Energy efficient wireless communication technique based on Cognitive Radio for Internet of Things

Qureshi, FF, Iqbal, R & Asghar, MN

Original citation & hyperlink:
Qureshi, FF, Iqbal, R & Asghar, MN 2017, 'Energy efficient wireless communication technique based on Cognitive Radio for Internet of Things' *Journal of Network and Computer Applications*, vol 89, pp. 14-25
https://dx.doi.org/10.1016/j.jnca.2017.01.003

DOI 10.1016/j.jnca.2017.01.003
ISSN 1084-8045

Publisher: Elsevier

Energy efficient wireless communication technique based on Cognitive Radio for Internet of Things

Faisal Fayyaz Qureshi

University of Bedfordshire, UK

Rahat Iqbal

Coventry University, UK

Muhammad Nabeel Asghar

Bahauddin Zakariya University, Pakistan

Abstract

Due to the drastic growth and an upsurge in the wireless communication devices in the world in recent years, there is a high demand of uninterrupted and intelligent connectivity in a self-organising manner amongst the users. It becomes more challenging for the emerging users because of scarcity of bandwidth. To overcome the unforbidden challenges in the advanced technologies like smart cities, 5G and Internet of Things (IoT), Cognitive Radio provides the solution to achieve high throughput and continuous connectivity for reliable communication. A primary challenge in the Cognitive Radio (CR) technology is the identification of dependable Data Channels (DCHs) for Secondary Users (SUs) communication amongst the available channels, and the continuation of communication when the Primary Users (PUs) return. The objective of every SU is to intelligently choose reliable DCHs, thereby ensuring reliable connectivity and successful transfer of data frames across the cognitive networks. The proposed Reliable, Intelligent and Smart Cognitive Radio protocol consumes less computational time and transmits energy with high throughput, as compared to the benchmark Cognitive Radio MAC (CR-MAC) protocols. This paper provides new applications of CR technology for IoT and proposes new and effective solutions to the real challenges in CR technology that will make

IoT more affordable and applicable.

Keywords: MAC protocol, SU, PU, CR, CRN, IOT, Smart technology

1. Introduction

Cognitive Radio (CR) technology exploits the opportunistic access of the frequency bands to the Secondary Users (SUs) or Cognitive Users (CUs) called the unlicensed users. It increases the spectrum efficiency. When Primary Users (PUs) called the Licensed Users are not transmitting, white spaces or spectrum holes are created in the spectrum. Without interfering with PUs, SUs opportunistically access these spectrum holes by using white spaces owned by PUs [1] [2]. It has also been asserted that CR technology has opened new horizons in emerging areas such as smart technology, Internet of Things, satellite communications, defense, public safety, health monitoring and next generation technologies [3] [4].

By implementing a Cognitive Radio Network (CRN) at small-cell technology, interference can be avoided effectively since cognitive small cells will not select the same channels identical to the neighbouring small-cells [5]. The network capacity can be increased by exploiting the spectrum holes to enhance bandwidth utilisation and higher data transfer rate [6].

1.1. Cognitive Radio Internet of Things

The Internet of Things (IoT) is an emerging and novel paradigm that incorporates various technologies such as wireless and wired sensor networks and actuators, mobile phones, distributed intelligence of smart devices and enhanced communication protocols through the Internet. The main idea behind IoT is to connect numerous heterogeneous devices through internet to operate intelligently and efficiently. It enhances the behaviour of potential users and several aspects of everyday life [7] [8]. The Cognitive Radio Internet of Things (CRIoT) can be used in communication, e-health, logistics and security [9], smart technology, social media, wireless sensor networks, etc. [10]. The integration of the

IoT with CR technology develops the effective communication system among the SUs [11]. Security is one of the challenging concerns in Cognitive Radio technology because hackers can alter channel information and can either get access, or get energy, or any other resources to control the SUs. In order to prevent hacking and reduce damages, multi-layered security, provides the secure communications among the users [12]. Moreover, the management of data technology manages the exchanging of channel information among the SUs during the disaster situation in the CRIoT networks and establish the successful communication without experiencing a downtime [13]. The security and data management will be addressed in the communication of SUs in the CRIoT to enhance the performance of the technology [14].

The most extricated physiognomies of CRIoT is to increase inter-connectivity amongst a number of emerging applications and services. Though, large number of IoT applications are stagnant reliant vastly on human beings for cognition processing[15]. One of the incentives of this paper is to introduce the integration of Cognitive Radio networks with IoT, where SUs interact with the physical environment with less human intervention. The benefit of this technique is to select Reliable Data Channel(s), reduce collision among the SUs, save communication time and enhance throughput of the SUs in the CRN.

1.2. Cognitive Radio for Internet of Things Paradigm

Figure 1 discusses the integration of CR, IoT and other related technologies, where many issues need to be addressed. Primary issues such as providing a higher level of effectiveness, enhancing the adaptability based on the existing environment, standardisation and industrialisation, interoperability of interconnected devices and most importantly guaranteeing trust and security in the pervasive environment need to be addressed in the long run growth of both technologies [16].

Existing wireless sensor networks use Industrial, Scientific and Medical (ISM) bands for communication [17]. These bands are utilised by many other technologies, which can cause a long waiting time, especially for delay sensitive traffic such as Voice over Internet Protocol. Research has proved that this co-existence in the ISM band could decrease the performance of the wireless sensor networks and increase the wait time. Therefore, wireless sensor networks require to interconnect with the physical world and to make the intelligent decision based on the surrounding environment using cognitive technology [18].

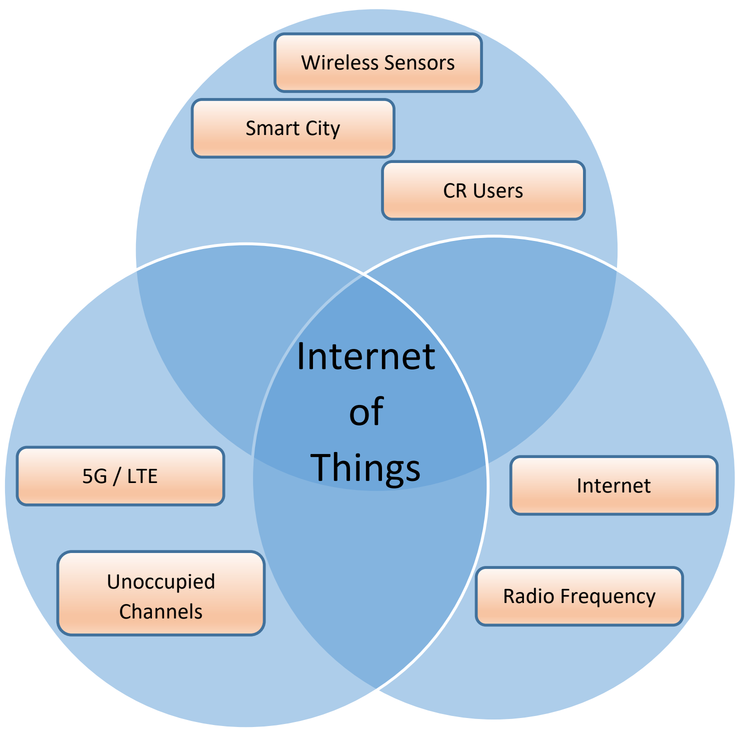

Figure 1: Cognitive Radio for Internet of Things Paradigm

1.3. Data channel selection criteria of Cognitive Radio Internet of Things

The selection criteria of the DCHs are centred on numerous factors, such as an initial selection based on the determined free time logged by the SUs over the DCH channel ranking. The channel ranking is proportional to the number of positive or negative acknowledgements, and the recent history of DCHs obtained during the previous handshaking among the SUs. If more than two DCHs have an identical value during the second, third and following iterations, then the DCHs are selected based on the total free time. The main primaries of the DCHs are then assigned based on Reliable Data Channels (RDCH), which are: RDCH 1, RDCH 2, RDCH 3, and RDCH 4 respectively (where RDCH 1 and RDCH 2 have the uppermost priority, DRCH 3 and RDCH 4 have the next priority, and so on). This is based on communication time, energy transmitted, throughput, and delay for the saturation network, where the SUs always have data to exchange over the DCH with multiple sizes of payload. A new data frame is available to each SU once the last data frame has been transmitted successfully [19] [20]. Therefore, the SUs are continuously seeking unused spectrum bands for communication. In contrast, the SU may have an empty queue in a non-saturation network [21]. In order to make the model realistic, the CRN co-exists with PUs by utilising the same spectrum bands, and the number of PU pairs are equal to the number of licensed channels, as shown in Fig.1. The number of SUs, and the data to be transmitted, may vary. Without a loss of generality, the frames related to the SU arrive according to the Poisson process. The PUs can use their licensed channels and follow the independent and identical ON/OFF renewal process. The ON state indicates the presence of the PUs and the OFF state indicates the absence of the PUs. In contrast, when it comes to the SUs, the ON state indicates that there is no opportunity for the SUs to utilise the licensed channel, and the OFF state indicates that there is an opportunity for the SUs to utilise and exchange their data information. Each SU has a sensor [22] to record the activity of the PUs while its transceivers are busy exchanging the information over the DCHs. The function of the sensor is to sense when the PU returns and updates the SU to switch to another channel, called a BDC. Moreover, the RECR-MAC protocol assumes that the CCH is always available and dedicated for the SUs to exchange their control information. As shown in Figure 4, each SU has two transceivers (TX1/RX1 and TX2/RX2) and a sensor which records both the free time and the PU returns. A1 and B1 represent the transmitters of SU1, and A2 and B2 are the receivers of SU2 and Channel 1, Channel 2, etc. represent the DCHs. The data frames split into two parts and are transmitted over two DCHs simultaneously. The ACK is generated by the receiver of SU2, once complete data is received from SU1. The SUs are unable to transmit data until a minimum of two DCHs become available for communication to enhance the chance of continuous data transmission for the RECR-MAC protocol. Moreover, the SUs consume energy at each layer when exchanges control and data frames, as shown in Figure 2. Based on Open Systems Inter-connection layered model for wireless networks, SUs devour maximum energy for communication (idle, transmitting and receiving). The requirement of energy consumption among the SUs can be increased from the application layer to link layer to establish the seamless communication. Therefore, the paper proposed channel selection criteria in the CRIoT network, where SUs select the most Reliable Data Channels for the communication and saves energy. However, if the number of re-transmissions could be reduced, and Backup Data Channel (BDC) is introduced to continue the communication when the PU returns, this would save a significant amount of transmitted energy over the MAC layer as compared to any other layers.

