right] \end{aligned} \tag{17}$$

The derivation of equation of $E(H)$ is written in standard form after employing Taylor's infinite series theorem as

$$\begin{aligned} E(H) &= \left(\lambda_{pu} \left(q_{s2} + q_f\right) - \lambda_{pu} \mathrm{Pr}_v\right) f_{T_{scu}}^{*(1)} \left(\lambda_{pu} \left(q_{s2} + q_f\right)\right) \\ &+ \lambda_{pu} \left(q_{s2} + q_f\right) \left[F_{T_{scu}}^{*} \left(\lambda_{pu} \left(q_{s2} + q_f\right)\right) - \lambda_{pu} q_{s1} F_{T_{scu}}^{*(1)} \left(\lambda_{pu} \left(q_{s2} + q_f\right)\right) \right] \end{aligned} \tag{18}$$

5.1.7 Non-execution probability

CRN long-time performance is explained by the non-execution probability of a CRIoT. The service execution probability P_{ne} of a CRIoT and throughput of the CRN are closely related. Due to the presence of PUs throughput during its service time, the CRIoT objects are interrupted and the service execution probability in that case is evaluated. First, execution of spectrum handoffs of the n intrapool are done successfully. Next, the execution of $(n - 1)$ intrapool including the n^{th} interpool spectrum handoffs are done. Therefore, P_{ne} is written as (Hoque and Arif, 2019).

$$\begin{aligned} P_{ne} &= 1 - \sum_{n=0}^{\infty} \Big[\Pr\big(S_n < t_{cu} < S_{(n+1)}\big)\big(q_{s1} + (1 - \Pr_v)\big)^n \\ &\quad + \Pr\big(T_{cu} > S_n\big)\big(q_{s1} + (1 - \Pr_v)\big)^{(n-1)} q_{s2} \Big] \\ &= 1 - \Big[f^*_{T_{scu}} \big(\lambda_{pu}\big(q_{s2} + q_f\big)\big) + \lambda_{pu} q_{s2} F^*_{T_{scu}} \big(\lambda_{pu}\big(q_{s2} + q_f\big)\big)\Big] \end{aligned} \tag{19}$$

where S_n is the of primary users' throughout inter arrival time, and obeys an Erlang distribution (Kleinrock, 1975). So, S_n has been expressed as

$$f_{S_n}(t) = \frac{\lambda_{pu}{}^n t^{(n-1)} e^{(-\lambda_{pu} t)}}{(n-1)!}, \; n \geq 1 \tag{20}$$

Here, $S_n = t_{(pu.1)} + t_{(pu.2)} + t_{(pu.3)} + \ldots\ldots + t_{(pu.(n-1))} + t_{(pu.n)} = \sum_{(n-1)}^{m} t_{(pu.n)}$ and $t_{(pu.n)}$ is the inter-arrival time between the n^{th} and $(n-1)^{\text{th}}$ PUs.

5.1.8 Blocking probability

Whenever the PU including other CRIoT objects already hold all the network channels in the system then CRIoT's services will be blocked. The blocking probability of a CRIoT is completely supervised by the occupancy of PU and other CRIoT objects in the same or the availability of channels in that particular system. The joint probability, $P_{x,y,z}$ of PUs and CRIoT objects available in the system, and must be determined. The P_b of CRIoT is achieved by using the joint probability $P_{x,y,z}$. Consider the availability of PUs in LSP-1 and LSP-2 are x and y, respectively. However, CRIoT tries to reach the system to initiate its transmission with an arrival rate of λ_3 described in the Figure 4. Consider 'x' is the total channels consumed by the PUs in LSP-1. Therefore, the available channels for CRIoT in LSP-1 is $(C_1 - 1)$. Again, consider 'y' is the number of PUs presented in LSP-2. Thus, $(C_2 - y)$ is the number of channels are available for CRIoT in LSP-2. Therefore, CRIoT use available channels in the entire system. It totally depends on the channels which are used by the PU is represents as $k = C_1 + C_2 - (x + y)$. So during the transmission the PUs occupy total $(x + y)$ no. of channels. If $(x + y) < (C_1 + C_2)$, then utmost number of channels will be available for CRIoTs. Thus, P_b can be defined by following expression

$$P_b = \sum_{x=0}^{C_1} . \sum_{y=0}^{C_2} . \lambda_3 P_{(x,y,C_1+C_2-(x+y))} \tag{21}$$

After computing the value of $P_{(x,y,C_1+C_2-(x+y))}$ and $P_{(0)}$; P_b is derived from (Jee et al., 2020)

$$P_b = \lambda_3 P_0 \rho_3^{(c_1+c_2)} \sum_{x=0}^{C_1} \frac{\rho_1^x \rho_3^{(-x)}}{x!} \sum_{y=0}^{C_2} \frac{\rho_2^y \rho_3^{(-y)}}{y!\big(C_1 + C_2 - (x+y)\big)!} \tag{22}$$

