A Distributed Multichannel MAC Protocol for Multihop Cognitive Radio Networks

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***Abstract*—A cognitive radio (CR) network should be able to sense its environment and adapt communication to utilize the unused licensed spectrum without interfering with licensed users. In this paper, we look at CR-enabled networks with distributed control. As CR nodes need to hop from channel to channel to make the most use of the spectrum opportunities, we believe distributed multichannel medium access control (MAC) protocols to be key enablers for these networks. In addition to the spectrum scarcity, energy is rapidly becoming one of the major bottlenecks of wireless operations and has to be considered as a key design criterion. We present here an energy-efficient distributed multichannel MAC protocol for CR networks (MMAC-CR). Simulation results show that the proposed protocol significantly improves performance by borrowing the licensed spectrum and protects primary users (PUs) from interference, even in hidden terminal situations. Sensing costs are evaluated and shown to contribute only 5% to the total energy cost.**

***Index Terms*—Cognitive radio (CR), medium access control (MAC), multichannel MAC (MMAC) protocols, wireless communications.**

I. INTRODUCTION

DUE TO the accelerated deployment of broadband communication systems and the current fixed-frequency allocation scheme, the spectrum is becoming a major bottleneck. However, experiments show that up to 85% of the spectrum remains unused at a given time and location, indicating that a more flexible allocation strategy could solve the spectrum-scarcity problem [1]. This observation has recently led to the new paradigm of opportunistic spectrum access, where users can actively search for unused spectrum in licensed bands and communicate using these *white holes*. This vision is supported by regulatory bodies, such as the Federal Communications Commission [2] and the European Commission [3]. The concept is also often referred to as cognitive radio (CR)[1] [6].

A centrally controlled CR scheme has been standardized in the IEEE 802.22 Working Group, which defines the physical and medium access control (MAC) layers for a novel air interface based on the CR paradigm [7]. The aim is to provide a standard for wireless regional area networks by exploiting unused spectrum in the TV bands. The 802.22 system specifies a fixed point-to-multipoint wireless air interface, whereby a base station (BS) manages its own cell and all associated consumer premise equipment. In addition to the traditional role of a BS, the BS also manages the spectrum-sensing feature.

Beside such centrally controlled solutions, a clear need for distributed CR schemes exists, which would enable cognitive behavior in mesh and ad hoc networks. Distributed control reduces infrastructure cost, as well as providing larger flexibility and robustness.

As CR networks need to use several channels in parallel to fully utilize the spectrum opportunities, the MAC layer should accordingly be designed. Candidate protocols can be found in the class of multichannel MAC (MMAC) protocols. In a CR setting, these protocols have clear advantages over single-channel MAC protocols: They offer reduced interference among users, increased network throughput due to simultaneous transmissions on different channels, and a reduction of the number of CRs affected by the return of a licensed user [8].

Many MMAC protocols have been proposed in the literature, which can be organized according to their principle of operation [9]. We can distinguish *single rendezvous* (SRV) and *multiple rendezvous* (MRV) schemes. In SRV protocols, exchange of control information occurs on only one channel at any time, whereas the MRV schemes use several channels in parallel for this purpose. Within the SRV schemes, we can further distinguish three different classes: one class using a common control channel [10], [11], another class using common hopping [12], [13], and a last class using a split-phase approach [14], [15].

In comparison with the aforementioned standard work on MMAC protocols, which assumes that all nodes get equal access to the medium, we develop an SRV scheme to enable

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[1]The term CR was first coined in [4] and meant a radio that uses model-based reasoning to autonomously change its transmission parameters based on interaction with the complex environment (radio scene, application, and user requirements) in which it operates [5]. In this paper, we focus on a shorter term and spectrum-centric view of CR, i.e., a radio system that coexists with incumbent wireless systems by using the same spectrum resources without significantly interfering with these incumbents [6].

secondary spectrum access. An SRV scheme is considered, since control information can then be more efficiently distributed. The protocol is able to protect the licensed users from CR interference even if these licensed users are hidden (i.e., when a communication interferes with the licensed user, but neither source nor destination is able to scan the licensed user). This is done through distributed sensing.

