Efficient Discovery and Recovery of Common Control Channel in Cognitive Radio Wireless Ad-hoc Networks

Munam Ali Shah, Sijing Zhang and Carsten Maple

Department of Computer Science & Technology, University of Bedfordshire, Luton, LU1 3JU, UK; e-mail: {munam.shah, sijing.shang, carsten.maple}@beds.ac.uk

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Abstract

The most important aspect of cognitive radio (CR) networks is to search, scan, and access the control channel to advertise the free channel list (FCL) amongst the participating CR nodes. Subsequent communication could not take place until there is an access to a well-known and agreed upon control channel to dialogue the initial configuration. In this paper, a novel protocol for searching, scanning, and accessing the control channel is proposed. The protocol consists of two levels of selection: rapid channel accessing and reliable channel accessing. In rapid channel accessing, nodes quickly and efficiently converge to a newly found control channel. In reliable channel accessing, switching to the backup control channel is performed when necessary. Furthermore, our reliable channel accessing allows CR nodes to access more than one control channel simultaneously. We evaluate the performance of the proposed approach through analytical modelling. The performance results show that our protocol can achieve efficient channel access time and fairness.

Keywords: MAC protocols, common control channel, co-operative communication, channel searching.

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1 Introduction

The most important resource for wireless communications is radio spectrum [1]. Recent studies have revealed that spectrum is largely under-utilized most of the time [2]. Cognitive radio (CR) technology [3–5] has emerged as a promising solution to address the problem of spectrum shortage and inefficiency of its utilization in wireless networks. The CR technology significantly increases the spectrum efficiency by giving opportunistic access of the frequency bands to the unlicensed users (also called CR users or secondary users, SUs). Licensed users (also called primary users, PUs), while not transmitting, create spectrum holes, or white spaces in the spectrum. SUs use these white spaces owned by the PUs and opportunistically access these spectrum holes without interfering to PUs. In this paper, a decentralized scenario in ad-hoc cognitive radio networks (CRN) is considered.

A control channel is required by CR nodes to exchange the free channel list (FCL) and to dialogue initial configuration [6, 15]. Before SUs could start sending and receiving data, they exchange information on the control channel. This information could include sending and receiving FCL requests, availability of a spectrum hole and the time to be taken for the communication to last. CR nodes must have the capability to identify the characteristics of an unoccupied channel such as its available time and bandwidth, etc. Since PUs could arrive on their own spectrum bands, SUs must be able to sense the PUs claim in time and must quit the transmission on the occupied channels to avoid interference to PUs. If a PU claim is sensed during a communication, CR nodes must suspend their transmission. Consequently, CR nodes have to switch to another unoccupied channel to resume the transmission or re-dialogue configuration on control channel to agree upon a new white space for subsequent communication. Therefore, channel sensing and channel accessing are two main operations of CRN. Channel sensing deals with information about vacant channels in the environment, creating FCL and detecting PU presence while spectrum accessing is to exchange control information on a well-known control channel and to transmit data on a white space before a PU claims. Channel sensing is the task of physical layer and would be beyond the scope of this paper. For the rest of this section, we discuss the design issues of channel sensing and channel accessing and then review some of the related studies.

1.1 Design Constraints

Design constraints for channel accessing for CR users include efficiency of control channel, efficiency of data channel and efficiency of vacating a channel.