Table 2 Review of CRNs for IoT related articles in literature

Reference	*Year of publication*	*Technical approach*	*Description*
Zhang et al. (2012)	2012	Cognition in IoT network integration	Modeling of cognitive process for optimisation of network performance as per current conditions autonomously in cognitive-radio-based IoT networks.
Qu et al. (2012)	2012	Spectrum allocation system model	IoT-based spectrum allocation system model on HE social model by the help of spectrum idle matrix, interference matrix.
Zhang and Chen (2012)	2012	Distributed sharing	Utilisation of Nash bargaining solution, surplus portion of PUs' spectrum used for IoTs and improvement of multi-objective function.
Tragos and Angelakis (2013)	2013	Communications for IoT in opportunistic manner and access the spectrum in ISM bands	The adaptability of CRN had been studied on the M2M communications and energy efficient CR-based smart objects has been designed.
Shah et al. (2013)	2013	IoT challenges for CR network applications	Challenges in IoT & CRN architecture.
Miz and Hahanov (2014)	2014	Cyber-physical, road traffic management system CTMS, smart traffic light	Supervision of cognitive traffic system-based IoT approach and its application to conceptualise the global e-government.
Shigueta et al. (2014)	2014	Study of channel assignment	Better performance in practice is noticed with respect to theoretical approach in channel assignment strategy to access spectrum in licensed TV channels and transmission of Traffic volume in transmission layer.
Aijaz and Aghvami (2015)	2015	Cognitive M2M communication for IoT-a protocol stack	Protocol design guidelines and study of licensing technologies for IoT and Cognitive MAC protocols for centralised and distributed cognitive M2M Communication.
Khan et al. (2016)	2016	Spectrum sensing, cloud services for CRIoT network	Demand for CR in IoT by the help of function of CR, self-reconfigurable IoT, cloud services, spectrum sensing etc.
Moon (2017)	2017	Spectral efficiency, packet delivery ratio throughput, interference, delay	Derivation of the blocking probability of carried traffic to improve the performance of Pus.
Liu and Xie (2017)	2017	Delay, energy consumption, channel allocation	Minimisation of the engagement time between two IoTs by deriving an equation which unify the CRIoTs hopping moment.
Zhu et al. (2017)	2017	Throughput, packet delivery, energy consumption	Determination of packets transmission from different buffers using deep learning; the state transformation of the system is described by Markov decision process-based model.
Matin (2017)	2017	Spectrum allocation, secure spectrum management, DSA	Management and efficient access of the WCS through Spectrum allocation by DSA.
Khan et al. (2017)	2017	CRIoT systems, architectures, frameworks, spectrum-related functionalities	CRIoT frameworks have the cognitive capability to make smart decisions about the spectrum and perform a smart operation by examining network conditions.

Table 2 Review of CRNs for IoT related articles in literature (continued)

Reference	*Year of publication*	*Technical approach*	*Description*
Alberti et al. (2017)	2017	ICT, cooperative spectrum sensing, NovaGenesis architecture	Successful convergence of CRN, IoT and a FIA called NovaGenesis consists two novel services. It includes the CRN for the services like SSS and RMS.
Kim (2017)	2017	Inspection game, CSS, RUBS, reciprocal fairness	The main issue in CRIoT with CSS is to make a selfish SU collaboration with others and is modeled by capturing the key features of the inspection game.
Wu (2018)	2018	Spectrum sensing, perceptual location, trustful cluster, wireless network	(TCBCSS) algorithm has been proposed for orientation of the malicious user environment. The channel condition has been detected using the compressed spectrum sensing algorithm.
Rajpoot and Tripathi (2018)	2018	IoT, RFID, CRN, primary communication, power control	PURx information is accessed by the RFID system. The results show less energy is required to run the network. It results a notable improvement in average throughput and reduction in delay for increasing CR traffic.
Han et al. (2018)	2018	Cognitive radio, spectrum allocation, multi-objective optimisation.	The spectrum allocation problem is formulated as an MOP and converted into a solution in genic algorithms.
Li et al. (2018)	2018	Narrowband IoT, CR, SS, random access, throughput optimisation	Maximisation of the NB-IoT network level throughput to suppress the spectrum sensing overhead. It investigates the trade-off between the random access NB-CR-IoT network throughput and the sensing accuracy.
Shahini et al. (2018)	2018	Wireless energy harvesting, EE, resource allocation, network optimisation	An optimisation framework has been designed that releases a fundamental tradeoff between EE and the spectral efficiency of the network. It targets NP-hard problem.
Salameh et al. (2019)	2019	Spectral efficiency, throughput	Find out the optimal distribution of (Guard bands) idle blocks using linear programming among CRIoTs.
Bauwens et al. (2019)	2019	MAC design architectures, portability, compatibility, cross-platform design, ContikiMAC, TSCH	The performance of MAC protocol become unsuitable for the different hardware platforms. If the timing differences become too large, it result in asymmetrical link behavior.
Kaur et al. (2019)	2019	Cognitive radio, CDE, IoT, multicarrier system, meta-heuristic optimisation	The investigation has been done for parameter reconfiguration in a CRIoT network for different transmission scenarios. MFO gives the best resolution for minimised power consumption and maximised throughput.
Ansere et al. (2019)	2019	CR-IoT, EE, DSS	A two-way information exchange DSS algorithms have been proposed to increase energy efficiency for data transmission in licensed channels.
Das et al. (2019)	2019	IoT, CR, ISM band, multi-hop paths	An energy balancing strategy has been proposed with efficient frequency planning using CR due to expected ISM band overload and unutilised licensed spectrum, that offers energy incentive for relaying packets. It saves energy significantly with a marginal increase in average scanning overhead.