In addition to spectrum scarcity, energy consumption is also becoming a key concern. Today, we are witnessing a continuously growing gap between the available energy, resulting from battery technology evolution and the exponentially increasing energy requirements of emerging radio systems and applications. This is particularly true for reconfigurable radio implementations, which are seen as enablers for CR systems [16]. On top of enabling opportunistic spectrum sharing, the proposed MMAC protocol is designed by taking this energy constraint into account.

The main contribution of this paper is the design of a MMAC protocol for CR networks (MMAC-CR). This MMAC protocol is based on the SRV scheme [15]. By allowing the terminals to enter a doze state when no communication is taking place, the MAC protocol achieves energy-efficient communication. Furthermore, the sensing algorithm relies on two phases: 1) a low-power inaccurate scan and 2) a high-power accurate scan. By using the low-power scan for periodically scheduled scans and only using the accurate scan when the low-power scan detects a change, the sensing algorithm also achieves energy-efficient operation. Distributed sensing is done using an efficient physical implementation of the OR rule. The other contribution of this paper is the evaluation of MMAC-CR using realistic power models of the software-defined radio (SDR) developed at the Interuniversity Micro-Electronics Center (IMEC). Although not specific to this hardware, this shows the benefit of the protocol in a realistic setting. We also develop an analytical model to analyze the performance in single-hop networks. This model is verified with simulations. The MMAC protocol is then further extended to allow operation in multihop networks. Finally, the proposed MMAC protocol is evaluated in the most demanding scenario, where the hidden incumbent problem is present.

The remainder of this paper is structured as follows: In Section II, we discuss related work. Background on the IEEE 802.11 standard is given in Section III. In Section IV, we describe the system considered. We introduce the novel MMAC-CR in detail in Section V. A detailed system analysis is given in Section VI. In Section VII, the proposed solution is evaluated with simulations and is shown to drastically improve performance while effectively protecting the primary user (PU). Finally, we present our concluding remarks in Section VIII.

II. Related Work

Recently, other MMAC-CRs have appeared in the literature. In [17], a cognitive MAC protocol for multichannel wireless networks (C-MAC) is presented. In a similar way as the protocol presented here, it avoids intrainterference (i.e., interference from other CRs) during scan periods and offers solutions for the multichannel hidden-terminal problem [15]. Energy efficiency, however, is not taken into account. The results are also focused on CR performance, whereas the main focus should be on the protection of the PU in this context. This protocol also requires tight synchronization, which is difficult to achieve in a multihop network. The protocol in this paper requires less-tight synchronization. In [17], the scan periods are furthermore quite short. This means that the CRs can only protect PUs that have duty cycles of 100%. False alarm rates and missed detections are also not taken into account. As a last point, we note that, in [17], the hidden incumbent problem is only handled by the sender and the receiver. In the present protocol, this problem is handled by sharing scan data from the entire neighborhood. This allows for better protection in the case of fading and shadowing.

In [18], a distributed coordinated spectrum-sharing MAC protocol for CR is presented. This protocol is based on the dynamic channel allocation (DCA) protocol presented in [10] and hence suffers from problems like control channel starvation and the need for two transceivers. On top of this, no measures have been taken to avoid intrainterference. Energy efficiency is also not taken into account. In [19], the protocol in [18] has been updated by migrating to an MMAC-based protocol [15]. This protocol, next to [20], is the most similar to the protocol presented in this paper. However, it does not consider energy efficiency and still focuses on single-hop networks.

