SWITCH: A Multichannel MAC Protocol for Cognitive Radio Ad Hoc Networks

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***Abstract*—Cognitive radio (CR) technology will empower wireless devices with the capabilities to dynamically exploit opportunities in both licensed and unlicensed spectra. Thus, the spectrum shortage problem that occurs due to the ever-increasing of wireless devices can be handled. In CR ad hoc network, a secondary user (SU) is allowed to utilize a channel of the primary system provided the channel is idle from primary user (PU) activity. In this environment, the way the SU copes with a sudden appearance of the PU is the most important feature of distributed CR-MAC protocols. In this paper, a multichannel CR-MAC protocol, which reacts efficiently to PU appearance, is developed. The new protocol is named opportunistic Spectrum access WITh backup CHannel (SWITCH). The SWITCH protocol is a decentralized, asynchronous, and contention-based MAC protocol for CR ad hoc networks. The proposed protocol operates over both licensed and unlicensed spectra. In addition, the concept of backup channel is introduced and employed to make the SU extremely robust to the appearance of PUs. The simulation results show that SWITCH accomplishes 91% throughput gain over other CR-MAC protocols.**

I. Introduction

In the existing literature, several MAC protocols have been extensively studied in the context of classical ad hoc networks. However, they cannot be applied directly to CR ad hoc networks, which have some unique characteristics that clearly distinguish them from their classical counterparts. Firstly, the SUs should have the ability to seek adaptively and dynamically for opportunities in both licensed channels (LCs) and unlicensed channels (UCs). Secondly, the SUs should react efficiently to the sudden and the consecutive appearance of PUs. These two characteristics make the design of an efficient CR-MAC protocol a challenge.

An extensive survey of CR-MAC protocols has been given in [1]. According to this survey, CR-MAC protocols can be classified in: contention-based protocols, time slotted protocols and hybrid protocols. Contention-based MAC protocols are based on the classical CSMA/CA principle. In addition, one or more features are added to these protocols to be adapted to the CR environment. For contention-based MAC protocols, no synchronization is needed between the SUs to access the available channels. The DCA-MAC protocol [2] is an example of this class. Time-slotted MAC protocols need a global synchronization between SUs. Therefore, the time is divided in slots for both the control and the data transmission. Examples of this class are the Cognitive MAC (C-MAC) protocol [3] and the Opportunistic Spectrum Access (OSA-MAC) protocol [4]. Hybrid MAC protocols use a partially slotted transmission, in which the control signaling generally occurs over synchronized time slots. In addition, the following data transmission may have random channel access schemes, without time synchronization. The SYNchronized MAC (SYN-MAC) protocol [5] is an example from this class. Most of aforementioned protocols operate over LCs only.

In [6], the authors have categorized MAC protocols for CR into two major groups according to the way the SU copes with the sudden appearance of the PU: 1) MAC protocols that enable buffering of SU connections preempted by the PU arrival, and 2) MAC protocols that enable switching of SU connections to a vacant channel when the SU preempted. The disadvantage of the former group is that the SU buffers its connection even if there is another free channel. Furthermore, it may happen that the SU will not be able to re-establish its connection after buffering because of continuous PU transmissions which leads to a high delay. The disadvantage of the latter group is the control message overhead between transmitter/receiver pair to access the new channel. However, this problem is already considered by the Opportunistic Spectrum Access with Backup channel (OSAB) concept [7].

To benefit from the OSAB concept, a flexible MAC protocol, that coordinates the access to the medium (LCs and UCs), should be developed. Therefore, the main goal of this paper is introducing such a protocol. The proposed protocol is called opportunistic Spectrum access WITh backup CHannel (SWITCH) protocol. The SWITCH protocol is a decentralized, asynchronous, and contention based MAC protocol for CR ad hoc networks. The proposed protocol operates over both LCs and UCs. In addition, the concept of Backup Channel (BC) is introduced and employed to make the SU extremely robust to the appearance of PUs.

The remainder of this paper is organized as follows. The proposed protocol is described in details in Section II. The cognitive cycle of the proposed protocol is presented in Section III. The performance of the proposed protocol is evaluated by simulation in Section IV. Next, in Section V, we present and discuss selected results from our analysis. In Section VI, we summarize the paper.