1.4. Contributions

In this paper, numerous contributions have been incorporated among the CR and IoT to enhance the existing infrastructure such as optimisation of the control frames and reducing the number of handshakes over the control and data channels. In addition, channel selection criteria and avoiding re-transmission are proposed for reliable data communication in CRAHNs for SUs to utilise IoT based devices. Moreover, the impact of PU activities on different channel selection strategies have been extensively studied and analysed. A BDC is introduced to continue the communication if a PU returns. It is also noted that the reliable channel selection strategy and BDC plays a vital role in reducing the communication time between SUs for task completion. The reduction in communication time between SUs over the control and data channels directly impacts the performance of CRAHNs in terms of energy consumption and throughput.

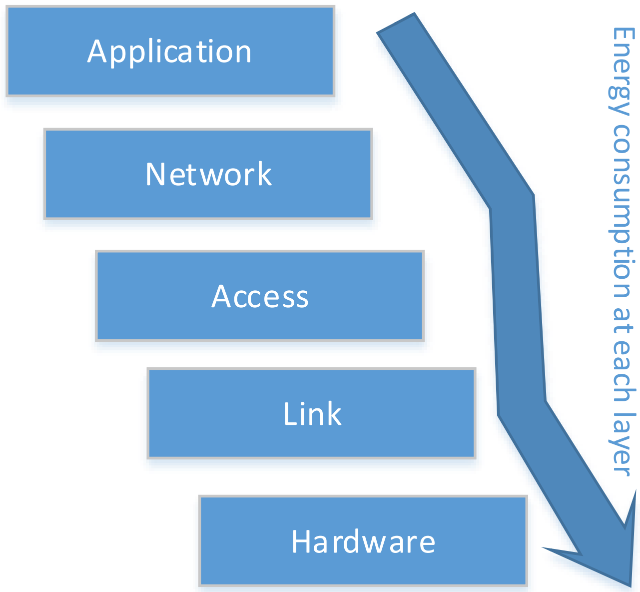

Figure 2: Energy consumption at each layer

1.5. Organisation of the paper

This paper discusses the performance of the Reliable and Energy Efficient Cognitive Radio Multi-Channel Medium Access Control Protocol for Ad-hoc Networks (RECR-MAC). Furthermore, we discuss the characteristics of the RECR-MAC protocol and its comparison with other selected benchmark protocols, such as the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols [23] [24]. The remainder of the paper is organized as follows: Section 2 is about the importance of energy saving for RECR-MAC. Section 3 explains the proposed network model. Section 4 describes the impact of contributing factors of the energy consumption for RECR-MAC. Section 5 analyses the energy saving between RECR-MAC and benchmark CR-MAC. Section 6 discusses the impact of contributing factors over the performance of throughput for RECR-MAC. Section 7 provides a throughput analysis of the RECR-MAC with benchmark CR-MAC Protocols without and with PU interference. Finally the conclusion is drawn in Section 8.

2. Importance of energy saving for RECR-MAC

Information technology utilises 2% of all energy consumed globally, and 0.5% is consumed by wireless technology [25]. Between 2006 and 2014, there has been a growth of 92% in wireless technology [26]. The Wireless World Research Forum has forecasted that 7 trillion wireless devices will serve the 7 billion people by 2017 [27]. Lucent technology, and other energy efficient CR-MAC protocols [28] [25] [29] [30], indicates that the utilisation of the transmitting energy is higher (or sometimes double) than that of the receiving energy for any data size of the wireless network. The authors in [31] [32] [33] also believe that a large amount of energy is consumed during the processing and transmitting activity of the SUs. The processing energy is consumed by the detection of the free time over the CCH, and other signal processing activities, before the communication begins. There are multiple techniques used to minimise energy consumption at the MAC layer, which have been discussed in [34] [35] [32] [36] [37] [33] [38] [39] [40]. It is to be noted that the unnecessary control frames handshake over the CCH, and a large number of re-transmissions over the DCHs, utilise large amounts of transmitted energy in the CRAHNs. The consumption of unnecessary transmitted energy decreases the efficiency of the network.

3. Proposed model of CRIoT-MAC protocol

CR-MAC protocols exchange their control frames, such as Availability of Control Channel (ACL), Acknowledgement (ACK), Ready to Sent (RTS) and Clear to Sent (CTS) over the DCCH and non-DCCH. As discussed above in this paper, it is assumed that SUs exchange control information over the DCCH which is always reliable and available and may be owned by the service provider. The control information is a pre-requisite for all CR nodes before switching DCHs. The properties of selected CR-MAC protocols have been presented and their features and parameters are shown in Table 2.3. These can help develop and design new CRIoT-MAC protocol to overcome the existing shortcomings in the CRAHNs as shown in Figure 3. The next subsection presents the proposed network model of the RECR-MAC protocol.

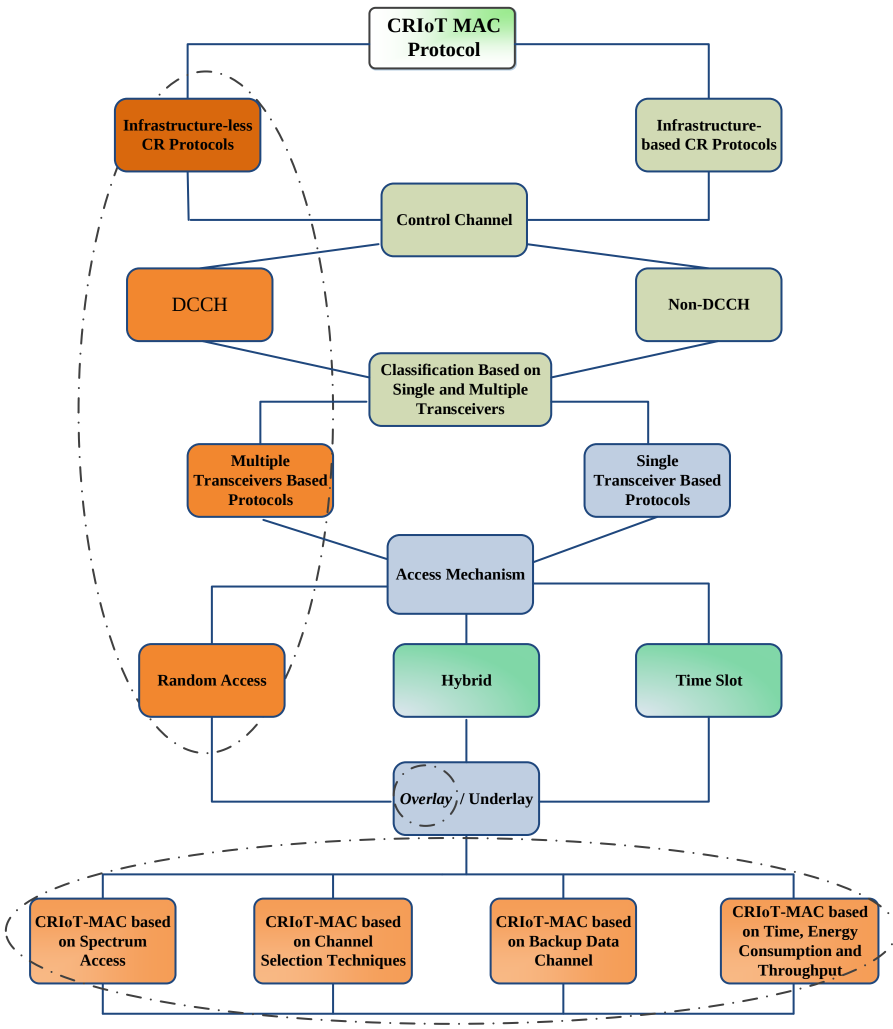

Figure 3: Flow of CRIoT-MAC protocols

3.1. RECR-MAC protocol - network model

CR technology is anticipated to offer solutions to the problems experienced on wireless networks that result from limited available spectrum bands and inefficient, by opportunistically exploiting the existing wireless spectrum bands [41]. In this section, a network model is presented based on how SUs use the CRIoT network. The proposed CR multi-channel network scenario, presented in Figure 4, is without a centralised entity, and network operations such as spectrum sensing, channel selection strategy and switching to BDC are performed by the SUs. The proposed network model is composed of two sets of users: the PUs can access their respective licensed spectrum bands without permission and their activities have a direct impact on the performance of the SUs and play a vital role in the channel selection decision. It is assumed in this study that the PUs activity can be modelled as a continuous process, known as alternating ON (i.e. the PU is in transmitting state or the ON state) and OFF (i.e. PU is not in transmitting state/the OFF state) Markov renewal process. The SUs record the ON/OFF activity of the PUs for the period of time in which the channel can be utilised effectively by the SUs without generating harmful interference to the PUs. It is further assumed that the SUs use the DCCH, which is always dedicated and may be owned by the service providers to exchange their control frames.

