An overview of DSA via multi-channel MAC protocols

Panorama des protocoles MAC multicanaux pour l'accès dynamique au spectre

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Résumé

Nous présentons un panorama de différents protocoles MAC « multicanaux » (MC-MAC). Ces protocoles ont été proposés pour améliorer l'utilisation du spectre ; ils permettent des transmissions multiples dans des canaux fréquentielles indépendants. Un objectif, pour ces protocoles, est d'améliorer la performance globale de mécanismes basés sur la technique d'accès MAC du Wi-Fi (ou IEEE 802.11) qui utilisent le DCF (*Distributed Coordination Function*). Cependant, cette technique n'a pas été conçue pour fonctionner dans un environnement multi canal. Dans ce rapport, nous présentons différents protocoles MC-MAC et nous décrivons leurs mécanismes d'accès. Nous faisons une comparaison des principales caractéristiques, en fonction du nombre d'éléments transmetteurs, des contraintes de synchronisation, de la présence de CCCH (canal de contrôle commun) et des différentes manières de faire des « rendez-vous ». On montre dans ce rapport la façon dont les différents protocoles MC-MAC font face aux problèmes d'accès DSA (*Dynamic Spectrum Access*, ou Accès Dynamique au Spectre).

Mots clés : *Protocoles MAC « Multicanaux », Accès Dynamique au Spectre*.

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An Overview of DSA via Multi-Channel MAC Protocols

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***Abstract*—Multi-channel MAC protocols have been proposed to improve spectrum utilization and to increase network throughput by allowing multiple transmissions in a set of frequency channels. The purpose of these multi-channel MAC protocols is to enhance the overall performance of Wi-Fi like protocols (using IEEE 802.11 based mechanisms) with Distributed Coordination Function (DCF) as Medium Access Control (MAC) technique. However, this technique was not designed to work in a multi-channel environment. In this paper, we present an overview of different Multi-channel MAC protocols; we describe their access mechanisms and we make a comparison of key features of each protocol according to the number of transceivers (TRx), the need for synchronization, the need for a CCCH (Common Control Channel) and the different ways to make "rendezvous". The aim of this paper is to show the different ways that each multi-channel MAC protocol faces up to the numerous problems in Dynamic Spectrum Access (DSA).**

Keywords- Multi-Channel MAC Protocols; Dynamic Spectrum Access;

I. Introduction

Nowadays new radio access technologies appear and there are few spectrum bands to be allocated. This phenomenon obstructs the further development of wireless technology and communication services [1]. Moreover, spectrum occupancy measurements [2] indicate that fixed channel allocations result in low efficiency in spectrum utilization because a large portion of the spectrum remains underutilized [20].

One approach capable of dealing with the above problem is Dynamic Spectrum Access (DSA) which allows spectrum sharing. In such an approach, unlicensed users, known as secondary users (SUs), dynamically look for unused spectrum in licensed bands and communicate using "spectrum holes". These idle bands represent spectrum portions assigned to licensed users (known as primary users, PUs) that are not being used [10].

Many researchers have proposed different multi-channel MAC protocols to increase network throughput and to reduce interference caused by secondary use of the spectrum. Many of these studies consider Wi-Fi like protocols (or IEEE 802.11 based mechanism).

The physical layer of IEEE 802.11b is divided into 11 channels for the FCC or North American domain and 13 channels for the ETSI or European domain; these channels are located 5 MHz apart in frequency and each one has an overall channel bandwidth of 22 MHz [4] [5]. To be non-overlapping (or orthogonal), these channels must be located 25 MHz apart. Thus only channels 1, 6 and 11 can be used simultaneously without interference [9].

A Cognitive Radio (CR) [6] is an intelligent communication device, capable of adapting its transmission parameters (channel frequency, modulation and power) based on the interaction with its environment [21]. Common MAC protocols do not provide, in general, mechanisms for channel switching. When having multiple independent channels to be used simultaneously, the need for enhanced Multi-channel MAC protocols becomes paramount. The IEEE 802.11 standard uses a distributed coordination function (DCF), as the fundamental Medium Access Control (MAC) technique. However, the distributed coordination function, which employs carrier sense multiple access with collision avoidance (CSMA/CA), was not designed to work in a multi-channel environment [9].