II. SWITCH Protocol

In this section, the SWITCH protocol is described in detail. Firstly, the design features are presented. Secondly, the assumptions are listed. Finally, the basic protocol operation is given.

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A. Design features

OSAB [7] [8] is an abstract concept that does not answer questions such as: How does the transmitter/receiver pair coordinate access to the available spectrum? How does the SU cope with the sudden appearance of the PU? Thus, a detailed MAC protocol is needed to answer the aforementioned questions. This was a motivation for us to develop SWITCH.

For amending the first issue mentioned above, SWITCH is a contention-based MAC protocol to coordinate the access to the available channels. Contention-based MAC protocols are asynchronous MAC protocols. This feature makes this class an appropriate candidate for designing a MAC protocol for CR ad hoc networks. In addition, this class utilizes a Common Control Channel (CCC) as a rendezvous channel for the exchange of control packets for the whole network. Thus, all nodes in the networks are aware of the spectrum availability in their vicinity. The End-to-End Reconfigurability (E2R) project [9] has shown that CCC is very suited for CR networks. On the contrary, time slotted protocols and hybrid MAC protocols need synchronization among the nodes in the network which is quite a challenge in an environment that lacks a centralized entity.

To handle the second issue, SWITCH uses the BCs concept proposed by OSAB. The BC is negotiated between the transmitter and receiver prior to the actual data transmission. Thus, when a PU appears (For simplicity, we assume that PU appearance is sensed by both transmitter and receiver), both transmitter and receiver switch to the BC without additional control messages. This minimizes the control overhead required to find a new channel in the case of PUs appearance. Furthermore, all nodes in the transmission range of both nodes are informed about such a switch and therefore, the number of data collisions is reduced.

B. Assumptions

SWITCH is developed based on the following assumptions:

- Two types of users affect the SU's performance: PUs and Classical Users (CUs) which are wireless devices without cognitive radio capabilities such as devices using the conventional standards e.g. IEEE 802.11 and Bluetooth.
- Two types of channels are assumed: a CCC and data channels. The CCC is used as a rendezvous channel by SUs for coordinating access to the medium. The selection of the CCC is beyond the scope of this paper and we assume that is statically assigned. The data channels are of two types: LCs and UCs. The maximum number of LCs and UCs are C_1 and C_2 respectively. The C_1 channels are used as operating channels in the case of PUs absence. In addition, the LCs are shared between PUs and SUs with high priority for PUs to access the channels. The C_2 channels are used as BCs in the case of PUs appearance (Note: if there are no free channel from UCs, the channel with the least PU activity is selected as a BC). The UCs are shared between SUs and CUs with equal priority.
- Each SU is equipped with two transceivers (TRx): The first transceiver, TRx1, is devoted to operating over the CCC. The second transceiver, TRx2, consists of a Software Defined Radio (SDR) module. The SDR module can tune to any of the available channels, LCs and UCs, to sense for the unused spectrum and moreover receive/transmit the SUs packets.

III. COGNITIVE CYCLE OF SWITCH

To facilitate the description of the proposed protocol, we present a simplified cognition cycle for the SWITCH protocol. This cycle contains the following components: spectrum sensing, spectrum allocation, spectrum sharing and spectrum mobility. The SWITCH cognitive cycle is consistent with the generic cognition cycle presented in [1].

A. Spectrum sensing

Spectrum sensing is an essential component of the cognitive cycle of the SWITCH protocol. It is used to identify unused channels regardless of the fact that these channels are LCs or UCs. In this paper, we assume that SUs use cooperative spectrum sensing as a spectrum sensing strategy. In this strategy, the sensing results (i.e. available channels from LCs and UCs) are combined from all SUs in the network. Thus, the chance of missing signals from PUs, CUs, and other SUs can be reduced which leads to better utilization of the available spectrum. To achieve this goal, coordination and cooperation between both transceivers (i.e. TRx1 and TRx2), employed by each SU, are essential to sense available channels and to distribute the sensing information among SUs. The coordination between both transceivers can be done by using SDR transceiver, TRx2, to sense one of C channels randomly, say k-th channel, $(1 \leq k \leq C; C = C_1 + C_2)$. Afterwards, the SU tunes to its TRx1 to inform other neighbors about the availability of this channel over the CCC.