3.2. RECR-MAC protocol - operational framework

In this subsection, the operability of the RECR-MAC protocol for CRIoT is discussed with the assistance of the flowchart depicted in Figure 5, where it is classified into four phases:

PHASE I: In the startup stage, a SU adopts the IEEE 802.11 DCF, which is the fundamental MAC technique for accessing the channel in the Wireless Local Area Networks (WLAN). The DCF mechanism employs a CSMA/CA with a binary exponential Back Off (BO) algorithm to sense the wireless channel and gain access to the CCH. The Beacon Time (BT) includes the control and data communication time for the SUs. Figure 5 shows that the SU must wait a short

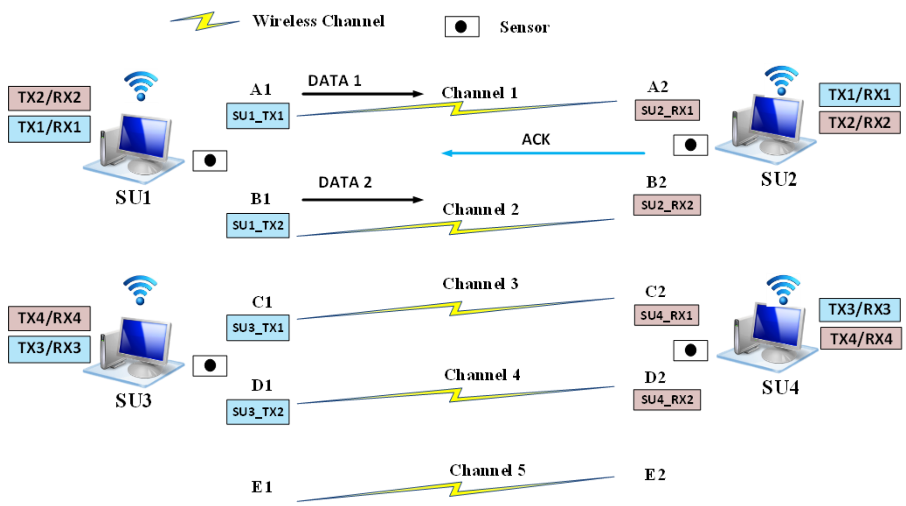

Figure 4: Network model consists of PUs, SUs, data channels, sensors, TXs and RXs

while before transmission to avoid collision, even though the channel is idle; this is known as Inter Frame Spacing (IFS). In wireless adhoc networks, IFS has two intervals with different priorities, namely the Distribution Inter-Frame Space (DIFS) and Short Inter-Frame Space (SIFS). The value of SIFS is smaller than DIFS, demonstrating its priority over other transmitting nodes. If the medium is observed as being idle for longer than the DIFS, then the cognitive nodes can transmit the frames. Alternatively, if the medium is observed as busy, the SU performs random BO by selecting a BO counter, which is not greater than the interval called the Contention Window (CW). The value of CW size has to be reset before and after every successful communication between the nodes. The BO counter decreases its value after the channel is found idle, and when the BO counter reaches zero the SUs can access the channel to exchange information.

PHASE II: In this phase, the flow of the protocol splits into two sub-phases: 1) the available SU can transmit/receive the Available Channel List (ACL) frame, which is a modified version of Ready to Send (RTS) frame, to/from the other SU within the range; or 2) if the SU receives the ACL, then the SU replies with Acknowledgement of the ACL (AACL) frame, a modified version of the

Clear to Send (CTS), to the sender SU. Then a pair of SUs must exchange the control frames such as ACL and AACL in order to meet the following constraint:

$$\mu \geq 2 \tag{1}$$

Where μ is the number of available white spaces for simultaneous communication among the SUs. The SUs must reserve two free spaces for the data communication known as Primary Data Channel (PDC) and Backup Data Channel (BDC).

PHASE III: In this phase, if no ACL frame is found, then it is assumed that the SU will launch the ACL itself. After the SIFS time, if the SU successfully receives the AACL frame, then it must satisfy the criteria established in Equation 1. If the SU is unable to receive the AACL then it must wait until the expiration of the BT. Moreover, when neighbouring SUs pick up the communication between the active SUs, they then suspend their transmission for a period of time called the Network Allocation Vector (NAV). In other words, neighbouring SUs are forbidden from accessing the DCCH, until the active SUs complete their transmission and switch to the DCHs. The complete process is called Virtual Carrier Sensing (VCS), and provides updated information to the sender and receiver which is to be reserved for the next communication.

PHASE IV: It is important to note that although the reservation of the two white spaces for the SUs gives the appearance of a loss of white space, in reality it simply reduces the network convergence time by switching to the BDC if the PU returns during the communication. It also reduces the RECR-MAC protocol rescanning time, which in turn may help the SUs conserve energy, thereby reducing the computational cost. Therefore, on the basis of PHASE II and PHASE III, when the SU has satisfied Equation 1, it switches to a DCH for data communication.

The novel contributions in this subsection are: when the CRAHNs are initialised, both selected DCHs are considered PDCs. If one of the DCHs become unavailable due to the PUs return, the traffic on the affected channel switches to the other DCH, which behaves as a BDC in regard to the affected traffic and continues the communication without restarting the entire process. If no PU returns during the data communication over the PDCs, then the SUs' receiver must send an ACK message to conclude communications between the SUs.

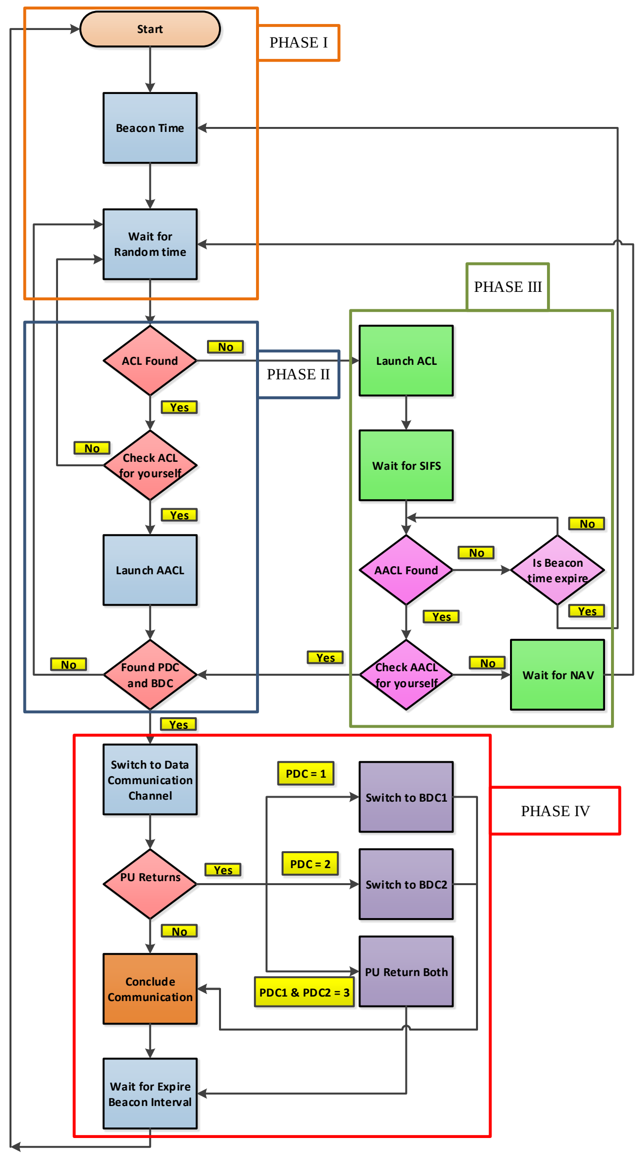

Figure 5: Operational framework of the RECR-MAC protocol with phases

4. Impact of contributing factors over the energy consumption for RECR-MAC

As discussed above, it is imperative to design the proposed RECR-MAC protocol to use less transmitted energy with high throughput. The RECR-MAC protocol utilises the contributing factors which helps to propose the effectiveness of CRIoT network:

4.1. Reducing number of handshaking over control and data channels

The successful exchange of the control information permits the SUs to start the communication over the DCHs. However, the situation gets critical if the SUs are unable to exchange their control information, which requires restarting the control process. As previously discussed, some protocols utilise additional handshaking over the control and data channels to avoid the restarting process. For example, some CR-MAC protocols (such as CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC) require 4 or 6 or more numbers of control and data frames in order to exchange their information. The additional number of control and data frames requires a greater number of handshakes over the control and data channels, which requires extra transmitting time to process these frames. This consumes additional transmitted energy. Furthermore, the SWITCH-MAC and RMC-MAC protocols require additional handshaking if the PU returns over the DCH during the data communication. Therefore, the framework of the RECR-MAC protocol has been designed to overcome the existing shortcomings, without degrading the reliability and effectiveness of the proposed protocol. The RECR-MAC protocol has introduced two-way handshaking over CCH, and two-way handshaking over DCH, irrespective of whether the PU returns or not during the communication. Figs.3 and 4 demonstrates the benefits of reducing the number of handshakes over the control and data channels [42] [43].