- Efficiency of control channel: This is reflected by the time required for CR nodes to discover a common control channel. Subsequent communication amongst CR nodes could not occur until CR nodes are aware of a control channel that is available for all CR nodes. The control channel efficiency depends on the selection criteria for control channel. The control channel could be either well known and publically available, commonly called global common control channel (GCCC) which is usually in industrial scientific and medical (ISM) band, or it could be one of the most reliable and available white spaces (non-GCCC). The former category is 24/7 freely available for any wireless application with no licensing issues but suffers from the drawbacks such as saturation of the GCCC (since it is widely available for anyone, which imposes high computational cost from backing off), no traffic differentiation (QoS unaware) and security attacks like denial-of-service (DoS). The latter category of control channel has worse searching efficiency, but once the control channel is discovered by all CR nodes in the vicinity, nodes spend less time in exchanging control information and get ready quickly to transmit data. Some of the researchers do not delve into selection criteria of control channel and simply assume that a control channel has already been found and established [7, 8]. This assumption is too strong because finding a control channel is a challenging task in CRN and actual data transmission could only take place until a successful and secure FCL transaction has taken place on a well-known and agreed-upon control channel.
- Efficiency of data channel: Data channel efficiency is defined as the time required for two CR nodes to conclude transmission on a data channel. In high traffic loads of PUs, CR users send only one data frame and then vacate the channel. However, when the chances of PU claiming are low and CR nodes still have data to send, more than one data frames will be transmitted in one transaction. The data channel efficiency could be increased by using more than one data channel simultaneously [9, 10]. On the other hand, determining the length of a spectrum hole could also help increase data channel efficiency.

- Efficiency of vacating a channel: CR users must vacate the occupied channel when the PU claims in order to minimize the interference. The majority of the CR MAC protocols found in literature assume that nodes are aware of the presence of PUs. However, the unrealistic assumption is criticized because CR nodes cannot sense PU presence when transmitting and PUs cannot generate interruptive signals to SUs on occupied channels. The performance of both PUs and SUs largely depends on whether or not the PU activity can be sensed in a timely manner. Equipping CR nodes with sensors in conjunction with transceivers could help alleviate the assumption and are less costly than transceivers [7].

2 Related Work

One of the challenging issues in CRN is to design an efficient MAC protocol that is capable of empowering the cognitive radio systems to handle changes at physical layer, eliminating the collisions as much as possible to avoid frame retransmissions, saving mobile energy and improving the network throughput by routing the packets to the destination with the minimal delay. Since the inception of CRN, a number of MAC protocols have been designed and developed. CR MAC protocols make use of either GCCC or non-GCCC to exchange control information before they can actually start communication.

Cognitive radio-enabled multi-channel MAC (CREAM-MAC) [7] is a decentralized CR MAC protocol that applies a four-way handshake with communicating nodes on the control channel under the assumption that the control channel is always available and reliable. Emphasis has been given on data transmission with complete ignorance of the overheads of determining and agreeing upon the control channel. It is strongly believed that finding a common channel to dialogue on the exchanged control information is the primary task of cognitive nodes, and that subsequent operations could not take place if the existence of the control channel has not been addressed. So the assumption of control channel being always available is not a well-built justification.

In opportunistic-cognitive MAC (OC-MAC) [8], initially all nodes reside on a non-global common control channel, perform three-way handshakes to select a data channel from the FCL, and then confirm the data transmission through an acknowledgement. CR nodes in OC-MAC predict the length of spectrum hole, but this prediction is strongly criticized because the CR network is an opportunistic network and it is very hard to find the exact length of time during which the PU is not utilizing the spectrum so that the length of the available spectrum hole could be calculated.

The cognitive MAC protocol using Statistical Channel Allocation for wireless ad-hoc networks (SCA-MAC) [9] is a decentralized GCCC-based CR MAC protocol that can speed up transmission by using more than one channel for data transmission and can wait for some time for a channel with higher bandwidth to become available. Again, the protocol emphasizes on data transmission and ignores the pre-transmission overheads such as the time required in dialogue to exchange initial configuration and the time required to converge on the common control channel.

Cognitive MAC (C-MAC) protocol for multi-channel wireless networks [11] selects the so-called R channel within the white spaces and sets this channel as a control channel and manages the communication on R channel. However the selection criterion for the R channel has not been clearly defined, and also the clarification about which node will select the R channel and how the rest of nodes will be synchronized is missing.