II. Background

A. *Secondary Use of Spectrum*

There are two different approaches of secondary use of spectrum in cognitive radio context. One is in the form of overlay, opportunistic usage of idle bands in the PU spectrum by cognitive radios and another in the form of underlay, using Ultra Wide Band (UWB) technology [7].

The rules in secondary use of frequency spectrum specify that licensed users, known as PUs, have the rights to transmit and to receive without interference from other users in certain spectrum bands. When these bands are free from the presence of PUs, they can be used by SUs. As soon as a PU starts activity in its channel, the SU has to leave that channel to avoid interference [3]. However, a cognitive radio (using a half-duplex transceiver) can not scan the spectrum and transmit simultaneously. Then, a limit of detection or sensing time must be established for the protection of PUs. This detection interval represents the maximum time of interference, from SUs, which a PU can accept before it begins transmission [1].

B. *Rendezvous in Multi-Channel Protocols*

In multi-channel MAC protocols, MSs exchange control information to concur on the channel for data transmission in the user plane. Proposed protocols vary in how MSs negotiate the channel to be used for data transmission and the way to solve medium contention; these protocols can be divided according to their principal characteristics of operation [8].

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In single rendezvous protocols, the rendezvous between a sender and its receiver can take place on at most one channel at any time, while in Multiple Rendezvous protocols, several rendezvous can take place in different channels simultaneously, thereby mitigating the control channel congestion [8].

C. Multi-Channel Hidden Terminal Problem

This problem occurs when mobile stations (MSs) in the network listen to different channels missing the RTS/CTS procedure.

The Multi-Channel Hidden Terminal Problem (MCHTP) is illustrated in figure 1 inspired from [9]. Initially, MS “A” wants to communicate with “B”, then “A” sends an ATIM RTS (A-RTS) which includes the data channel selection to “B” on the CCCH (Channel 1). After receiving the A-RTS, MS B selects the Channel 2 to communicate with “A” and sends back an A-CTS, notifying their neighbours that the data channel number 2 has been selected. In a single channel environment the RTS/CTS exchange avoids collisions in the transmission ranges of “A” and “B”. However, in multi-channel environments other MSs could be involved in communication in different channels when the RTS/CTS procedure took place. That could be the case of MSs “C” and “D”, as they were communicating in channel 3 they did not hear the CTS sent by “B”. When they finish their communication on Channel 3, MSs “C” and “D” switch to Channel 1 and now they select Channel 2 to reinitiate communication. When MS “C” sends the first message to “D”, this message will cause collision to MS “A” and “B” on Channel 2.

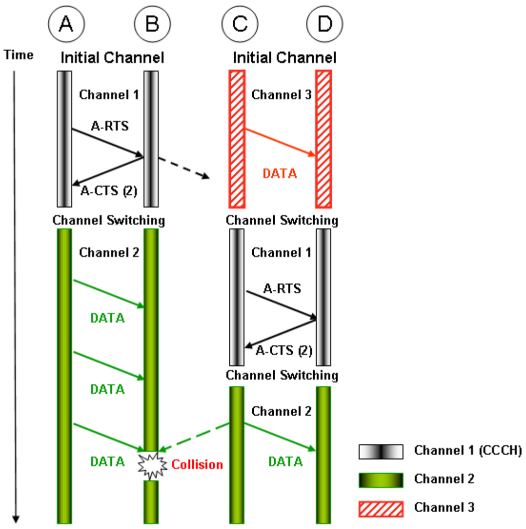

Figure 1. Multi-Channel Hidden Terminal Problem.

One possible solution would be a unique channel or moment in which every MS in the network listens to; thereby, ensuring that the RTS/CTS procedure can be heard by all the MSs, thus avoiding the (MCHTP).