4.2. Minimising the size of control frames

Based on the above discussion, it is important to optimise the control frames by avoiding and reducing unnecessary fields. The optimisation of the control frames in an intelligent manner requires reducing the communication time among the SUs. This has a direct influence on the energy consumption in the CRAHNs, as shown in Fig. 5. Moreover, the following section of the numerical example of the performance evaluation reveals the benefits of saving transmitted energy based on reducing the size of the control frames. The operation of benchmark CR-MAC protocols provides more or less similar functions, including avoiding collisions and the hidden terminal problem, high throughput, and re-establishing the connection if PU returns, etc. The RECR-MAC protocol efficiently designs the control frames to handle collisions and hidden terminal problems, and to reduce re-transmission based on channel selection criteria. It also consumes the least communication time between the SUs over the control and data channels, thus saving transmitted energy. To conclude, by reducing the size of the control frames, less communication time is required among the SUs in order to exchange the control information over the CCH, eventually saving greater amounts of energy in the CRAHNs [44]. Figure 6 shows the trade-off between communication time and energy utilised. In this paper, sections 6 and 7 discuss in-depth process of reducing the communicating time among the SUs which helps to save the energy in the entire network.

4.3. Reducing re-transmission among SUs

The aim of CR technology is to enable the SUs to select and utilise the spectrum bands not in use by the PUs. If the PU returns to its licensed channel, then the SU switches to unavailable alternative channel without any interference to the PU. The majority of the CR-MAC protocols discussed in the literature review are unable to address the re-claiming of the PU, along with the restarting, searching and scanning of the other available spectrum bands and re-transmission over the control and data channels. This significant feature of the CR-MAC protocol has not been intensively researched. It is a procedure

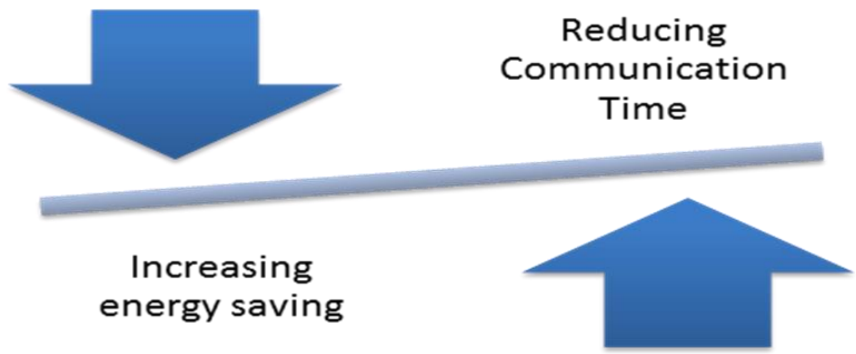

Figure 6: Relation of communication time vs. energy saving

that consumes not only additional time, but also utilises additional energy due to the re-transmission of the control and data frames. As discussed earlier, the selected characteristics of the RECR-MAC protocol provides an advantage lacked by other CR-MAC protocols. The RECR-MAC protocol introduces the channel selection criteria, which selects reliable channels with the least PU activity in order to minimise the probability of interference between the SUs and PUs. Also, the RECR-MAC protocol is able to deal effectively with the return of the PU over the licensed spectrum band and re-establish the SUs communication without re-starting the entire process. Selecting the reliable channels, and switching to the BDC if PU returns, saves additional energy and reduces the wait time of the SUs to exchange their information. Thus, the effective framework and design of the RECR-MAC protocol provide an opportunity for the SUs to initiate their communication in the CRAHNs, and if any PU returns over the DCH, the BDC is available to avoid re-transmission. Therefore, CR technology requires the RECR-MAC protocol features in order to avoid the search for the free channel and additional re-negotiations over the control and data channels [45].

5. Analysis of energy saving between RECR-MAC and benchmark CR-MAC

As discussed in the sections above, the CR network consumes high transmitted energy as compared to the energy consumed during processing and receiving. The focus of this paper is therefore to reduce the transmitted energy (E) consumption of the RECR-MAC protocol, then compare this with other benchmark CR-MAC protocols (such as CREAM-MAC, DSA-MAC, SWITCH-MAC, and RMC-MAC) over the control and data channels. The transmitting energy is calculated by using Equations (1) and (2) for the RECR-MAC and benchmark protocols without, and with, BDC.

$$E_{without\_PU\_Return} = \int_0^{T1} P_1(t)\, dt \tag{2}$$

$$E_{with\_PU\_Return} = \int_0^{T2} P_2(t)\, dt \tag{3}$$

Where T1 and T2 are the total communication times of RECR-MAC and other benchmark CR-MAC protocols over control and data channels without and, with a BDC, respectively. The values of P1 and P2 represent the power consumed during the transmission of control and data channels without, and with, a BDC. The total communication time of each protocol is calculated based on the physical layer parameters, as discussed in the previous section. The transmitted power of each SU is set to 100 mW [11]. The average transmitted energy is calculated for each protocol without, and with, BDC based on the values as summarized in Tables 1 and 2. The analytical results obtained by using Equations (1) and (2) and the values of Tables 1 and 2 are portrayed in Figures 7 and 8 with, and without, BDCs. The average energy consumed by RECR-MAC protocol is less when compared with other benchmark CR-MAC protocols with a payload of 1000 bytes, 500 bytes and 50 bytes respectively.

Table 1: Communication time (in bytes) of CR-MAC protocols without BDC

	1000 **B**	500 **B**	50 **B**
$T_{RECR-MAC}$	800	618	455
$T_{CREAM-MAC}$	1216	853	526
$T_{DSA-MAC}$	1210	847	520
$T_{SWITCH-MAC}$	1186	821	496
$T_{RMC-MAC}$	1163	803	477

Table 2: Communication time (in bytes) of CR-MAC protocols with BDC

	1000 **B**	500 **B**	50 **B**
$T_{RECR-MAC}$	1169	805	478
$T_{CREAM-MAC}$	1689	1325	999
$T_{DSA-MAC}$	1655	1291	965
$T_{SWITCH-MAC}$	1190	826	500
$T_{RMC-MAC}$	1221	857	531

In Figure 8, the clear reason for this difference in energy utilisation is based on the optimisation of the number of control frames and the selection of reliable DCHs.

Moreover, by the introduction of the BDC, the RECR-MAC protocol does not need to re-establish the entire process and saves increased transmitted energy when compared to other benchmark CR-MAC protocols with a payload of 1000 bytes, 500 bytes and 50 bytes as shown in Figure 8. Multiple experiments have been conducted with different sizes of data in order to validate the performance of the RECR-MAC protocol and its comparison with other selected benchmark CR-MAC protocols.

The results in Figures 7 and 8 validate the proposition that the proposed framework of the RECR-MAC protocol is applicable for multiple sizes of payloads. By considering 1000 bytes for communication, the RECR-MAC protocol saves approximately 35%, 33%, 32% and 31% energy without PU returns over

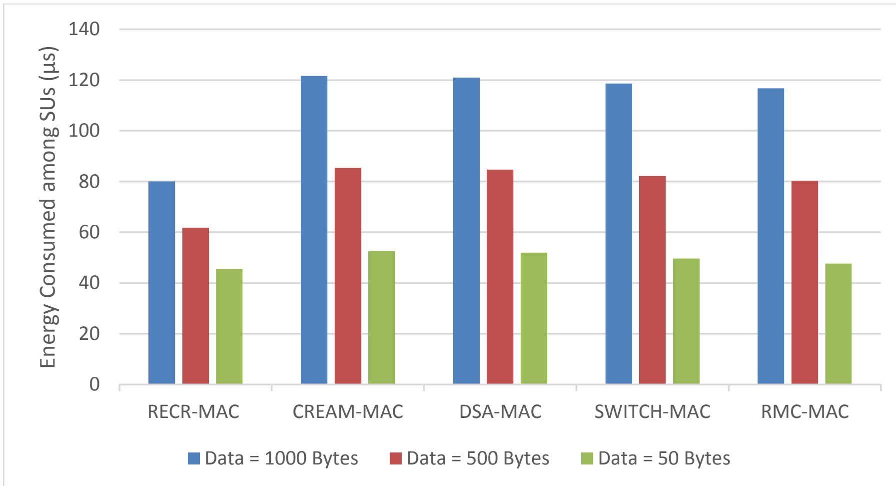

Figure 7: Energy consumed among SUs (μs) for data = 1000, 500, 50 Bytes (No PU returns)

the data channels during the communication as compared to CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols respectively. RECR-MAC protocol also saves approximately 30%, 29%, 2.5% and 6% energy, even though PU returns their respective data channels during the communication, as compared to CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols respectively. The energy consumption during the transmission of control and data information proves that the RECR-MAC protocol is an energy efficient protocol and a useful contribution in the area of CR technology. Moreover, the framework of the RECR-MAC protocol is suitable for developed countries, where energy saving is a major challenge, and performs in an effective and efficient way, as compared to the other benchmark CR-MAC protocols adopted for the purposes of comparison. Thus, it concludes that the introduction of the optimization of the control information, and BDC techniques, helps to utilise less energy during the transmission of the data over the control and data channels, as compared to other CR-MAC protocols.