An efficient MAC protocol for improving the throughput for CR networks (A-MAC) [10] belongs to a decentralized non-GCCC family of CR MAC protocols, in which the spectrum sensing is done using a half-duplex transceiver before the channel state information is made available to nodes. The protocol exchanges the FCL with communicating partners on the most reliable control channel. Although the results provided show that a higher throughput is achieved, a clear description of the mechanism used by CR nodes to converge on the reliable channel is missing. Also, a clear methodology is required to address the hidden terminal problem using a half-duplex transceiver.

Dynamic Open Spectrum Sharing MAC (DOSS-MAC) protocol for wireless ad-hoc networks [12], which makes use of three transmitters, presents a control channel algorithm to enable coordination among cognitive nodes and implements network layer multicasts. The hidden terminal problem is efficiently addressed in DOSS-MAC using three transceivers. It is suggested that similar functionality could be achieved using sensors instead of transceivers which could be a more cost effective solution.

SYNChronized MAC (SYNC-MAC) protocol for multi-hop cognitive radio networks [13] chooses one of the channels common between itself and neighbours to exchange control signals while other channels are selected to send data. It is not possible to decide a common channel until a CR pair have exchanged their FCLs.

2.1 Objectives

This paper aims to design a dynamic, decentralized, and hybrid medium access control protocol, named DDH-MAC for an overlay ad-hoc CRN. The protocol is dynamic because whenever a PU claim happens, CR nodes efficiently agree upon a newly found control channel to maintain control channel efficiency. The architecture of the protocol is decentralized, not infrastructure-based. DDH-MAC is hybrid in nature making partial use of both GCCC and non-GCCC families of CR MAC protocols. The framework for DDH-MAC has been presented in our previous work [14]. In this paper, we enhance our research by introducing the multi-layer reliability factor and we present an efficient and robust control channel access mechanism that emphasizes on the control channel efficiency. CR nodes implementing the proposed mechanism are always in a state where they have access to at least one control channel even after the PU interference has been sensed. CR users in the proposed mechanism, without renegotiations, switch to another control channel whenever there is a PU claim. CR nodes have access to three control channels at the same time. This unique feature smartly and intelligently addresses the PUs' channel re-occupancy, reduces the impact of re-exchange of control information and leads towards reliable communication in CRN.

The rest of the paper is organized as follows. The detailed operation of proposed scheme has been described in Section 3. The reliability factor and efficiency of the protocol have been computed through some mathematical calculations in Section 4. Section 5 discusses results before the paper is concluded in Section 6.

3 An Efficient and Robust Decentralized Control Channel Access Mechanism for CRN

In this section, we make some assumptions, define control frames, and then describe DDH-MAC phases and the operation. The protocol sets the following assumptions.

- Each CR node is equipped with two transceivers: G-Transceiver (GT) to continuously and rapidly scan global control channel, and D-Transceiver (DT) to transmit data.
- CR nodes utilize the CSMA/CA mechanism to access control channel.
- Spectrum has been sensed by the physical layer and FCL has been populated by each CR node.

- Each CR node is equipped with two sensors: one sensor senses the PU activity on a local control channel (PCCH or BCCH) and other sensor senses the PU activity on the data channel.

Four control messages are exchanged in DDH-MAC. One control message is delivered through GCCC.

1. Beacon Frame (BF) is launched in GCCC by the first node in the CRN to inform all the other CR nodes about the primary control channel (PCCH) and backup control channel (BCCH). Both PCCH and BCCH are one of the white spaces and will be used as a local control channel (non-GCCC). Two parameters are carried in BF: channel ID of PCCH and channel ID of BCCH. Channel IDs are arbitrarily selected by the first CR node, and are the first two channels that the CR node has sensed. Channel ID has a numeric value, where $0 \leq$ Channel ID $< N$.
   The local control channel (PCCH or BCCH) delivers three types of control frames.
2. DDH-MAC Control Frame (DMCF) is utilized by a potential CR sender to inform all the CR nodes in the vicinity that it is ready for communication.
3. Free channel list (FCL) is utilized by the same CR sender who sent DMCF which includes channel IDs of all channel that could possibly be used as data channels for subsequent transmission.
4. ACK is utilized by a CR receiver, who wins the contention on PCCH. The receiver replies with its own FCL identifying the channels common between CR pair for possible data transmission.