B. Spectrum allocation

The accuracy of spectrum allocation process has a great impact on both the network throughput and the overall spectrum utilization. In SWITCH, there are two spectrum allocation data structures, Neighbors Channel List (NCL), and Free Channel List (FCL). The NCL is used by each node X to keep record of the channels occupied by neighboring nodes. The NCL is constructed by listening to control messages sent on the CCC. The data structure for the NCL can be described as follows: $NCL(i).node$ presents the neighboring node i of node X. $NCL(i).ch.no$ indicates the channel used by node i. $NCL(i).ch.index$ presents the type of the channel (LC or UC). This field has two values, 1 or 2, which indicates the channel type, LC or UC, respectively. $NCL(i).time$ shows how long $NCL(i).ch.no$ will be occupied?

The FCL contains the available channels in the transmission range of the node (i.e. channels not used by other neighbors). A node updates its NCL and FCL, once it receives a new control messages. The data structure for the FCL of node A can be described as follows: $FCL(i).ch.no$ presents the channel number. $FCL(i).ch.index$ shows the type of the channel (LC or UC). $FCL(i).ch.priority$ indicates the priority of each channel to be used by the node. Each channel may be assigned one of three priorities: L, M or H which presents the channel always has low, moderate or high priority to be used, respectively. The priority is assigned to a channel according to PU and CU activities. The channel with least PU and CU activities is given the highest priority (i.e. $FCL(i).ch.priority = H$) to be the data channel. If there are more than one channel with high priority, then the data channel is selected randomly. After maintaining the FCL, the next logical step is the selection of the Proposed Data Channel (PDC) and Backup Channel (BC) for data transmission preparation. The PDC is selected firstly from the LCs (i.e. channels with $ch.index = 1$) as mentioned before. The transmitter checks its FCL and selects the first channel with the least PU activity (i.e. $FCL(i).ch.priority = H$) as the PDC. The BC is selected firstly from the UCs (i.e. channels with $ch.index = 2$). If all UCs are busy, the second channel with the least PU activity from the LCs, is selected as a BC.

C. Spectrum sharing

In this section, we describe the spectrum sharing process of SWITCH. First, we introduce the control packet format. Second, we present the two handshake modes used by SWITCH.

1) Control packets format: The control packet format of SWITCH is similar to the IEEE 802.11 packet format. However, some modifications are added to support the CR operation. For Request To Send (RTS): Three more fields are added to the packet format of the original RTS: PDC, BC and FCL fields. For Clear To Send (CTS): Two fields are added to the packet format of the original CTS: The Selected Data Channel (SDC) and BC fields which indicate the data channel selected by the receiver and the BC suggested in the case of PUs appearance, respectively. In addition, a new packet named Notification To Reserve (NTR) is added. This packet has the same format as CTS. The NTR is sent by the transmitter to its neighbors only in the case that the PDC or/and BC carried by the RTS control message is not equal to the SDC or/and BC carried by the CTS.

2) Handshake process: SWITCH has two modes of handshake: Two-way RTS/CTS handshake and Three-way RTS/CTS/NTR handshake. The usage of each mode depends completely on: 1) the channel availability in both the transmitter and receiver sides, and 2) the activity of PUs, CUs and other SUs.

Figure 1. shows an example of the spectrum sharing process. Suppose that we have five SUs: A, B, C, D and E. Each user constructs its FCL during the spectrum sensing process. There are two types of channels: four LCs and two UCs. One of the LCs ($Ch.no = 1$) is selected as a CCC. We assume that two LCs (i.e. $Ch.no = 2$ and $Ch.no = 3$) and one UC (i.e.$Ch.no = 5$) are available for transmission. Both $Ch.no = 4$ from LCs and $Ch.no = 6$ from UCs are busy. This explains why those channels are not listed in the FCL.