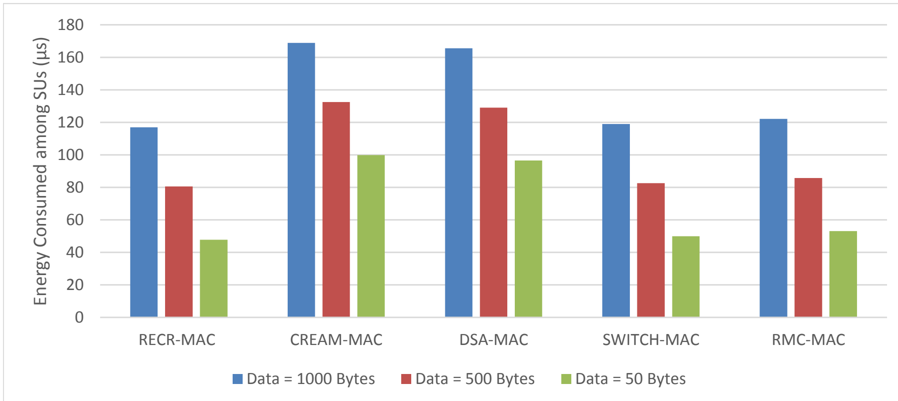

Figure 8: Energy consumed among SUs (μs) for data = 1000, 500, 50 Bytes (PU returns)

6. Impact of contributing factors over the performance of throughput for RECR-MAC

Throughput is another contributing factor in the analysis of the performance of the RECR-MAC protocol in the CRAHNs. In related studies, the majority of researchers has discussed and computed throughput: it is described as the average amount of successful data delivery over a wireless channel, i.e. "data transmitted per unit time". However, the throughput can be affected by multiple factors during the exchange of control and data information. These include the availability of the CCH, the probability of access to the CCH, the number of handshakes over the control and data channels, the size of the control frames, the selection criteria of the DCHs, the available number of DCHs with respect to the number of SUs, the number of successes and failed acknowledgements, and the ON/OFF time of the PU returns. In this paper, the communication time among the SUs plays a vital role and directly impacts the performance on the CRAHNs in terms of energy consumption and throughput. If SUs take more than the expected communication time, then this decreases the efficiency of the CRAHNs in terms of energy consumption and throughput of the network. The throughput of the proposed RECR-MAC protocol can be affected by multiple parameters, as shown in Table 3. These parameters are directly related to each other, and may increase and decrease the throughput of the RECR-MAC protocol. For example, the number of re-transmissions increases the communication time, which eventually contributes to the delay. The probability that the SUs are unable to continue the communication if PU returns also increases delay and decreases overall throughput of the CRNs.

6.1. Minimisation of channel switching among SUs

The process of channel switching among SUs plays a vital role in the performance of the CRN. Frequent returns of PUs and the selection of bad quality channels require a high number of re-connections among the SUs in order to accomplish the task. High numbers of re-connections maximises the rate of the channel switching and consume significant time for the successful exchanging of control and data frames. The high communication time consumes large amounts of transmitting power among the SUs, which reduces network throughput [46]. However, RECR-MAC channel selection criteria overcome this issue by selecting reliable primary and backup data channels, which may require less (or even no) channel switching activity.

6.2. Secondary Users transmission probability

CR technology is an opportunistic technology. The probability that the SUs can transmit over the control and data channels therefore heavily contributes to the performance of the CR-MAC protocols, including communicating time, energy consumption, delay and throughput. In a contention based CR environment, all SUs share the same medium to be transmitted. Therefore, there is competition among all participant SUs to win the medium. A large number of SUs may increase the probability of collision amongst each other in the CRAHNs. In the RECR-MAC protocol, the channel access scheme by SUs is based on the IEEE 802.11 MAC protocol. The SUs only begins transmitting after an idle period equal to the Distributed Inter Frame Space (DIFS). If a channel is occupied by another SU, the participating SU randomly selects a back off interval from 0, W-1, where W represents the size of the Contention

Window (CW). The value of the CW is taken from the set: 16, 32, 64, —-, 512. For simplicity, the value 32 is used for the numerical and simulation purposes. There is a probability that SUs may collide during the contention process. It is important to consider that the PU always has a higher priority than the SUs, based on their right to use the licensed channel any time, even though communication is continuing among the SUs. It is also considered that each SU always has the information to transmit at any time. The probability of collision during the contention process for accessing the CCH among SUs has been derived from [47] as follows:

$$P_c = \left(1 - \frac{1}{CW}\right)^{NSU_S - 1} \tag{4}$$

Where Pc is the probability of collision and N SUs represents the number of SUs attempting to access the CCH, it is the standard process in IEEE 802.11b that a large number of SUs increases the probability of a collision. The size of the CW increases to the maximum value denoted as CWmax. Based on Equation (3), the probability that the SUs may not collide with each other and successfully access the DCCH can be represented as:

$$P_s = 1 - \left(1 - \frac{1}{CW}\right)^{NSU_S - 1} \tag{5}$$

where P_s is the probability of successful access to the CCH by the SUs.

6.3. Additional contributing factors

Multiple additional factors influence the performance of RECR-MAC protocol. There is always a trade among the multiple factors while designing the framework of a CR-MAC protocol. This leads to the researcher having compromise between factors, according to the design and requirements, including: channel quality, primary and backup data channels selection criteria communication time energy saving delay, the number of transceivers, the number of control and data channels hardware costs and throughput, etc. The following are the contributing factors in the RECR-MAC protocol and its relationship with throughput [48] [49] [50].

a) Number of Transceivers: The number of transceivers can be represented as T_xR_x. Additional transceivers transmit additional data, which eventually increases network throughput.

b) Number of Data Channel(s): The Number of Data Channels can be represented as DCH(s). Transmitting over multiple DCHs simultaneously decreases transmission time and signal power and increases the transmission rate of data, also increasing network throughput.

c) Payload: Payload can be represented as P_L. A larger amount of data to be transferred across the multiple DCHs increases the network throughput as compared to other CR-MAC protocols. If the PU returns during the communication, the PDC's data switches to BDC and continue the communication instead of re-start the entire process.

d) Data Rate: Data rate can be represented by D_{Rate}. The D_{Rate} for the control and data channels is set to 11 Mbps as constant.

e) Probability of Successful Access of Dedicated Control Channel: The probability of successful access of DCCH can be represented as P_s. Higher probability of successful completion of the frames over the DCCH will result in faster initialisation of data communication. Faster network initialisation reduces communication time and increases network throughput.

f) Number of Secondary Users: The Number of SUs can be represented as NSU_s, where n represents the number of SUs. Additional SUs contending for the CCHs may reduce the chances in order to seize the opportunity for accessing these channels.

g) Communication Time: Communication time during the control and data channels can be represented for each protocol such as $T_{(RECR-MAC)}$ for RECR-MAC protocol, $T_{(CREAM-MAC)}$ for CREAM-MAC, respectively. Higher communication time decreases network throughput, and vice versa.

h) Probability of False Alarm: Probability of false alarm can be represented as P_{FA}. Minimising the value of P_{FA} provides the maximum opportunity for the SUs to access the spectrum and improves network reliability by selecting unoccupied and reliable channel(s). The value of the probability of false alarm is set to 0.1 as a constant. The detail of the P_{FA} will be discussed in Section 6.2.

The above factors from a) to e) are directly proportional to the network throughput. The above factors from f) to h) are inversely proportional to the network throughput.

7. Evaluation and results

Internet of Things (IoT) is based on heterogeneous networks, which is being extensively deployed for advanced and emerging services. However, the existing infrastructure requires a reliable connectivity and uninterrupted communication among the devices. In this evaluation, we address this problem through reliable selection of the channels among the SUs which enhances the communication and increases network throughput.

In this section, an analytical model is developed, based on the contributing factors above to analyse the throughput of the RECR-MAC protocol with benchmark CR-MAC protocols under the saturation condition.

7.1. Parameters for the throughput analysis of RECR-MAC protocol

For the convenience of presentation, Table 3 lists the contributing parameters for the throughput analysis of the RECR-MAC protocol, and its comparison with other benchmark CR-MAC protocols. The contributing factors impact the performance of the throughput for the CRAHNs which utilise the design of analytical models for RECR-MAC protocol. Due to the cognitive behaviour of RECR-MAC protocol, it could be utilized to improve the performance of the relevant technologies such as Smart City, IoT and Mobile technologies such as LTE and 5G.

7.2. Throughput analysis of the RECR-MAC with benchmark CR-MAC protocols

It is noted that the concept of CR was introduced to manage communication among the SUs without licensing, due to the unavailability and the shortage of

Table 3: Parameters for the throughput analysis of RECR-MAC protocol

Parameter	**Proportionality and notations**	**Relations with Throughput**
Number of Transceivers	$\alpha T_X R_X$	Additional transceivers transmit large amount of data, so increasing network throughput
Number of Data Channels	$\propto DCHs$	Transmitting over multiple data channels simultaneously increases the throughput
Payload	$\propto P_L$	Larger amount of data across multiple data channels increases throughput
Data Rate	$\propto D_{RATE}$	Higher data rates allow large amount of data be transmitted, increasing network throughput
Probability of successful access of control channel	$\propto P_S$	Higher probability of successful completion increases network throughput
Number of Secondary Users	$\propto \frac{1}{NSU_s}$	Increased number of SUs contending for the control channels may reduce the chance to size an opportunity to access the control channel, so reducing network throughput
Communication Time	$\propto \frac{1}{T}$	Higher communication time decreases the network throughput and vice versa.
Probability of False Alarm	$\propto \frac{1}{P_{FA}}$	High probability of a false alarm provides the minimum opportunity to the SUs to access the spectrum,which decreases the network throughput.

the licensed spectrum. Therefore, consideration of the saturation condition is a valid assumption in this paper for the CRAHNs. If each SU is equipped with a sensor and two transceivers, the RECR-MAC protocol is capable of reserving a number of free channels and utilizing these channels effectively based on the number of SUs participating in the network. The throughput for the SUs is denoted by η. The following equations help to measure the performance of the throughput for the proposed protocol and its comparison with benchmark CR protocols.