DDH-MAC consists of two phases: rapid channel accessing and reliable channel accessing.

3.1 Phase 1: Rapid Channel Accessing

When a CR node wants to transmit data, it first scans the GCCC for BF. There are two possibilities:

1. If any BF is found (Figure 1②), the information about PCCH and BCCH is learnt. This also means that the node will join an existing CRN and now PCCH needs to be scanned to learn more about the network.
2. If the CR sender does not find any BF in GCCC, then this node becomes the first CR node in CRN and is responsible for three functions: setting one of the white spaces in its FCL as PCCH and another as BCCH; form-

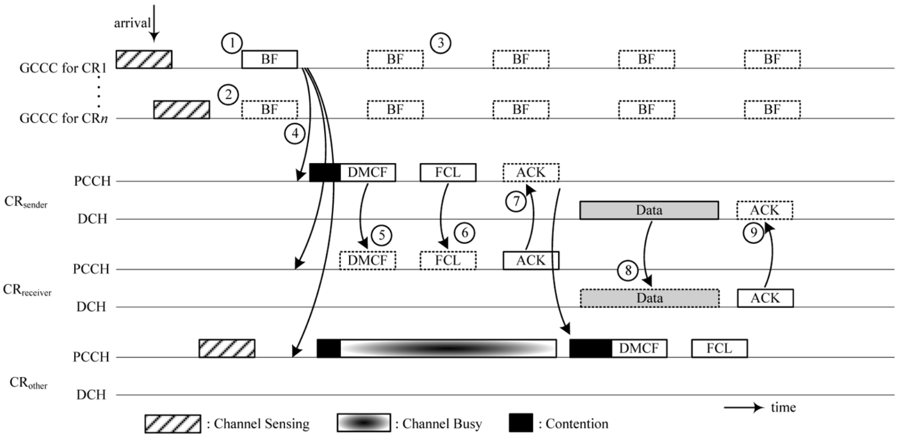

Figure 1 An example of Phase 1 operations.

ing and launching BF in GCCC (Figure 1①); and keeping transmitting copies of BF at regular intervals (Figure 1③).

In both cases, the CR node starts scanning the PCCH and observes the activities on the local control channel (Figure 1④). CR sender and receiver then exchange three control information frames through PCCH. Firstly, DMCF is launched (Figure 1⑤), followed by transmitting the FCL (Figure 1⑥). DMCF and ACK also serve to avoid the hidden terminal problem which is traditional in ad-hoc networks. The intended recipient checks its FCL to see if a common channel exists. If a common channel is found, a reply with an ACK is sent to the sender (Figure 1⑦). The pair then switch to the identified common data channel and start transmitting data using DT (Figure 1⑧). All the data frames are acknowledged using data ACK (Figure 1⑨). Other nodes will wait for PCCH to become idle and will contend to dialogue the control information after it is sensed free. GT will be used by all CR nodes in the network to scan the local control channel to have knowledge about all the activities carried out by other CR nodes in the network. The CR pair which just finished communication could remain unaware of the status of other CR nodes, and thus continuously scanning the control channel helps track the record of other CR nodes' activities. This ultimately avoids the hidden terminal problem. In rapid channel accessing, nodes can access the control channel efficiently and rapidly. Any new node joining the network firstly searches for a beacon frame which could be read for information about local control channel(s). After this, nodes simply switch to the newly discovered control channel for

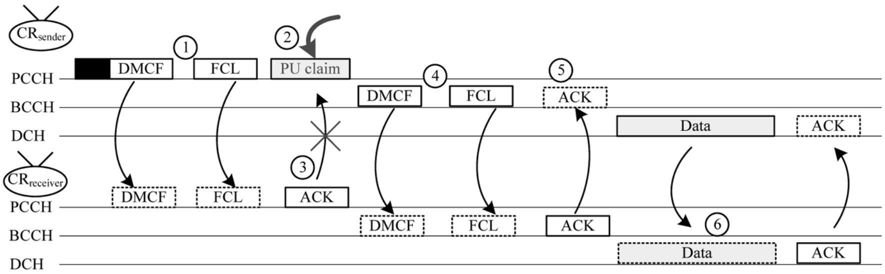

Figure 2 Phase 2 operations.

the most crucial part of communication i.e., FCL transactions, which leads to data frames transmission.