FCL for node B

Ch.no	Ch.index	Ch.priority
1	1	-
3	1	H
2	1	M
5	2	H

FCL for node C

Ch.no	Ch.index	Ch.priority
1	1	-
3	1	H
2	1	M
5	2	H

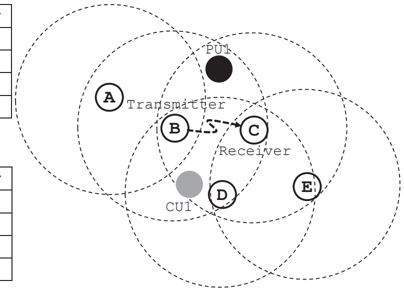

Fig. 1. Node B communicates with node C depending on FCL

To establish a communication between B and C, the nodes use one of the previously mentioned handshake modes.

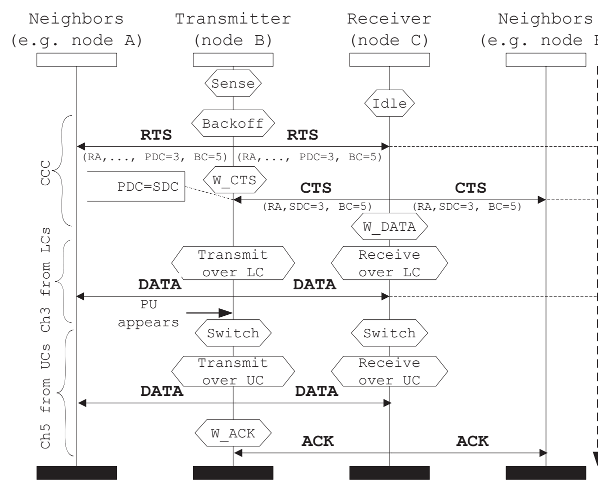

Fig. 2. MSC for RTS/CTS handshake with SU interruption

In the two-way RTS/CTS handshake mode, the normal handshake RTS/CTS, like IEEE 802.11 MAC, is used. Figure 2 presents the Message Sequence Chart (MSC) for this mode. In this figure, the hexagon represents the state of both transmitter and receiver. The RTS/CTS mode is used when the receiver (node C) agrees with the transmitter's (node B) proposal. In Figure 2, the proposal from node B is $Ch.no = 3$ as PDC and $Ch.no = 5$ as BC. On receiving RTS and CTS, the neighboring nodes (e.g. node A and node E) update their NCL accordingly. Afterwards, both node B and node C tune their TRx2 to $Ch.no = 3$ and start data transmission. If a PU appears during the data transmission between B and C, both nodes wait for a time, T_{Switch} and then switch to the BC ($Ch.no = 5$) from the UCs if available. T_{Switch} can be defined as the time required by the SU to sense and switch to the BC. This process is called spectrum mobility. This process is presented by the Switch state in Figure 3. There is no need to inform the neighboring nodes about such a switch since they are already informed before by listening to the RTS and CTS. The T_{Switch} time should be less than DIFS. If this condition is not satisfied then there is a probability that another SU in the vicinity of the transmitter wins the contention and thus

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Data rate	1 Mbps
Number of LCs and UCs	varies
Transmission range for PUs	150m
Transmission range for SUs, CUs	50m
RTS size	24 Byte
CTS size	16 Byte
NTR size	16 Byte
DATA size	2300 Byte
ACK size	14 Byte
SIFS	10 μs
DIFS	50 μs
T_{Switch}	40 μs

the switching fails. If the BC is available, both users will not perform any additional handoff since the UCs are free from PUs. If the BC is not available, the transmitter/receiver pair restart the negotiation process again.

The three-way RTS/CTS/NTR handshake is used when the receiver (node C) did not agree with the transmitter's (node B) proposal. For example, it may happen that the proposal from node B is $Ch.no = 3$ as PDC and $Ch.no = 5$ as BC. However, $Ch.no = 3$ from LCs is not included in the FCL of node C (i.e., $Ch.no = 3$ is busy). Therefore, node C will match both its FCL with the FCL of node B to select a new data channel. Based on this matching, C selects for example $Ch.no = 2$ from LCs as the SDC and sends a CTS. Based on this change on the data channel, a NTR control message is sent by node B to inform its neighbors. The neighboring nodes change the tentative reservation that happened for the PDC as a response to the RTS with the new information carried by the NTR message. If a PU appears on $Ch.no = 2$, both nodes will wait for T_{Switch} and after that switch to the BC from the UCs if available and follows the same procedure like the aforementioned example. Remark: there is a possibility that after performing a channel switching, the transmitter or the receiver find the BC to be busy, this may occur due to one of the following reasons: Conflicting reservations due to loss of control packets or a CU occupies the BC during SU transmission since we assume a soft reservation of the BC. Soft reservation means that the BC can be utilized by other CUs if there is no free UC.