In Equation 6, impact of throughput is directly proportional to number of transceivers, DCHs involved in the communication among the SUs, payload, data rate of the channel, and the probability of no collision among the SUs for accessing the CCH:

$$\eta \propto T_x R_x * DCHs * P_L * D_{Rate} * Ps \tag{6}$$

In Equation 7, throughput is inversely proportional to the number of contributing SUs, total communication time of each protocol and probability of a false alarm:

$$\eta \propto \frac{1}{NSU_S * T_{CR-MAC} * P_{FA}} \tag{7}$$

Equation 8 calculates the throughput for different numbers of SUs without and with PU returns for the RECR-MAC and benchmark CR-MAC protocols, where payload set as 1000B, 500B and 50B as shown in following figures:

$$\eta \propto \frac{T_x R_x * DCHs * P_L * D_{Rate} * Ps}{NSU_S * T_{CR-MAC} * P_{FA}} \tag{8}$$

The next subsections analyse and measure the performance of the throughput for the CRAHNs: i) throughput analysis without PU interference and ii) throughput analysis with PU interference.

7.3. Throughput analysis without PU interference

The interference generated by the return of the PUs heavily contributes to the performance of the CRAHNs. The SUs observe the activity of the PUs, then select the most reliable DCHs based on the channel selection criteria, then effectively utilise the free time for their communication. As discussed above, the value of P_{FA} is never equalled to zero. Figures 9 to 11 demonstrate that the throughput value changes with different numbers of SUs. When there are only two SUs participating in the CRAHNs for their communication, then a high throughput is achieved, due to less competition among the SUs to access the CCH.

The RECR-MAC protocol reduces less communication time and energy with higher throughput as compared to benchmark CR protocols. Few samples have been discussed in percentages to show the validity of the proposed protocol when there is no PU returns during the communication. For example, in Figure 9, when considering 2 SUs for 1000 bytes, the throughput of RECR-MAC protocol is 64% higher than SWITCH-MAC protocol. In Figure 10, the throughput of RECR-MAC protocol is 61% higher than DSA-MAC protocol for 500 bytes. Similarly, the throughput of RECR-MAC is 54% higher than RMC-MAC protocol for 50 bytes as shown in Figure 11. The high throughput of the RECR-MAC protocol is expected higher than benchmark CR-MAC protocols due to the fact that when there are high numbers of SUs contending for CCH there are fewer chances to seize the opportunity.

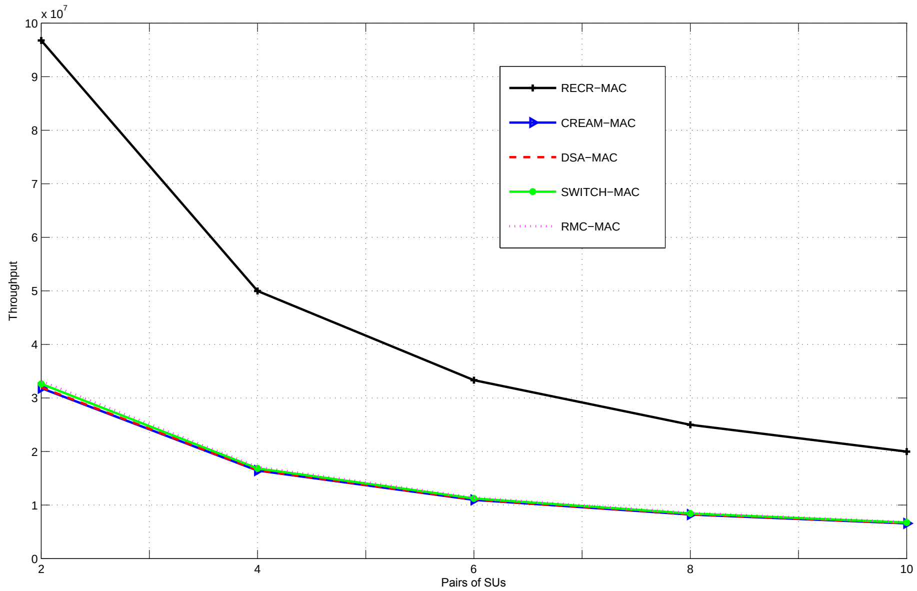

Figure 9: Throughput vs. pairs of SUs for data = 1000 bytes (No PU returns)

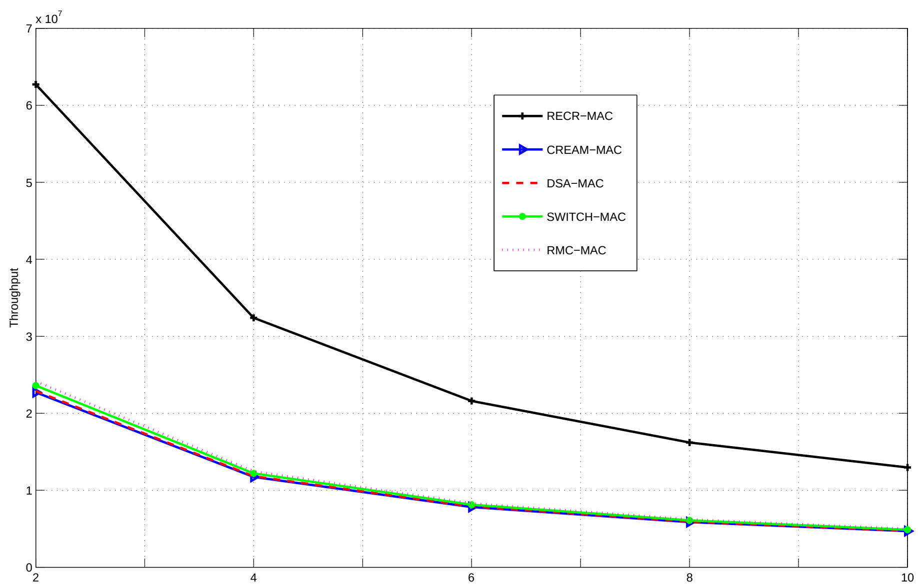

Figure 10: Throughput vs. pairs of SUs for data = 500 bytes (No PU returns)

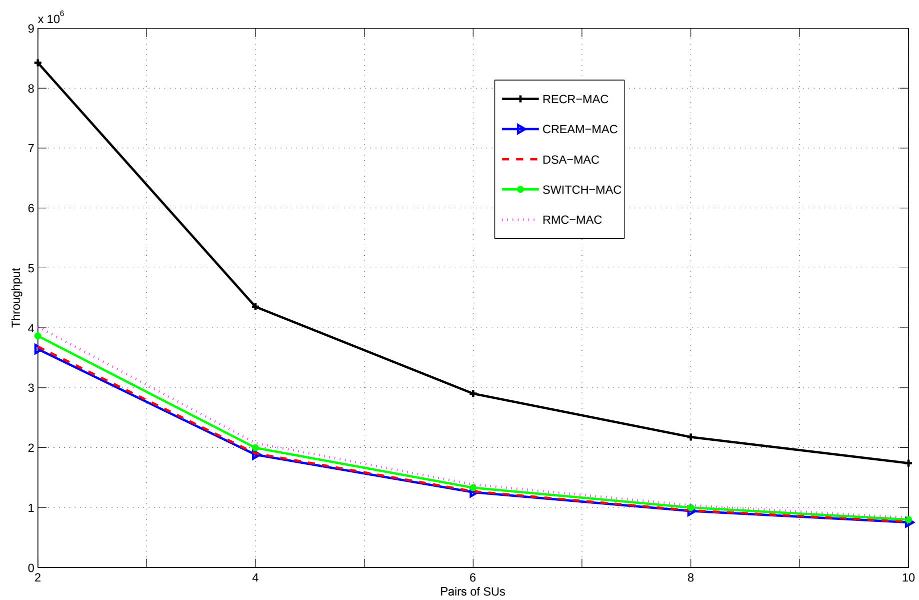

Figure 11: Throughput vs. pairs of SUs for data = 50 bytes (No PU returns)

7.4. Throughput analysis with PU interference

As discussed above, the frequent PU returns during the communication, massively reduces the performance of the CRAHNs. To overcome PU interference, the BDC is introduced for the proposed RECR-MAC protocol, which re-establishes the connection among the SUs if the PU returns to its licensed DCHs during the communication. Table 2 is also utilised for the analysis of the RECR-MAC protocol and its comparison with other CR-MAC protocols, based on Equation (7) with different payloads. Figures 12 to 14 show the analysis for the RECR-MAC protocol, and its other benchmark CR-MAC protocols.