3.2 Phase 2: Reliable Channel Accessing

The PCCH and BCCH make use of the most readily available white spaces scanned and setup by a CR user. Unlike GCCC, which is publically available to everyone and is more prone to security vulnerabilities, FCL could be exchanged privately and secretly amongst CR nodes through PCCH after the nodes in the vicinity has converged on this local control channel. Since the PU can claim any occupied channel any moment of time, PCCH could also be claimed and as a result, nodes using PCCH for control information have to either abort the configuration dialogue or renegotiate on other white spaces. The proposed mechanism efficiently deals with this situation by using BCCH to resume the exchange of control information if there is a PU claim on PCCH. Figure 2 illustrates the example of Phase 2 where the CR sender is transmitting control information on PCCH (see Figure 2①) and is awaiting ACK from the recipient. Meanwhile, a PU claim is sensed on PCCH (see Figure 2②) due to which ACK could not be delivered (Figure 2③).

CR nodes can switch to BCCH without re-negotiations and re-searching control channel, and resume transceiving the control information (see Figure 2④⑤), followed by the data transmission on an agreed data channel (see Figure 2⑥). In the worst case scenario when BCCH is also claimed by the PU, CRN will execute operations of Phase 1 and will converge on new PCCH and BCCH. This dynamicity of local control channels provides the nodes an extra security feature. An adversary, planning to attack PCCH or BCCH and manipulating information on control channel, has to re-compile the attack every time when new PCCH and BCCH are set up. The reliable channel access gives CR nodes the assurance that they always have access to three channels simultaneously and any channel could be used for subsequent exchange of control information.

4 Performance Analysis

In this section, we first discuss different case scenarios, and then model the process of control channel efficiency and reliable channel efficiency, and finally calculate the time it takes for exchange control information.

As previously discussed, the proposed scheme performs a few operations before the network is fully converged. These operations include scanning/sensing GCCC, exchanging FCL on PCCH or BCCH (if there is a PU claim on PCCH) and lastly concluding transmission on the agreed white space(s). Each of the above listed operations requires time for its completion such as time required to sense/scan BF in GCCC, time required to launch BF, time to read BF and time required to exchange FCL on PCCH/BCCH. All these operations form part of pre-transmission time which heavily affect the throughput and QoS as nodes holding delay-sensitive data will be highly affected through varied values of pre-transmission time. Let T denote any of the above mentioned operations and T_{PT} represent the pre-transmission time which is further expressed as

$$T_{PT}^{DDH-MAC} = \{T_{BS}, T_{BF}, T_3, T_{FCL}^{PCCH}, T_{FCL}^{BCCH}, T_{DMCF}, T_{ACK}\} \qquad (1)$$

where T_{BS} is the time required to scan GCCC for BF, T_{BF} is the time to read BF or launch BF in GCCC, T_3 is the waiting time before a CR node can launch BF. Note that this waiting also aims to avoid duplication of BF by multiple CR nodes. T_{FCL}^{PCCH} and T_{FCL}^{BCCH} are the amount of time a CR node takes to broadcast its FCL in PCCH or BCCH if there is a PU claim. T_{DMCF} and T_{ACK} are control frames similar to RTS/CTS and are used to avoid the traditional hidden terminal problem. They are exchanged between communicating nodes before actual transmission can take place and lastly, $T_{PT}^{DDH-MAC}$ denotes the Pre-Transmission time.