Table 2 Review of CRNs for IoT related articles in literature (continued)

Reference	*Year of publication*	*Technical approach*	*Description*
Awin et al. (2019)	2019	SS, IoT, MAC, spectrum accessing, data privacy, blockchain	The design factors of CRIoT and the proper spectrum sensing and access approaches are selected. It also explored emerging technologies, such as blockchain and maximum likely hood.
Tarek et al. (2020b)	2020	CRIoT, CR spectrum assignment, challenges	Cognitive radio networks is merged with IoT by addressing channel allocation and packet scheduling.
Tarek et al. (2020a)	2020	CRIoT, PSO, fog, spectrum sharing packets' scheduling	A centralised time-slotted algorithm has been proposed. It uses DPPSO for scheduling packets with the protocol SDP-PSO.
Amini and Baidas (2020)	2020	CRN, collision probability, diversity transmission, energy harvesting, IoT	The performance of UR-EH-CR-IoT networks has been analysed. It shows analytical derivations for different IoT network metrics, such as GoodPut, reliability, collision probability, availability, and stability.
Yu and Zikria (2020)	2020	CRN, IoT, WSN, 5G, spectrum sensing, spectrum sharing	The authors represent innovative ideas of CRNs. The state-of-the-art research developments has been analysed in the respect of CRIoT and Wireless Sensor Networks.
Singh et al. (2020)	2020	IoT, CCRN, SWIPT, DF, Nakagamim fading, outage probability (OP)	The investigation on overlay spectrum sharing system in combination with the SWIPT. It enables communications for the IoT applications with improved link reliability.
Nurelmadina et al. (2021)	2021	LoRa, Sigfox, cognitive LPWAN, industrial IoT	Numerous tools and protocols for industrial IoT applications have been reviewed. It focused essential factors for designing the critical research gaps of the existing LPWAN cognitive-enabled IIoT.
Amini and Baidas (2021)	2021	CR, energy-harvesting, finite block length, IoT, low-latency, ultra-reliability	URLL combined with concepts of EH and CR analyse IoT networks much more complex. It measures the performance of uplink EH-CR-IoT networks with URLL requirements.
Benmammar (2021)	2021	IoT, CRN, standard communication protocols, RFID	IoT is defined with its potential applications, challenges, including its enabling technologies where particular importance is given to CRN. It integrates cognitive radio in IoT to serve as self -reconfigurable solutions for IoT applications.
Nallarasan and Kottilingam (2021)	2021	IoT, CRN, CRIoT, spectrum management	The distribution of channels and preparation has been discussed on the distribution of combining CRN with IoT. The spectrum-based features and heterogeneity in cognitive IoT security also has been analysed.
Sardar et al. (2021)	2021	CRIoT, smart city, MPT, discrete time Markov chain	Authors included MPT technique for its greater energy transmission efficiency over long-distance. DTMC method is modeled the framework in periodic nature for the spectrum-sensing process. CR-IoT operating in opportunistic mode, that enables various smart city facilities.