IV. SIMULATION

As saturation throughput is a major performance measure to evaluate MAC protocols [10], we use it as the main performance metric. The saturation throughput means that SUs always have data packets in their queue to transmit.

The scenario used in our simulation can be described as follows: There are 24 SUs, 12 CUs and 12 PUs. SUs are static. Each two SUs establish a session. We assume that each SU has always a packet in its queue to send. The SUs coexist with both the PUs and CUs. Each SU in this network independently generates traffic of fixed-size packets. Table I presents the simulation parameters. All reported results are averages over three different runs of the simulation. Each run is equal to transmit $30,000$ SU packets on aggregate.

SWITCH is comparatively evaluated along with CR-MAC and DCA-MAC [2]. The CR-MAC protocol is a modified version of the IEEE 802.11 MAC protocol. The modification mimics and supports multichannel access methods. Like SWITCH, CR-MAC also uses a dedicated CCC for control packets exchange while using other channels for data communications. The data channels are assigned from the LCs only and other UCs are ignored. CR-MAC uses always two-way RTS/CTS handshake for coordinating access to the available channels. The FCL of the transmitter is carried by the RTS. Upon receiving RTS, the receiver matches this list with its own FCL and based on that the data channel is selected. DCA-MAC [2] uses always three-way RTS/CTS/Reservation(RES) handshake for coordinating access to the available channels. In addition, DCA-MAC is operating only over the LCs. SWITCH has the following features compared to the two aforementioned protocols

- it operates over both LCs and UCs,
- it reacts efficiently to the appearance of the PUs by using the BC's concept.
- it is flexible to use the two-way RTS/CTS handshake or three-way RTS/CTS/NTR handshake according to the channels availability in both the transmitter and receiver.

V. RESULTS

Simulation results are given as a function of the PU traffic load since the appearance of PUs is the most important event that affects CR ad hoc networks.

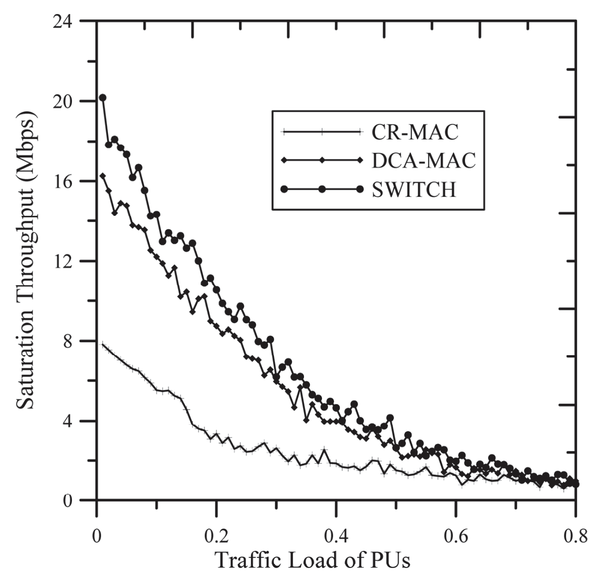

Fig. 3. Throughput of the SUs as a function of PU traffic load and using the LCs only: $C_1 = 12$ and $C_2 = 0$

Impact of PU traffic load: The PU traffic load has a great impact on the performance of SUs since once a PU appears in a channel occupied by an SU, the SU should vacate this channel and determine another free one. Figure 3 shows the saturation throughput of the SUs using the SWITCH protocol compared to DCA-MAC and CR-MAC vs. the PU traffic load and using the LCs only. The number of LCs is set to 12 channels. In this Figure, the impact of the UCs is not shown. Obviously, when the PUs traffic load increase, the throughput for the three MAC protocols decreases however with different levels. Although the UCs are not used here, the performance of SWITCH outperforms the performance of the other two protocols because of the BC concept. The throughput of SWITCH increases compared to CR-MAC and DCA-MAC by 91% and 19%, respectively.