4.1 Case Scenarios in DDH-MAC

Not all the operations are performed by cognitive nodes in DDH-MAC, and the number of operations performed depends on the role of a CR node and the case scenario. Currently, there are four cases in DDH-MAC. Case I represents network initialization phase where no control channels have been found and

Table 1 The parameters for the proposed scheme.

Parameter	**Assigned Value**
BF	14 Byte
DMCF	20 Byte
FCL	20 Byte
ACK	14 Byte
T_{BS}	10.181 μs
T_{BF}	10.181 μs
TDMCF	14.545 μs
T_{FCL}^{PCCH}	14.545 μs
T_{FCL}^{BCCH}	14.545 μs
T_3	30.543 μs
T_{ACK}	10.181 μs

CR Node 1 creates and launches the BF in GCCC. Case II represents the scenario where CR nodes after scanning GCCC find BF, read information about local control channel and then switch to PCCH. In Case III, the network initialization phase in addition to PU claim on the PCCH is considered. The last case is Case IV which is extension of Case II, in which nodes, after scanning GCCC and finding information about the PCCH, are forced to switch to BCCH due to PU arrival on the PCCH. Based on the number of operations performed in each case scenario, T_{PT} for all the four cases has been derived, as shown in the following equations:

$$T_{PT1}^{DDH-MAC} = \{T_{BS} \cup T_3 \cup T_{BF} \cup T_{DMCF} \cup T_{FCL}^{PCCH} \cup T_{ACK}\} \tag{2}$$

$$T_{PT2}^{DDH-MAC} = \{T_{BF} \cup T_{DMCF} \cup T_{FCL}^{PCCH} \cup T_{ACK}\} \tag{3}$$

$$\begin{aligned} T_{PT3}^{DDH-MAC} &= \{T_{BS} \cup T_3 \cup T_{BF} \cup T_{DMCF} \cup T_{FCL}^{PCCH} \\ &\quad \cup T_{ACK} \cup T_{DMCF} \cup T_{FCL}^{BCCH} \cup T_{ACK}\} \end{aligned} \tag{4}$$

$$T_{PT4}^{DDH-MAC} = \{T_{BF} \cup T_{DMCF} \cup T_{FCL}^{PCCH} \cup T_{ACK} \cup T_{DMCF} \cup T_{FCL}^{BCCH} \cup T_{ACK}\} \tag{5}$$

The above equations are used to compute the T_{PT} for DDH-MAC. We have used IEEE 802.11b as a benchmark to calculate values for above operations. Table 1 summarizes the values.

For simplicity, we have considered a static size for contention window, and channel conditions have been set to ideal. A total of 124 Bytes, 68 Bytes, 178 Bytes and 122 Bytes are exchanged in Cases I to IV of proposed scheme

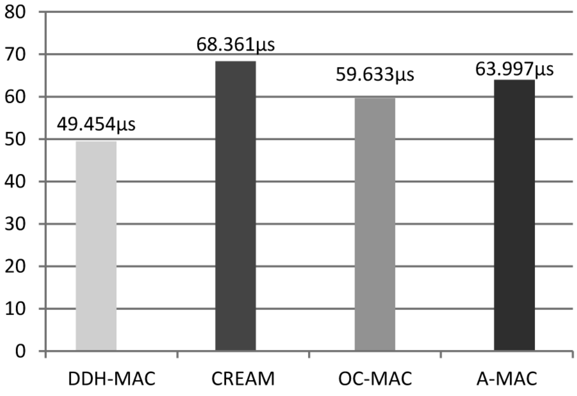

Figure 3 Case I: Network initialization phase.

respectively which yield following values of T_{PT}.

$$
\begin{aligned}
T_{PT1}^{DDH-MAC} &= 90.178\ \mu\text{s}\\
T_{PT2}^{DDH-MAC} &= 49.454\ \mu\text{s}\\
T_{PT3}^{DDH-MAC} &= 129.447\ \mu\text{s}\\
T_{PT4}^{DDH-MAC} &= 88.727\ \mu\text{s}
\end{aligned}
$$