5.1.9 Dropping probability

When CRIoT is engaging the channel, they need to evacuate the medium right away due to the sudden appearance of PU in the system. The dropping probability for the CRIoT is P_d, which depends on PU's activity model

$$P_d = \sum_{x=0}^{C_1-1} . \sum_{y=0}^{C_2-1} \frac{\lambda_1 . \lambda_2}{(C_1 - x)(C_2 - y)} . P_{(x,y,C_1+C_2-(x+y))} \tag{23}$$

After computing the value of $P_{(x,y,C_1+C_2-(x+y))}$ and P_0; P_d is derived from (Jee et al., 2020)

$$P_d = \lambda_1 \lambda_2 P_0 \rho_3^{(2c_1)} \sum_{x=0}^{C_1-1} \frac{1}{(C_1 - x)} . \frac{\rho_1^x \rho_3^{(-x)}}{x!} \sum_{y=0}^{C_1-1} \frac{1}{(C_1 - y)} . \frac{\rho_2^y \rho_3^{(-y)}}{y!(2C_1 - (x+y)!} \tag{24}$$

A CRIoT is blocked due to the lack of channels and cannot complete its service when $C_1 = C_2$. It happens due to the arrival of the PUs, and services are dropped during its transmission. Therefore, the P_{ne} of CRIoTs could be determined for those two situations like blocking and dropping respectively

$$P_{ne} = P_b + (1 - P_b) P_d \tag{25}$$

5.1.10 Throughput

The throughput is an important performance metric in CRN, and is almost related to the incomplete service of CRIoT objects. After computing the value of P_{ne}, $P_{x,y,z}$ and P_0; T is derived from (Jee et al., 2020)

$$T = \sum_{x=0}^{C_1} . \sum_{y=0}^{C_2} . \sum_{z=1}^{C_1+C_2-(x+y)} z(1 - P_b - P_d + P_b P_d) P_{(x,y,z)} \frac{\rho_1^x \rho_2^y \rho_3^z}{x!y!z!} P_0 \tag{26}$$

There are two different primary channels where the interrupted CRIoTs are switched their facilities to and from LSP-1 to LSP-2 and vice versa to enhance the network's throughput.

6 Results and discussion

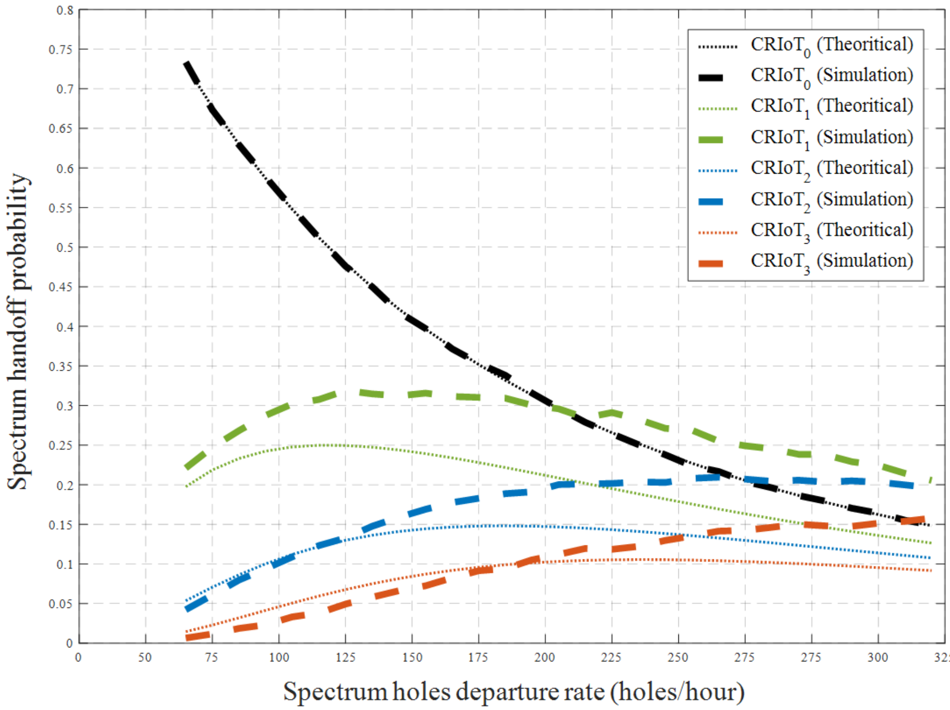
In our proposed model, we have considered two identical cells:

1 cell 1 as a source cell where a SUIoT starts its service

2 cell 2 as a target cell where the SUIoT completes or ends its service.

We also assumed that the non-stationary SUIoT object operates in the vacant licensed channel of cell 1 of LSP1 to begin its service. To explain the model, we discussed some attributes which affect the model to hold its place as a CRIoT network. To identify the spectrum for PU in scheme-1 intracell/intrapool handoff latency L_1 has been identified. Similarly, for the scheme-2 intercell/interpool handoff latency L_2 has been proposed. An extended neighbour cell that uses the same spectrum pool is called new destination or target cell. So that spectrum handoff for CRIoT object may follow the other type of latencies for intracell/interpool handoff and intercell/intrapool handoff as L_3 and L_4, respectively.