In this section we enumerate and analyze different Multi-Channel MAC protocols describing their access mechanisms:

1) *“Comparison of Multi-Channel MAC Protocols” [8]*

In [8], a comparison between different multi-channel MAC protocols is presented. These protocols are classified into four categories:

- Dedicated Control Channel: This type of protocol uses two half-duplex transceivers (TRx) per MS, one is used for control information exchange and the other is able to switch between channels for data transmission. In this approach, there is no need for global synchronization to make rendezvous because the control channel is always tuned by all the MSs in the network. However, this protocol presents two principal problems, the need for two TRx and the possibility of control channel bottleneck.

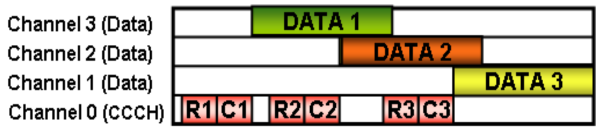

Figure 2. Dedicated Control Channel (inspired from [8]).

- Common Hopping: This type of protocol uses one TRx per MS; this TRx is able to switch between channels for control information exchange and data transmission. To make rendezvous, MSs hop synchronously over all channels and pause their hopping sequence when the agreement between sender and receiver is made. The merit of this protocol is the use of all channels for data transmission. However, the synchronization among MSs is crucial.

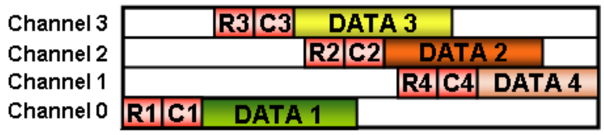

Figure 3. Common Hopping Approach (inspired from [8]).

- Split Phase: This type of protocol uses one TRx per MS, time is divided into control Phase and Data phase, this division has the objective to ensure that all MSs listen to the control phase, thus avoiding the MCHTP. Two important disadvantages of this approach are the need for global synchronization and the wasted data channels during the control phase. However, with only one TRx, this protocol solves the MCHTP and it can be used as an energy-efficient MAC protocol (Power Saving Mode of IEEE 802.11 standard).

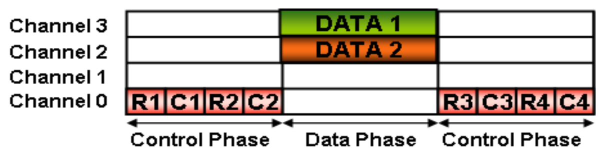

Figure 4. Split Phase Approach (inspired from [8]).

- Multiple Rendezvous: McMAC protocol uses one TRx per MS. In the beginning, a sender chooses a hopping pattern in a pseudo-random way using a seed to generate it. Neighbours learn its hopping sequence because is included in all the sender’s packets. To make rendezvous, a MS can deviate from its default hopping sequence and hops to the receiver's channel. In this protocol multiples rendezvous can be made in different channels at the same time, thus improving the network throughput and avoiding control channel bottleneck. However, the synchronization and coordination between MSs are essentials.

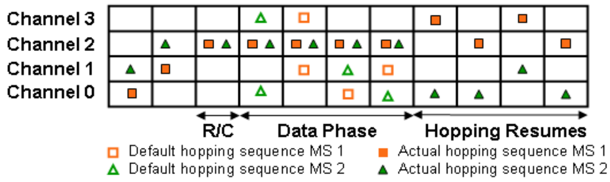

Figure 5. McMAC protocol (inspired from [8]).

2) "Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver" [9]

In MMAC protocol, each MS is equipped with one TRx. Time is divided into an alternating periods of control and data phases (split phase). An Ad Hoc Traffic Indication Message (AR), at the start of each control interval, is used to indicate traffic and negotiate channels for utilization during the data interval. A similar approach is used in IEEE 802.11's power saving mode (PSM). This scheme uses two new packets which are not used in IEEE 802.11 PSM: the ATIM ACK (AC) and the ATIM-RES (A-RE). These packets inform the neighbourhood MSs of the Sender (S) and Destination (D), of which channels are going to be used during the data exchange. During the control period, named ATIM window, all MSs have to attend the default channel and contend for the available channels. Once reservation is successful, the MSs switch to the reserved channel. With only one TRx this protocol solves the Multi-Channel Hidden Terminal Problem. A Preferred Channel List (PCL) is used to select the best channel based on traffic conditions. In this list all the channels are classified by the status: HIGH, MID, and LOW.