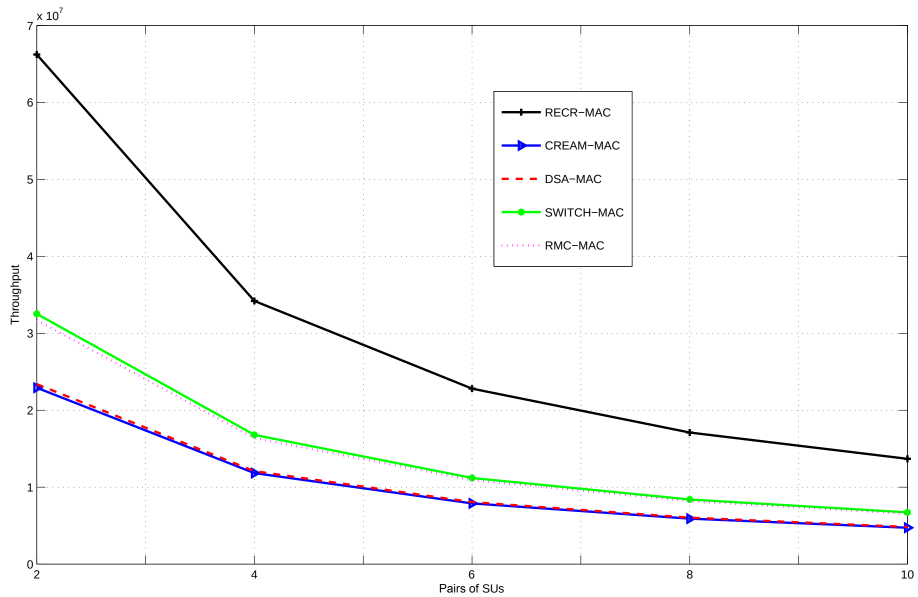

Figure 12: Throughput vs. pairs of SUs for data = 1000 bytes (PU returns)

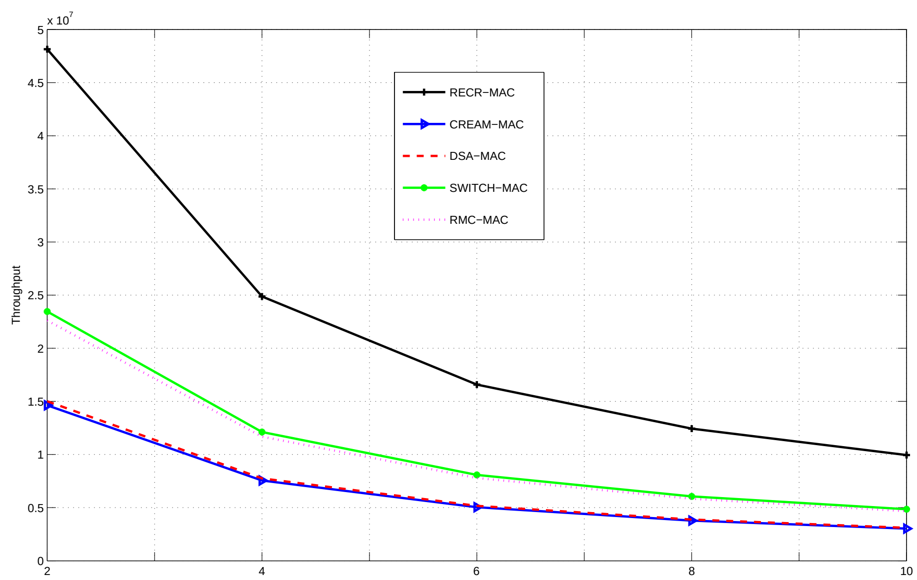

Figure 13: Throughput vs. pairs of SUs for data = 500 bytes (PU returns)

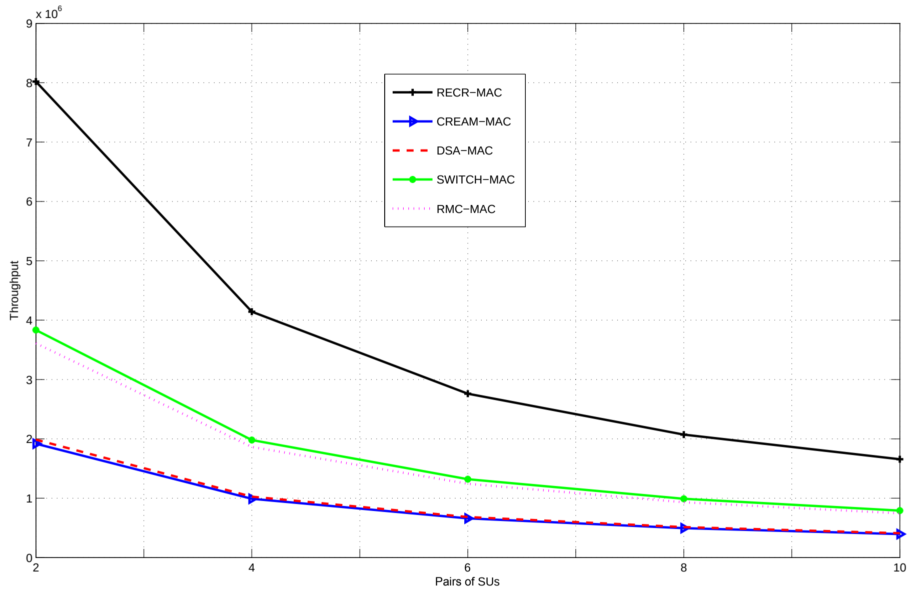

Figure 14: Throughput vs. pairs of SUs for data = 50 bytes (PU returns)

Figures 12 to 14 demonstrate that the proposed RECR-MAC protocol has a high throughput for the different numbers of SUs. These results are expected based on the BDC technique adopted by the RECR-MAC protocol. Moreover, CREAM-MAC and DSA-MAC do not use BDCs; hence if PU returns during the data communication, both protocols re-start the entire process. SWITCH-MAC and RMC-MAC have adopted BDCs without considering the situations; if PU returns over the PDCs, both protocols switch to BDCs. If the BDCs are already occupied, then both CR-MAC protocols are obliged to re-start the entire process, similar to CREAM-MAC and DSA-MAC. However, the RECR-MAC protocol utilises two DCHs simultaneously, instead of a single DCH for communication and, if PU returns on either of the DCHs, both DCHs act as a backup to each other and avoid the re-starting process.

This introduction of the BDC pattern saves communication time, transmitting energy and increases throughput as depicted in Figures 12 to 14. Few samples have been discussed in percentages to show the validity of the proposed protocol when there PU returns during the communication of 10 SUs. For example, in Figure 12, when considering 1000 bytes, the throughput of RECR-MAC protocol is 71% higher than DSA-MAC protocol. In Figure 13, the throughput of RECR-MAC protocol is 50% higher than SWITCH-MAC protocol for 500 bytes. Similarly, the throughput of RECR-MAC is 76% higher than CREAM-MAC protocol for 50 bytes as shown in Figure 14. It is noted that the RECR-MAC protocol has ability to achieve higher throughput as compared to the benchmark protocols due to the integration of proposed channel selection criteria and BDC.

8. Conclusion

In this paper, we have introduced the energy efficient Cognitive Radio communication for Internet of Things. The introduction of the selection of reliable DCHs for the IoTs devices, and its integration with BDC, has reduced communication time among the SUs, which plays a vital role, directly impacting the performance of the CRAHNs in terms of energy consumption and throughput. The importance of the energy consumption for the RECR-MAC and benchmark CR-MAC protocols have been analysed through the consideration of multiple factors. The analytical analysis demonstrates that the average energy consumed by the RECR-MAC protocol is lower in comparison to other benchmark CR-MAC protocols, with payloads of 1000 bytes, 500 bytes, and 50 bytes respectively without and with PU interference. Furthermore, an analytical model has been developed, based on multiple factors to analyse the throughput of the RECR-MAC protocol with benchmark CR-MAC protocols without, and with, PU returns. Thus, the above results demonstrate that the RECR-MAC protocol has a high throughput in comparison to the benchmark CR-MAC protocols. In this paper, therefore, we also examine the other contributing features of the RECR-MAC protocol, such as transmitted energy and throughput.

9. Future work

In this paper, research has been carried out to investigate the shortcomings of the existing energy for CRIoT networks. The RECR-MAC protocol has been proposed to address such gaps discussed in above sections. The integration of the Cognitive Radio and IoT technology could provide direct benefits to a large number of wireless users. For example, social media applications such as Facebook and Twitter; chess and playing card gaming applications are not delay sensitive and their users could derive benefits from the proposed protocol. Big data management could be solved by using CRIoT application where cognitive users can transfer the information as a rely on large networks. Security aspects are crucial in order to protect the network communication amongst authorised SUs within the network. In order to prevent hacking and reduce damages to the users, security will be addressed using cross layer techniques. Moreover, mobile and Voice over Internet Protocol (VoIP) users could be able to make free calls by using the proposed CRIoT protocol. If cognitive features are enabled in any wireless device, this device is capable of detecting free space and utilising these applications and free calls.

References

[1] F. F. Qureshi, A. G. Baksh, Reliable cognitive radio multi-channel mac protocol for adhoc networks, in: Communications, Signal Processing, and their Applications (ICCSPA), 2015 International Conference on, 2015, pp. 1–6.

[2] M. T. Zia, F. F. Qureshi, S. S. Shah, Energy efficient cognitive radio mac protocols for adhoc network: A survey, in: 2013 UKSim 15th International Conference on Computer Modelling and Simulation, 2013, pp. 140–143.

[3] S. Mahmud, R. Iqbal, F. Doctor, Cloud enabled data analytics and visualization framework for health-shocks prediction, Future Generation Computer Systems 65 (2016) 169 – 181, special Issue on Big Data in the Cloud.

[4] F. Doctor, R. Iqbal, An intelligent framework for monitoring student performance using fuzzy rule-based linguistic summarisation, in: 2012 IEEE International Conference on Fuzzy Systems, 2012, pp. 1–8.

[5] N. Panwar, S. Sharma, A. K. Singh, A survey on 5g: The next generation of mobile communication, Physical Communication 18 (2016) 64–84.

[6] C. X. Mavromoustakis, A. Bourdena, G. Mastorakis, E. Pallis, G. Kormentzas, An energy-aware scheme for efficient spectrum utilization in a 5g mobile cognitive radio network architecture, Telecommunication Systems 59 (1) (2015) 63–75.