Figure 5 Classical and proposed spectrum handoff schemes in variable network condition (see online version for colours)



In Figure 5, the spectrum handoff performance behaviour is explained. The demonstration is done under variable network conditions like OSB, OS, NSB and NS in terms of CRIoTs. In the earlier studies regarding intra-cell spectrum handoff aimed at general residual time distributions of spectrum holes under SU mobility, the research was done by the probability of intra-cell spectrum handoff due to new call-in progress at originating cell and post-inter-cell handoff call-in progress at the terminating cell by Monte Carlo iteration process. The exponential distribution for non-stationary SU call duration with general distribution of residual time of spectrum holes were done against SUs mobility μ_s, SUs' departure rate μ and spectrum holes λ (Hoque et al., 2018). Whereas the following outputs of CRIoT in Figure 5, has been considered in variable network conditions.

Figure 6 shows the relative nature of awaited number of spectrum handoffs, $E(H)$ all the way through total service time of the CRIoT in variable network conditions viz. OSB, OS, NSB and NS having different λ_{PU} / μ_{CRIoT}. As λ_{PU} / μ_{CRIoT} increases the $E(H)$ is also increases for OSB otherwise decreases after certain limit for all other variable network conditions. The comparison between results of $E(H)$ shows with and without switching delay in terms of λ and μ, respectively. The increasing value of λ signifies that a CRIoT needs higher spectrum holes during its whole connectivity. Hence, $E(H)$ of CRIoT increases with increasing λ as shown in figure.

Figure 6 Relative nature of $E(H)$ with λ_{PU} / μ_{CRIoT} in variable network conditions (see online version for colours)

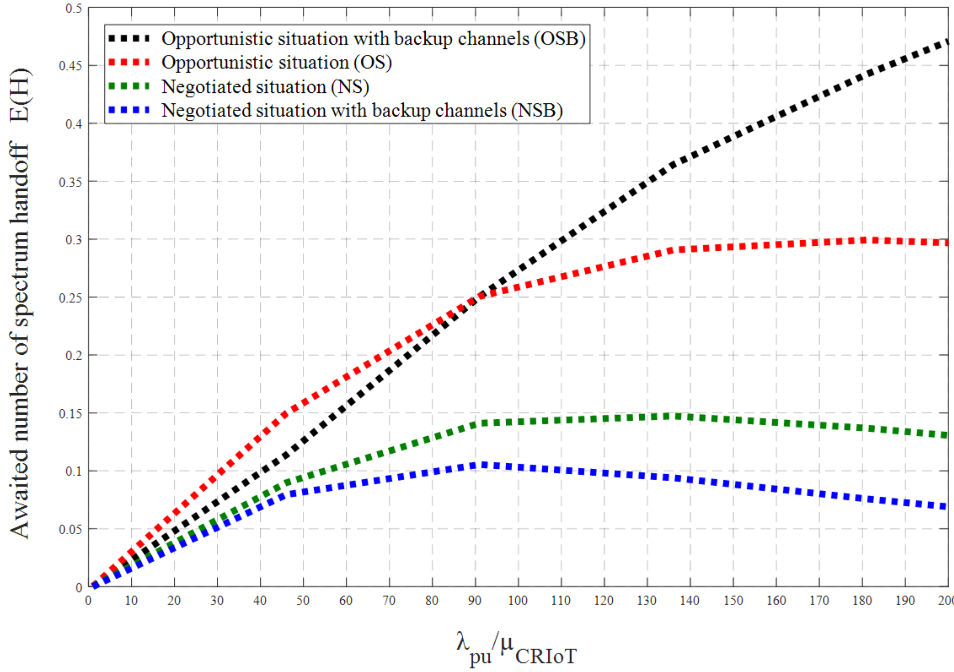


Figure 7 Link continuation probability in variable network conditions (see online version for colours)