The principal disadvantages in this protocol are the need for synchronization, which might be difficult to implement in Ad Hoc networks [19] and the wasted data channels during the control phase or ATIM window. However, with only one TRx this protocol solves the MCHTP.

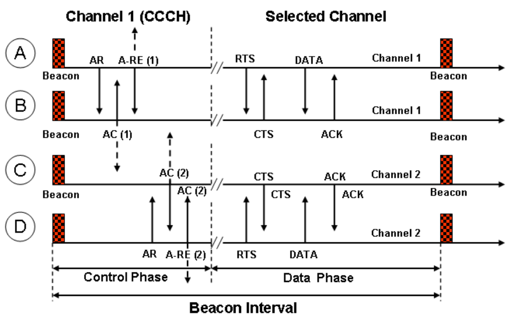

Figure 6. MMAC protocol (inspired from [9]).

3) "A Distributed Multichannel MAC Protocol for Cognitive Radio Networks with Primary User Recognition" [3]

In MMAC-CR protocol, time is split into alternating periods of control and data phase and each user is equipped with one TRx. A similar approach is used in IEEE 802.11 PSM. This protocol has two data structures: the Spectral Image of Primary users (SIP), which contains the channels used by PUs, and the Secondary users Channel Load (SCL), which is used to select the communication channel in terms of traffic.

The proposed protocol is divided into four phases: during phase I, the MSs contend to transmit a beacon and perform a fast scan; this scanning process is used to update the SIP value of the scanned channel. Phase II is used to determine the spectral opportunities by listening to C mini-slots (there is one mini-slot for each data channel).

Each MS informs the others of the presence of PUs by transmitting a busy signal in the corresponding mini-slot. In Phase III, using ATIM packets (AR and AC), the channels are negotiated. Phase IV is used for data transmission or fine sensing for idle MSs.

MMAC-CR with only one TRx solves the "Multi-Channel Hidden Terminal Problem". Alternating periods of control and data phases, this protocol avoids the possibility of control channel bottleneck. However, the synchronization and coordination between MSs are essential to make rendezvous which might be difficult to implement in Ad hoc networks.

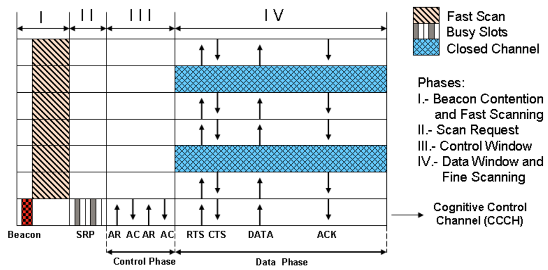

Figure 7. MMAC-CR protocol (inspired from [3]).

4) "Hardware-constrained Multi-Channel Cognitive MAC" [1]

In HC-MAC, each MS is equipped with one TRx. In this protocol, there is no need for global synchronization. To make rendezvous, HC-MAC transfers control packets using a CCCH. Time is divided into Contention phase, Sensing phase and Transmission phase and each phase has a RTS/CTS exchange:

- C-RTS/C-CTS: using the RTS/CTS mechanism of IEEE 802.11 DCF mode, a pair of MSs reserves all the channels (CCCH and data channels) for the following two phases (sensing and transmission).
- After sensing the different data channels, the pair exchanges a S-RTS/S-CTS on the CCCH to mutually inform about channel availability. A set of channels (only one in single TRx case) is then selected.
- After data transmission on the different selected channels, the communication pair informs the end of transmission by a T-RTS/T-CTS exchange. This allows neighbouring MSs to begin the contention phase with a random back off.

Authors outline two constraints for cognitive radios, sensing and transmission, the former used to optimize the stopping of spectrum sensing and the later used to optimize the spectrum utilized in transmission by SUs.

The major drawback of this scheme could be that after one communication pair wins the CCCH, using the C-RTS/C-CTS exchange; other MSs must defer their sensing and transmission. Then, for a certain time, only one pair uses all available channels and other users must wait for the T-RTS/T-CTS notification to contend again in the control channel.