[7] D. Giusto, A. Iera, G. Morabito, L. Atzori, The internet of things: 20th Tyrrhenian workshop on digital communications, Springer Science & Business Media, 2010.

[8] L. Atzori, A. Iera, G. Morabito, The internet of things: A survey, Computer networks 54 (15) (2010) 2787–2805.

[9] A. AlEroud, I. Alsmadi, Identifying cyber-attacks on software defined networks: An inference-based intrusion detection approach, Journal of Network and Computer Applications (2016) –.

[10] T. Maniak, R. Iqbal, F. Doctor, C. Jayne, Automated sound signalling device quality assurance tool for embedded industrial control applications, in: 2013 IEEE International Conference on Systems, Man, and Cybernetics, 2013, pp. 4812–4818.

[11] Y. Zhang, J. Zheng, H.-H. Chen, Cognitive radio networks: architectures, protocols, and standards, CRC press, 2016.

[12] V. Chang, Y.-H. Kuo, M. Ramachandran, Cloud computing adoption framework: A security framework for business clouds, Future Generation Computer Systems 57 (2016) 24 – 41.

[13] V. Chang, Towards a big data system disaster recovery in a private cloud, Ad Hoc Networks 35 (2015) 65 – 82, special Issue on Big Data Inspired Data Sensing, Processing and Networking Technologies.

[14] N. Kumar, R. Iqbal, S. Misra, J. J. P. C. Rodrigues, M. S. Obaidat, Bayesian cooperative coalition game as-a-service for rfid-based secure qos management in mobile cloud, IEEE Transactions on Emerging Topics in Computing PP (99) (2016) 1–1.

[15] P. Vlacheas, R. Giaffreda, V. Stavroulaki, D. Kelaidonis, V. Foteinos, G. Poulios, P. Demestichas, A. Somov, A. R. Biswas, K. Moessner, Enabling smart cities through a cognitive management framework for the internet of things, IEEE communications magazine 51 (6) (2013) 102–111.

[16] P. Rawat, K. D. Singh, J. M. Bonnin, Cognitive radio for m2m and internet of things: A survey, Computer Communications.

[17] F. Wu, L. Xu, S. Kumari, X. Li, J. Shen, K.-K. R. Choo, M. Wazid, A. K. Das, An efficient authentication and key agreement scheme for multi-gateway wireless sensor networks in iot deployment, Journal of Network and Computer Applications (2016) –.

[18] M. M. Alves, L. Pirmez, S. Rossetto, F. C. Delicato, C. M. de Farias, P. F. Pires, I. L. dos Santos, A. Y. Zomaya, Damage prediction for wind turbines using wireless sensor and actuator networks, Journal of Network and Computer Applications (2016) –.

[19] M. Gast, 802.11 wireless networks: the definitive guide, " O'Reilly Media, Inc.", 2005.

[20] X. Zhang, H. Su, Cream-mac: Cognitive radio-enabled multi-channel mac protocol over dynamic spectrum access networks, IEEE Journal of Selected Topics in Signal Processing 5 (1) (2011) 110–123.

[21] R. Hasan, M. Murshed, A novel multichannel cognitive radio network with throughput analysis at saturation load, in: Network Computing and Appli-

cations (NCA), 2011 10th IEEE International Symposium on, IEEE, 2011, pp. 211–218.

[22] Y. Liu, S. Xie, R. Yu, Y. Zhang, C. Yuen, An efficient mac protocol with selective grouping and cooperative sensing in cognitive radio networks, IEEE Transactions on Vehicular Technology 62 (8) (2013) 3928–3941.

[23] M. Haddad, Y. Hayel, O. Habachi, Spectrum coordination in energy-efficient cognitive radio networks, IEEE Transactions on Vehicular Technology 64 (5) (2015) 2112–2122.

[24] S. Althunibat, M. Di Renzo, F. Granelli, Towards energy-efficient cooperative spectrum sensing for cognitive radio networks: an overview, Telecommunication Systems 59 (1) (2015) 77–91.

[25] J. Kokkoniemi, J. Lehtomäki, Spectrum occupancy measurements and analysis methods on the 2.45 ghz ism band, in: Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2012 7th International ICST Conference on, IEEE, 2012, pp. 285–290.

[26] M. Pickavet, R. Tucker, Network solutions to reduce the energy footprint of ict, in: European conference on optical communications (ECOC 2008), Brussels, Belgium, 2008, pp. 21–25.

[27] M. Page, M. Molina, G. Jones, D. Makarov, The mobile economy 2013, ATKearney.[Online] URL: http://www. atkearney. com/documents/10192/760890/The Mobile Economy.

[28] L. T. Sørensen, K. E. Skouby, D. Dietterle, A. Jhunjhunwala, X. Fu, X. Wang, User scenarios 2020: a worldwide wireless future, WWRF Outlook (4).

[29] L. M. Feeney, M. Nilsson, Investigating the energy consumption of a wireless network interface in an ad hoc networking environment, in: INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer

and Communications Societies. Proceedings. IEEE, Vol. 3, IEEE, 2001, pp. 1548–1557.

[30] F. F. Qureshi, A reliable and energy efficient cognitive radio multichannel mac protocol for ad-hoc networks.

[31] I. F. Akyildiz, B. F. Lo, R. Balakrishnan, Cooperative spectrum sensing in cognitive radio networks: A survey, Physical communication 4 (1) (2011) 40–62.

[32] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher, E. Hepsaydir, Cellular architecture and key technologies for 5g wireless communication networks, IEEE Communications Magazine 52 (2) (2014) 122–130.

[33] N. A. Pantazis, D. J. Vergados, D. D. Vergados, C. Douligeris, Energy efficiency in wireless sensor networks using sleep mode tdma scheduling, Ad Hoc Networks 7 (2) (2009) 322–343.

[34] S. Kamruzzaman, An energy efficient multichannel mac protocol for cognitive radio ad hoc networks, arXiv preprint arXiv:1009.4520.

[35] S. A. R. Zaidi, M. Ghogho, D. C. McLernon, A. Swami, Energy efficiency in large scale interference limited wireless ad hoc networks, in: Wireless Communications and Networking Conference Workshops (WCNCW), 2012 IEEE, IEEE, 2012, pp. 24–29.

[36] F. F. Qureshi, Energy efficient cognitive radio mac protocol for adhoc networks, in: Wireless Telecommunications Symposium (WTS), 2012, IEEE, 2012, pp. 1–5.

[37] H. Su, X. Zhang, Cognitive radio based multi-channel mac protocols for wireless ad hoc networks, in: IEEE GLOBECOM 2007-IEEE Global Telecommunications Conference, IEEE, 2007, pp. 4857–4861.

[38] C. Y. Chen, et al., An innovative knowledge management learning cycle by lego nxt for science education, International Journal of Innovative Computing Information and Control 8 (1B) (2012) 791–798.

[39] D. M. Khan, N. Saher, F. Shahzad, N. Mohamudally, A relative study of load balancing and management techniques in a distributed system: The iub case study, Science International 27 (4).

[40] L. Hesham, A. Sultan, M. Nafie, F. Digham, Distributed spectrum sensing with sequential ordered transmissions to a cognitive fusion center, IEEE Transactions on Signal Processing 60 (5) (2012) 2524–2538.

[41] A. A. Khan, M. H. Rehmani, A. Rachedi, When cognitive radio meets the internet of things?, in: Wireless Communications and Mobile Computing Conference (IWCMC), 2016 International, IEEE, 2016, pp. 469–474.

[42] P. Katiyar, K. Rajawat, Channel-aware medium access control in multichannel cognitive radio networks, IEEE Communications Letters 19 (10) (2015) 1710–1713.

[43] A. Azarfar, J.-F. Frigon, B. Sansò, Delay analysis of multichannel opportunistic spectrum access mac protocols, IEEE Transactions on Mobile Computing 15 (1) (2016) 92–106.

[44] M. Zareei, A. M. Islam, N. Mansoor, S. Baharun, E. M. Mohamed, S. Sampei, Cmcs: a cross-layer mobility-aware mac protocol for cognitive radio sensor networks, EURASIP Journal on Wireless Communications and Networking 2016 (1) (2016) 1–15.

[45] Y. Saleem, F. Salim, M. H. Rehmani, Routing and channel selection from cognitive radio networks perspective: A survey, Computers & Electrical Engineering 42 (2015) 117–134.

[46] S. Kamruzzaman, E. Kim, D. G. Jeong, An energy efficient qos routing protocol for cognitive radio ad hoc networks, in: Advanced Communication

Technology (ICACT), 2011 13th International Conference on, IEEE, 2011, pp. 344–349.

[47] D. M. Khan, M. Nawaz, A comparative study of single-step and multi-step data mining tools, Journal of Computing 4 (10) (2012) 26–41.

[48] S. Zou, L. Gui, X. Zhong, C. Wang, C. Tian, A delay-centric parallel multi-path routing protocol for cognitive radio ad hoc networks, Wireless Communications and Mobile Computing.

[49] M. Elmachkour, A. Kobbane, E. Sabir, J. Ben-othman, et al., Data traffic-based analysis of delay and energy consumption in cognitive radio networks with and without resource reservation, International Journal of Communication Systems 28 (7) (2015) 1316–1328.

[50] X. Huang, T. Han, N. Ansari, On green-energy-powered cognitive radio networks, IEEE Communications Surveys & Tutorials 17 (2) (2015) 827–842.