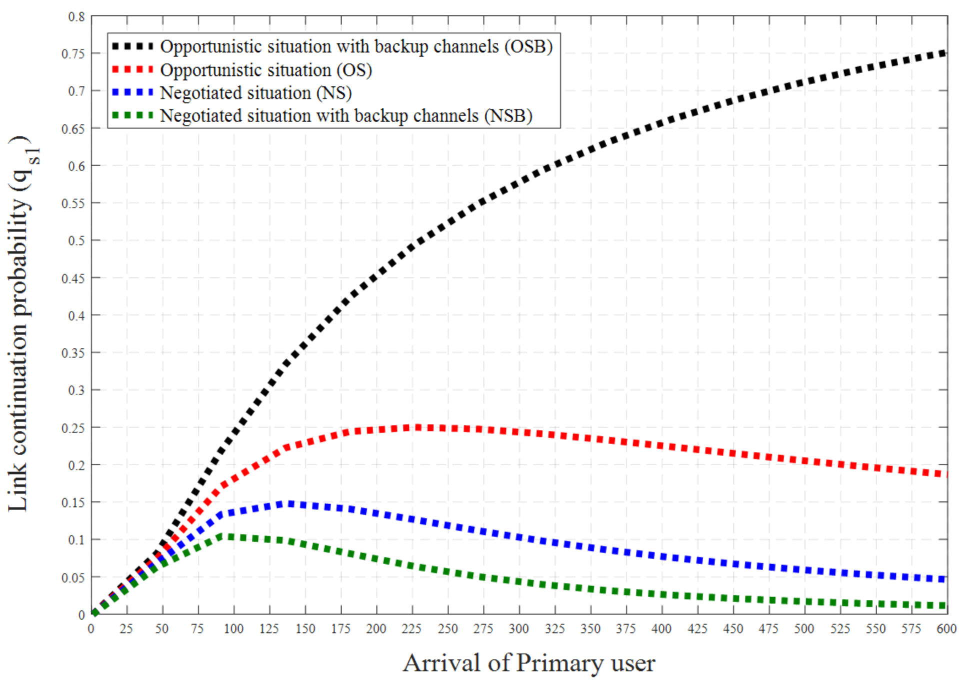
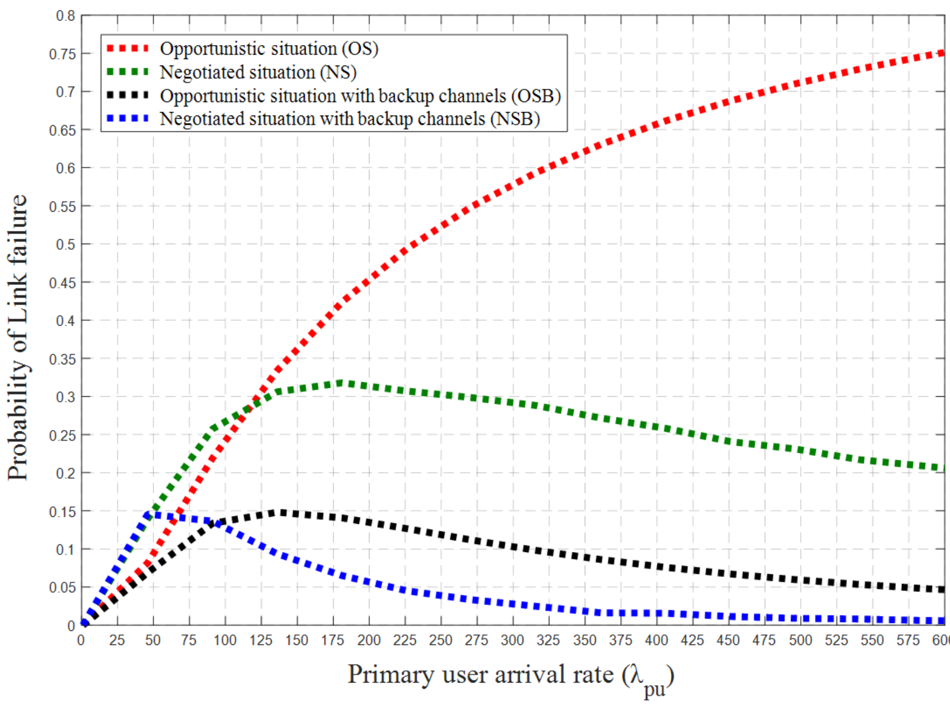


Figure 7 defines the link continuation probability q_{s1} migrates its service from one LC to another free LC in the same licensed spectrum pool LSP1, which defines intrapool spectrum handoff. In contrast, link continuation probability q_{s2} occurred while the LCs become full due to the interpool spectrum handoff. The comparison is drawn among the classical (OS, NS) and (OSB, NSB) as per system model of our consideration under the opportunistic and negotiated situations for q_s. It is important for the CRIOTs to leave the existing channel in LSP1 once the system is in state $(C_1 - 1)$ in NSB whereas the channel vacant probability is much better in opportunistic situation compared to the other one.

Figure 8 Link failure probability in variable network conditions (see online version for colours)