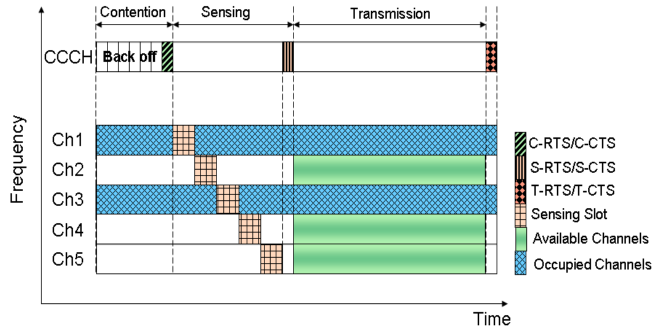

Figure 8. HC-MAC protocol (inspired from [1]).

5) "Distributed Coordinated Spectrum Sharing MAC Protocol for Cognitive Radio" [10]

This protocol uses two TRx per MS, one is used for control information exchange and the other is able to switch between channels for data transmission. There is no need for synchronization to make rendezvous because the control channel is always tuned by the MSs. In this protocol, SUs employ a time slot mechanism for cooperative detection of PUs around the communication pair by using the CHRPT (channel report slots). Each MS informs the others about the presence of PUs, in the sender and in the receiver side, by transmitting a busy signal in the corresponding mini-slot (there is one mini-slot for each data channel).

The source sends to destination the RTS which includes its available channel list. Neighbour MSs, which hear the RTS, compare the sender list with their own; if they detect a PU occupation in a channel, they reply with a pulse in the specified time slot during CHRPT (signalling occupied channels seen by the neighbours). If necessary, the source updates its RTS sending a RTSu. The same mechanism occurs in the destination side. After the RTS reception the destination waits to get the possible RTSu for certain time named UIFS, if the RTSu does not arrive, the destination will handle the first RTS. After the RTS reception, the destination sends to its neighbours the Channel Status Request (CHREQ), which includes the destination available channel list among the listed channels of the source. At the end of channel verification by the destination neighbours, the receiver sends the CTS with the chosen channel.

The major drawbacks of this scheme are the time wasted in channel verification by the neighbours and the need for two TRx. However, this procedure ensures the absence of PUs in the vicinity of the communication pair.

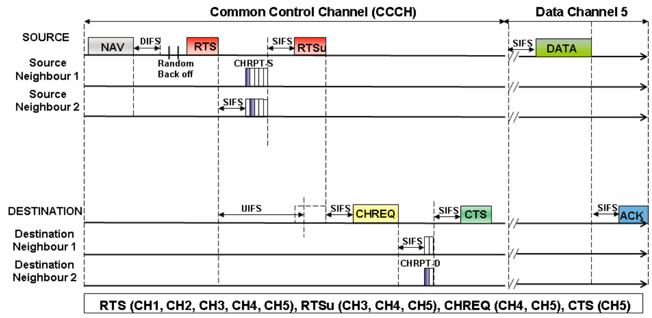

Figure 9. Procedure of the proposed protocol (inspired from [10]).

6) "Performance Evaluation of a Medium Access Control Protocol for IEEE 802.11s Mesh Networks" [11]

CCC protocol uses two TRx per MS, one is used for control information exchange and the other is able to switch between channels for data transmission. There is no need for global synchronization to make rendezvous because the control channel is always tuned by the MSs. The CCC protocol defines a CCCH, over which, mesh nodes will exchange control and management frames, the rest of the channels, called Mesh Traffic (MT) channels, are used to carry the data traffic. Reservations of the various MT channels are made by exchanging control frames on the CCCH.

This protocol has the same advantages and disadvantages presented by the dedicated control channel approach: there is no need for synchronization to make rendezvous. However, this protocol requires two TRx and the possibility of control channel bottleneck exists.