5 Results and Discussion

In this section, T_{PT} has been calculated for other CR MAC protocols [6–8] for performance comparison and evaluation. Figure 3 shows the T_{PT} for Case I. The obvious reason for the high value of T_{PT} is the fact that the network is in the initialization phase and Node 1 has to wait for a certain amount of time to avoid BF duplication. Since other protocols do not wait to launch BF and the network is initialized through scan activity (or under the assumption of the existence of available control channel) followed by exchange of control frames, T_{PT} is less for other protocols in Case I.

Case II in our protocol has the lowest T_{PT} of 49.454 μs when compared with other protocols. Nodes in DDH-MAC read the BF, simply switch to PCCH and contend to dialogue the control information (Figure 4).

The reliability of our scheme is revealed in Cases III and IV. The PU claim on control channel is efficiently addressed by switching to BCCH and resuming the exchange of control information. Unlike other protocols, CR

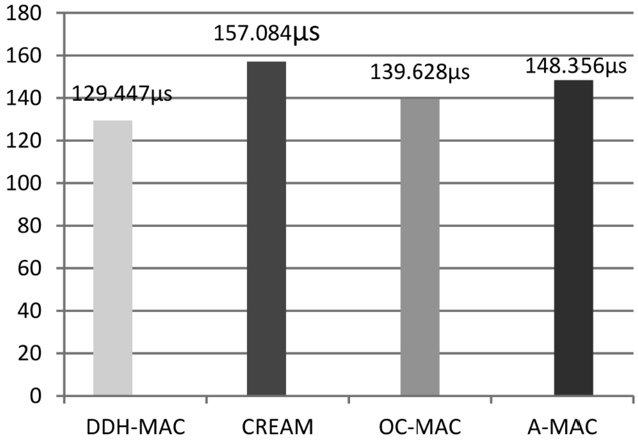

Figure 4 Case II: Network is initialized and control channel is found.

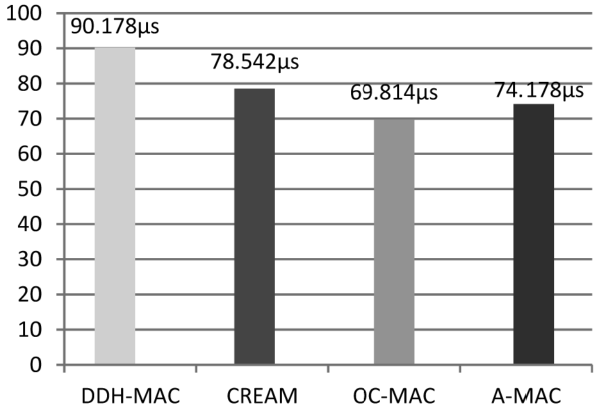

Figure 5 Case III: Network initialization phase, when PU interference is sensed in local control channel.

nodes in our protocol do not need to re-dialogue the entire configuration whenever the PU occupancy is detected. Figure 5 shows the efficiency of our scheme in Case III and also reveals that the more number of control frames are exchanged in CREAM-MAC, OC-MAC and A-MAC, yielding to high values of T_{PT}.

The proposed scheme outperforms other MAC protocols in case IV and consumes the least time before the nodes finish exchanging control information and start transmitting data on a data channel.

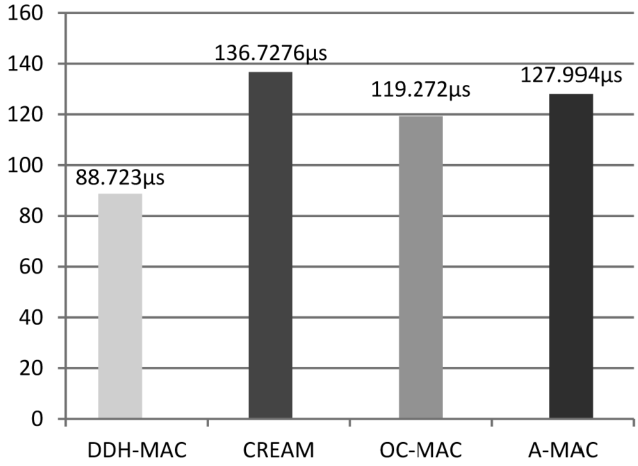

Figure 6 Case IV: The PU occupancy happens after the network is initialized, and control information is re-exchanged.