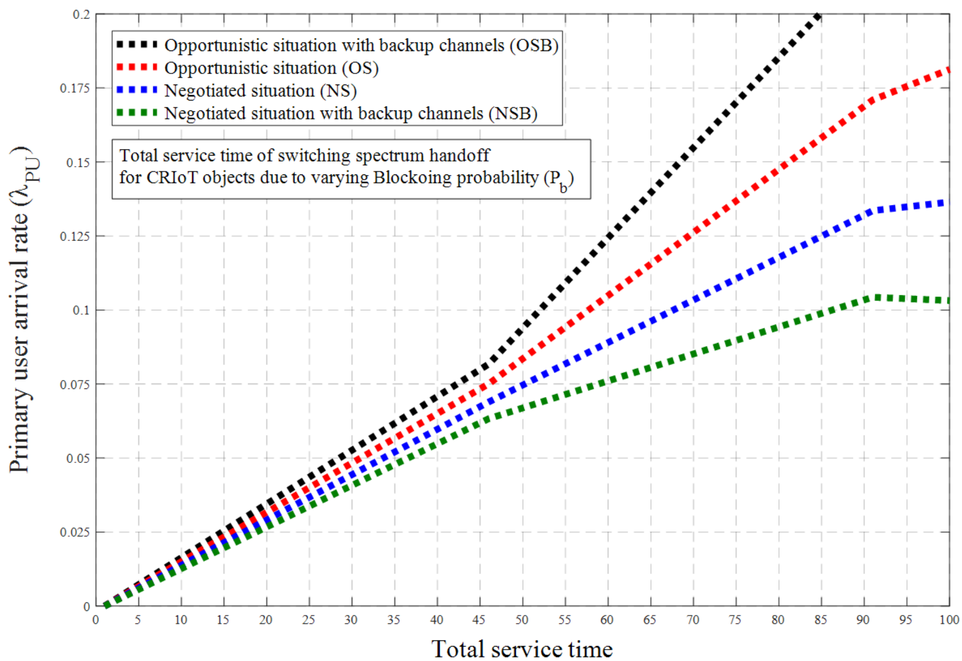


During the spectrum handoff the continuation of link will be terminated if there is no available channel; therefore link failure probability q_f has been presented in equation (15) and in Figure 8, q_f is reduced for both OSB and NSB as compared with the classical variable network situations like OS and NS.

The blocking probability is calculated in respect of average traffic of interrupted users like CRIOTs according to equation (21) and it defines all the waiting positions. The blocking probability P_b of a CRIoT is completely supervised by the occupancy of PU and other CRIoT objects in the same or the availability of channels in that particular system and derived in equation (22). A CRIoT is blocked due to the lack of channels and cannot complete its service because of the arrival of the PUs, and services are dropped during its transmission. Therefore, it affects the throughput which is an important metric in CRIoTN, and is almost related to the incomplete service of CRIoT objects.

Figure 9 depicts the result of Total service time of a CRIoT for spectrum handoff switching scheme with respect to changing arrival rate of the PU in variable network conditions. If the PUs' arrival rate increases the CRIoT's interruption during transmission is also increases. Therefore, a big arrival rate of PUs creates higher number of interruption in comparison to low arrival rate of PUs. The performance is near about same up to λ_{PU} = 0.025 for OS and OSB. Whereas performance begin to divert at λ_{PU} = 0.0275 for all variable network conditions.

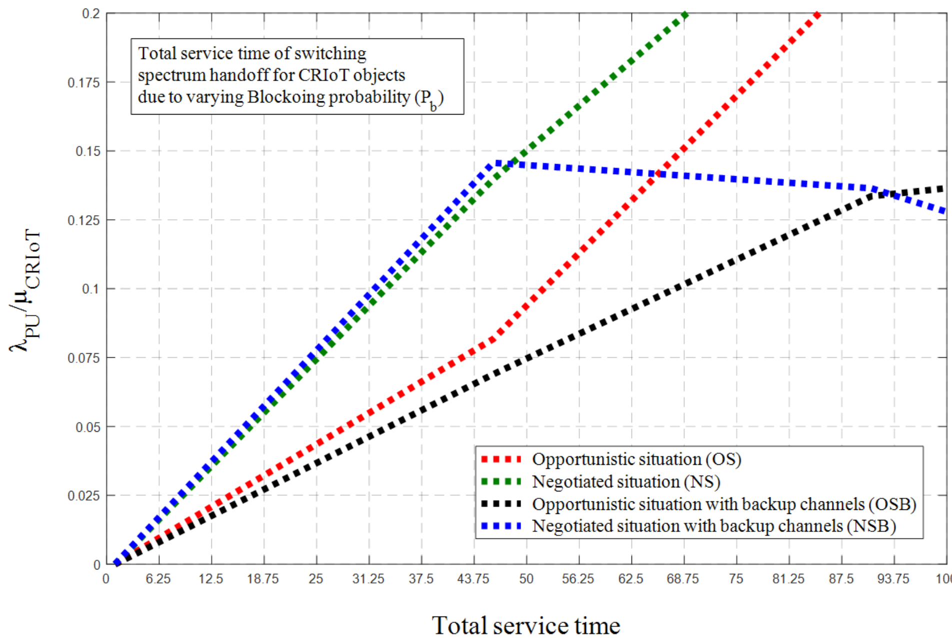
Figure 9 Relative nature of PU arrival rate throughout total service time for spectrum handoff switching (see online version for colours)