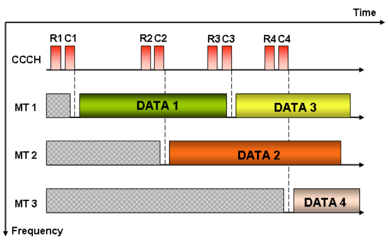

Figure 10. CCC MAC protocol (inspired from [11]).

7) "TMMAC: An Energy Efficient Multi-Channel MAC Protocol for Ad Hoc Networks" [12]

In TMMAC, each user is equipped with one TRx; time is divided into control phase (ATIM window) and data phase. The ATIM window size is not fixed and can be adapted based on traffic conditions. The data phase is slotted, only a single data packet can be transmitted or received during each time-slot. The purpose of the control window is twofold, the channel negotiation and the slot negotiation. In the data phase, each MS switches to the negotiated channel and uses its respective time slot for packet transmission or reception.

This protocol has the same advantages and disadvantages presented in split phase protocols: the need for global synchronization and the wasted data channels during the control phase. However, with only one TRx, this protocol solves the MCHTP.

8) *"Os-MAC: An Efficient MAC Protocol for Spectrum-Agile Wireless Networks" [13]*

In Os-MAC protocol, each SU is equipped with one TRx; this protocol uses the IEEE 802.11 DCF mode. This approach seeks to exploit the available spectrum opportunities using MSs coordination. One entity per channel is a "delegate", the delegates are chosen among all MSs and they make reports about channel quality. A single ACK notion is used in a "multicast group" named Secondary User Group (SUG).

OS-MAC divides time into periods; each period is named Opportunistic Spectrum Period (OSP). In each OSP, there exist three consecutive phases: Select, Delegate, and Update Phase. In the first phase, each SUG selects the "best" Data Channel (DC) based on traffic conditions and uses it for communication during the totality of the OSP period. During the second phase, a Delegate Secondary User (DSU) is chosen to represent the DC during the Update Phase, in which, all DSUs switch to the CCCH to update each other about their channel conditions, mean while, all non-DSUs continue communicating on their DCs.

An important aspect of this protocol is the notion of groups and the Delegate for each DC. This mechanism can improve the channel classification necessary to define the best channel, based in traffic conditions, which could be used for data transmission.

9) *"Single-Radio Adaptive Channel Algorithm for Spectrum Agile Wireless Ad Hoc Networks" [14]*

In the Single-Radio Adaptive Channel (SRAC) algorithm, each SU is equipped with one TRx. This algorithm proposes an adaptive channelization, where a radio combines multiple fixed channels with minimum bandwidth, named "atomic channels", based on its needs to form a new channel with more bandwidth, thus forming a "Composite channel". In this algorithm there is no need for global synchronization. SRAC also proposes "Cross-Channel Communication", utilized to enable transmission and reception when there are multiple jamming sources and there is no common idle spectrum between the transmitter and the receiver. A MS always has a pre-assigned channel for reception, which is well known by its neighbours and will be used to reach that MS; this channel can be modified but the selection must follow strict rules to enable future communications.

The merits of this algorithm are the adaptive channelization and the fact that it requires neither a CCCH nor synchronization because the MSs have a pre-assigned channel for reception.

10) *"SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks" [15]*

SSCH protocol uses one TRx per MS. In this protocol, each sender chooses one of the possible hopping patterns generated in a pseudo-random way (one hopping pattern for each available channel). To make rendezvous, a sender must wait until its current hopping pattern intersects with that of the receiver before it can send data. The principal disadvantage of this protocol is the time wasted waiting to coincide with the receiver. However, multiples rendezvous can be made at the same time in different channels and the control channel bottleneck is avoided.

11) *"A Full Duplex Multi channel MAC Protocol for Multi-hop Cognitive Radio Networks" [16]*

In this protocol, each SU is equipped with three TRx named: "Receiver, Transmitter and Controller". To communicate, the "Transmitter" of the sending MS and the "Receiver" of the receiving MS must be tuned to the same channel.

In [16], there is no need for synchronization because the CCCH is always tuned by the MSs using the "Controller". A MS selects an unused frequency band as its home channel (HCh); it tunes the "receiver" to its HCh and informs the others about the selected channel by broadcast in the CCCH. This protocol uses CSMA/CA scheme of IEEE 802.11 DCF mode. With the use of three TRx, MSs can reduce communication delay by transmitting packets while they are receiving. However, the need for three TRx will increase the overall cost.