The T_{PT} for the scenarios of PU claiming is computed and expressed in Figures 5 and 6. The typical response by CR nodes is to abort the transmission and re-exchange the control information to agree upon another white space to conclude transmission while the proposed protocol efficiently deals with the situation by switching to the BCCH. Less number of frames exchanged with other CR nodes results in faster network convergence, and nodes remain in the state where at least one control channel remains always available to all CR nodes.

6 Conclusion

Cognitive radio networks aim to be a promising technology to resolve the problem of spectrum scarcity. CR nodes must exchange the control information on a control channel before transmitting the actual data. The selection criteria of CCC make the CR technology reliable. In this paper a novel multifold reliable framework for CR networks has been presented, which uses more than one control channel at the same time. Rapid channel access makes the CRN converged fast and rapid while reliable channel access gives the nodes assurance that they have access to at least one control channel to set up initial configuration dialogue. T_{PT} plays a very important role in the performance of the CRN. We have computed and compared the T_{PT} with some other

CR MAC protocols. The small values of T_{PT} lead to mobile energy efficiency as nodes have to wait less before the actual communication starts. Currently, the proposed mechanism is being simulated for evaluation and performance comparison of parameters like throughput, delay and energy consumption.

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Biographies

Munam Ali Shah received his B.Sc and M.Sc degrees, both in Computer Science from University of Peshawar, Pakistan, in 2001 and 2003 respectively. He completed his MS degree in Security Technologies and Applications from University of Surrey, UK, in 2010, and is currently a final year PhD student at University of Bedfordshire, UK. Since July 2004, he has been a Lecturer, Department of Computer Science, COMSATS Institute of Information Technology, Islamabad, Pakistan. His research interests include MAC protocol design, QoS and security issues in wireless communication systems. Mr. Shah received the Best Paper Award of the International Conference on Automation and Computing in 2012.

Sijing Zhang obtained his B.Sc and M.Sc degrees, both in Computer Science, from Jilin University, Changchun, P.R. China in 1982 and 1988 respectively. He earned a Ph.D in Computer Science from the University of York, UK in 1996. He then joined the Network Technology Research Centre (NTRC) of Nanyang Technological University in Singapore as a Post-Doctoral Fellow. In 1998, he returned to the UK to work as a Research Fellow with the Centre for Communications Systems Research (CCSR) of the University of Cambridge. Dr. Zhang joined the School of Computing and Technology, University of Derby, UK, as a Senior Lecturer in 2000. Since October 2004, he has been working as a Senior Lecturer in the Department of Computer Science and Technology, the University of Bedfordshire, UK. His research interests include real-time scheduling algorithms, schedulability tests for hard real-time traffic, performance analysis and evaluation of real-time communication protocols, and wireless networks for real-time industrial applications.

Carsten Maple obtained his B. Sc. (Hons) degree at the University of Leicester, UK in 1994, and his Ph.D. degree in 1998. He joined the University of Luton, UK in 1998 as a lecturer in computer science before moving into senior lecturer role later the same year and a principal lecturer post by 2002. In 2004, he was appointed professor of applicable computing, and was promoted to head of the Department for Computer Science and Technology at the newly formed University of Bedfordshire, where he led the department from strength to strength before his promotion to pro-vice chancellor (Research and Enterprise) in 2010. His research interests include network and computer security, cyberstalking, ethical hacking, information security, trust and authentication in distributed systems, and optimization techniques.