The basic requirement of CRIoTN is the co-existence of CRIoT with PU, and these operate clearly for the primary system. Therefore, it is essential to examine the effect of CRIoT dynamics on the spectrum handoff performance for varying network conditions. $\lambda_{PU} / \mu_{CRIoT}$ represents the mobility of spectrum hole in CRIoT network. Figure 10, shows the relative nature of total service time with the mobility of spectrum hole in CRIoT network, i.e., $\lambda_{PU} / \mu_{CRIoT}$ to perform spectrum handoff switching. In Figure 10, at $\lambda_{PU} / \mu_{CRIoT}$ = 0.075 the performance of NS and NSB is almost same whereas the performances for OS and OSB are deviated respectively.

The instantaneous switching delay and the estimated switching delay are integrated as estimated switching cost an essential attribute while CRIoT objects move to neighbouring cell. During the same, awaited number of spectrum handoff is a key performance measuring metrics of spectrum handoff in CRIoT network. It harms the performance of the delay in handoff, service execution, and link continuation of CRIoTN. After calculating the non-execution probabilities P_{ne} in CRN long-time performance is explained by equation (19).

Figure 10 Relative nature of total service time during mobility of spectrum hole in CRIoT network (see online version for colours)



7 Conclusions

IoT and CRN are both promising technologies nowadays and have excellent research exposure presently. IoT offers a new lifestyle by revealing several purposes. However, IoT needs to integrate the CRN skills to avoid the bandwidth deficit. CRIoT is still underdeveloped compared to other advanced wireless communication technologies, but it brought some attention. Researchers used to focus on cognitive radios in IoT but do not present motives following the paradigm's paradigm. This paper explores some teletraffic attributes (to the best of our knowledge) for spectrum handoff and allocation/scheduling for CRIoT. Most of the research is done using a limited number of IoTs, which is not practical in most IoT applications. Soon, there would be a world of trillions of IoT objects in requisite of uninterrupted spectrum functionalities. Regular communication technologies would not resist this situation. Therefore, migration from ordinary IoT objects to CRIoT objects would be an assured solution to overcome the spectrum bottleneck situations.

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Appendix

Abbreviation	*Definition*
CRIoT	Cognitive radio internet of things
1G	First generation
5G	Fifth generation
IoT	Internet of things
CR	Cognitive radio
CRN	Cognitive radio network
DSA	Dynamic spectrum access
FSA	Fixed spectrum allocation
IDC	International data corporation
CAGR	Compound annual growth rate
M2M	Machine to machine
D2D	Device to device
RFID	Radio frequency identification
HAN	House area network
FAN	Family access network
WAN	Wide area network
ITU	International telecommunication union
IEEE	Institute of Electrical and Electronics Engineers
FCC	Federal communications commission
FDMA	Frequency division multiple access
TDMA	Time division multiple access
CDMA	Code division multiple access
MIMO	Multiple input multiple output
QoS	Quality of service
PU	Primary user
SU	Secondary user
SUIoT	Secondary user internet of things
HetSE	Heterogeneous spectrum environment
UHF	Ultra high frequency
WRC	World Radio communication Conference
WRAN	Wireless regional access network
OTG	On the go
INTRACC	Intra-cognitive communication
INTERCC	inter-cognitive communication
CIoT	Cognitive internet of things
LC	Licensed channel
LSP	Licensed spectrum pool
OSB	Opportunistic situation with backup channels

Appendix (continued)

Abbreviation	*Definition*
NSB	Negotiated situation with backup channels
OS	Opportunistic situation
NS	Negotiated situation
BA	Base area
BS	Base station
RF	Radio frequency
PBS	Primary base station
WCS	Wireless communication services
ICT	Information and communication technology
FIA	Future Internet architecture
SSS	Spectrum sensing service
RMS	Resource management service
RUBS	Relative utilitarian bargaining solution
TCBCSS	Trustful cluster-based cooperative compressed spectrum sensing
PURx	Passive primary receiver
EE	Energy efficiency
CDE	Cognitive decision engine
MFO	Moth–flame optimisation
DSS	Dynamic spectrum sensing
ISM	Industrial, Scientific and Medical
PSO	Particle swarm optimisation
DPPSO	Discrete permutation particle swarm optimisation
SDP-PSO	Scheduling based-on DP-PSO
UR-EH-CRIoT	Ultra-reliable energy-harvesting CRIoT
CCRN	Cooperative cognitive radio network
SWIPT	Simultaneous wireless information and power transfer
DF	Decode-and-forward
LPWAN	Low power wide area network
IIoT	Industrial internet of things
URLL	Ultra-reliability and low-latency
EH	Energy-harvesting
MPT	Microwave power transfer
DTMC	Discrete time Markov chain