12) *"CREAM-MAC: An efficient Cognitive Radio-EnAbled Multi-Channel MAC Protocol for Wireless Networks" [17]*

In the Cognitive Radio-EnAbled Multi-channel MAC (CREAM-MAC) protocol, each SU is equipped with one TRx that can dynamically utilize one or multiple channels to communicate and also has multiple sensors (there is one sensor for each data channel) that can detect multiple channels activity simultaneously.

The CREAM-MAC protocol employs a CCCH as the "rendezvous channel". This protocol does not require global synchronization. With one TRx, this protocol solves the Multi-Channel Hidden Terminal Problem employing a four-way handshake. These control packets are RTS/CTS and CST/CSR. The RTS/CTS exchange prevents the collisions among the SUs by reserving the CCCH for channel negotiation. The CST/CSR exchange avoids collisions between secondary and the PUs by allowing SUs to share sensing information about PUs channel occupation.

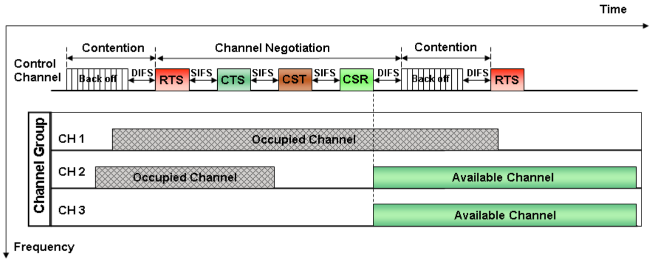

Figure 11. CREAM-MAC protocol (inspired from [17]).

The merits of the CREAM-MAC protocol are the fact that there is no need for global synchronization and with the use of only one TRx and multiple sensors, this protocol solves the MCHTP.

13) *"Distributed Coordination in Dynamic Spectrum Allocation Networks" [18]*

In [18], the notion of groups with similar views of spectrum availability is addressed. Each SU is equipped with one TRx. This protocol employs a voting scheme for selection of a "Coordination Channel" (CCH) for a group and this "user group" is assembled based in similar spectrum channel availabilities. The CCH is used as the only means to connect SUs, thus, only members of the same group can directly communicate with each other. To maintain network connectivity "bridge" nodes, located on the edge of each group, must manage at least two different CCH to transfer data packets between groups and connect users with different spectrum perspectives.

The merit of this approach is its possible application in the case of secondary use of the spectrum by WLAN devices in TV white spaces, principally, because the interference condition with PUs is determined by distance.

14) *"Primary Channel Assignment Based MAC (PCAM) A Multi-Channel MAC Protocol for Multi-Hop Wireless Networks" [19]*

In PCAM protocol, each user is equipped with three TRx. This scheme eliminates the need for a dedicated control channel that arise the possibility of control channel bottleneck when the traffic increases. In this protocol, a MS selects a frequency band as its primary channel using one TRx, this will be used as a receiver channel and a secondary channel is used as transmitter while the third TRx is used only for transmission and reception of broadcast messages. PCAM protocol removes the constraints of time synchronization and control channel saturation because the channels are pre-assigned. However, the need for three TRx will increase the overall cost.

III. CONCLUSIONS

In this paper a number of existing multi-channels MAC protocols are presented and analyzed. The advantages of several protocols are discussed with regard to different factors: the number of transceivers, the need for synchronization, the need for a CCCH and the different ways to make rendezvous for data transmission. As we showed, each multi-channel MAC protocol faces and resolves differently the various complications that arise in dynamic spectrum access.

In short, Cognitive Radio technology offers the possibility for additional use of radio spectrum by SUs. Multiple channel protocols allow dynamic spectrum access (DSA) due to the fact that different rendezvous and data transmissions can be performed on different channels. This type of protocols, compared to others that use a single frequency channel (IEEE 802.11mechanism), may improve spectrum utilization and increase total network throughput.

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