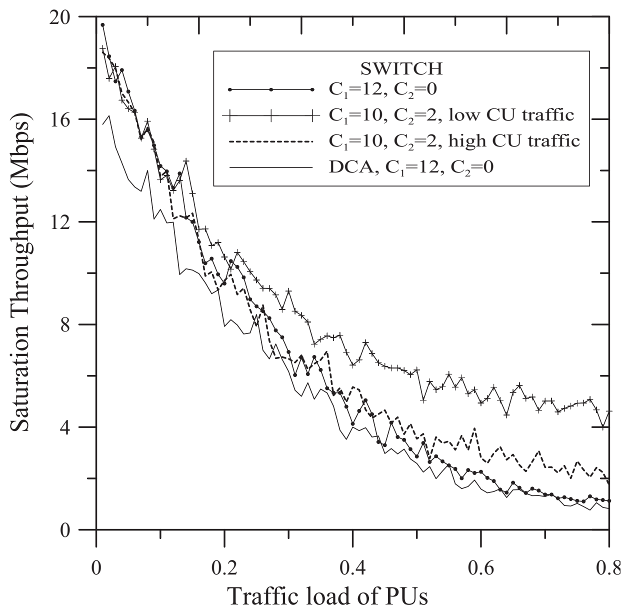

Fig. 4. Throughput of the SUs as a function of PU traffic load with different number of UCs: For SWITCH, $C_1 = 12$, $C_2 = 0$ or $C_1 = 10$, $C_2 = 2$. For DCA, $C_1 = 12$ and $C_2 = 0$

Impact of UCs: Figure 4 shows the throughput of the SUs using the SWITCH protocol as a function of the PU traffic load and using both LCs and UCs. In addition, we generate different CU traffic loads in the UCs to investigate the effect of CUs on the SWITCH protocol. To make a fair comparison between SWITCH and DCA-MAC, we use the same number of channels for each protocol. However, the type of channel will be different from one protocol to another. For DCA-MAC, $C_1 = 12$ and $C_2 = 0$ are used since this protocol operates over the LCs only. For the SWITCH protocol, $C_1 = 10$ and $C_2 = 2$. The Figure illustrates that the performance of the SWITCH protocol outperforms DCA-MAC. Furthermore, it outperforms the performance of the SWITCH protocol when operating LCs only. This improvement is expected within low CU traffic since the two UCs are utilized somehow exclusively by the SUs. On the contrary, when the PUs appears in DCA-MAC, the SU data transmission is interrupted and a new transmission is established. This process continues till the SU data transmission is completed. This explains the significant improvement on the throughput for the SWITCH protocol compared to DCA-MAC. For a high traffic load of CUs and using both LCs and UCs, SWITCH increases the throughput compared to DCA-MAC and SWITCH, using the LCs only, by 91.7% and 63.5%, respectively. Interestingly, although DCA-MAC utilizes 12 LCs and SWITCH utilizes only 10 LCs and two highly loaded UCs, SWITCH outperforms DCA-MAC. We can explain that as follows. Even if the two UCs are highly loaded, there is a chance for the SUs to access the UCs since all users in the UCs have the same priority to access the channels. In addition, the concept of BC reduces the time needed to establish a new connection.

VI. Conclusion

In this paper, a decentralized, asynchronous, and contention-based MAC protocol named SWITCH, has been developed. Using simulation, we were able to compare SWITCH with other MAC protocols in a cohesive manner. We draw important conclusions from our study such as: 1) A combination of channels from LCs and UCs as a spectrum environment for CR ad hoc devices is a better approach for efficient utilization of the available spectrum, 2) The concept of BC minimizes the overhead needed to maintain the SUs link in the case of PU appearance. In future work, the SWITCH protocol will be implemented using a SDR testbed developed at our university.

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