In [21], a hardware-constrained C-MAC protocol for efficient spectrum management is presented. Like in [17], the results are also focused on CR performance rather than on protection of the PU. The hidden incumbent problem is also handled only by the sender–destination pair. False alarms and missed detections are not taken into account. Intrainterference is not avoided, and spectrum utilization is not optimal. As the protocol presented here is based on MMAC [15], it would seem that it also suffers from spectrum wastage, as has been noted in [17]. This spectrum *wastage*, however, is efficiently used for a longer and detailed scanning, and therefore, the CR network is able to protect primary networks (PNs) that have a duty cycle of less than 100%.

We refer the interested readers to some excellent surveys on MMAC-CRs [22]–[24].

III. Background

We first present some background information on the distributed coordination function (DCF) of IEEE 802.11, which is the standard reference for MAC operations in an ad hoc network, and its power-saving mode (PSM) [25].

A. *DCF of IEEE 802.11*

The DCF of IEEE 802.11 relies on a continuous sensing of the wireless channel. The algorithm used is called carrier-sense multiple access with collision avoidance. If a station has a packet to transmit, then it transmits if the medium is sensed to be idle longer than a DCF interframe space (DIFS). If not, then it randomly chooses a backoff value from the interval $[0, W-1]$, where W is defined as the contention window. This backoff counter is decremented every slot after the channel is sensed idle longer than a DIFS. If the backoff counter reaches zero, then the station transmits.

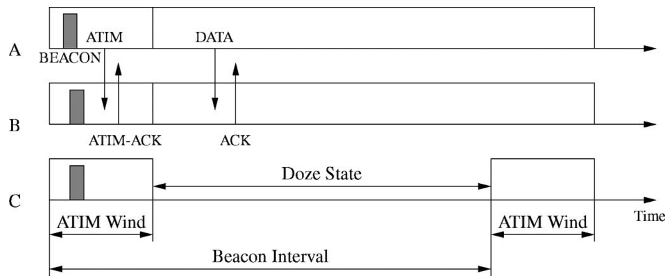


Fig. 1. PSM of IEEE 802.11 [15]. By allowing a node to sleep, when it has no pending transmission or reception, energy consumption can be reduced.

A station is also able to reserve the channel for data transmission by exchanging Ready To Send (RTS) and Clear To Send (CTS) packets. If a station has a packet ready for transmission, then it can try to send an RTS frame using the DCF. After receiving an RTS frame, the destination replies with a CTS packet. Both RTS and CTS frames carry the expected duration of transmission. Nodes overhearing this handshake have to defer their transmissions for this duration. The area around transmitter and receiver is now reserved for their data transmission.

B. *PSM of IEEE 802.11*

In this section, the PSM is explained. The idea is to let the nodes enter a low-power doze state if they do not receive packets. This solves the energy waste due to *idle listening*.[2]

In Fig. 1, we can see the operation of the 802.11 PSM. The time is divided into beacon intervals, and every node in the network is synchronized by periodic beacon transmissions. This means that each node starts and finishes each beacon interval at about the same time. At the start of the beacon interval, a small time frame, i.e., the ad hoc traffic indication message (ATIM) window, is reserved for the exchange of ATIM/ATIM-ACK handshakes. Every node should be awake during this window. If node A has packets buffered for node B, then it sends an ATIM frame to B during the ATIM window. When B receives the packet, it replies with an ATIM-ACK frame. Both A and B then stay awake during the entire beacon interval. Nodes that did not send or receive an ATIM frame enter a doze state until the next beacon interval.

Enhancements of this mechanism have been proposed to dynamically adjust the length of the ATIM window to the traffic load [26], [27]. Some MMAC protocols also make use of this timing structure. It can be used to solve the multichannel hidden-terminal problem [15] or to provide energy savings in these multichannel environments [28].

IV. System Description

In this section, we describe the considered network scenario and the radio architecture assumed for communication and sensing. Although not specific for the proposed solution, we use models from the state-of-the-art SDR, which were developed at IMEC [29]–[31], to evaluate our protocol in a realistic setting.

[2]*Idle listening:* A radio using the DCF function of 802.11 needs to be in the receive state, even if no packets are transmitted in the network.

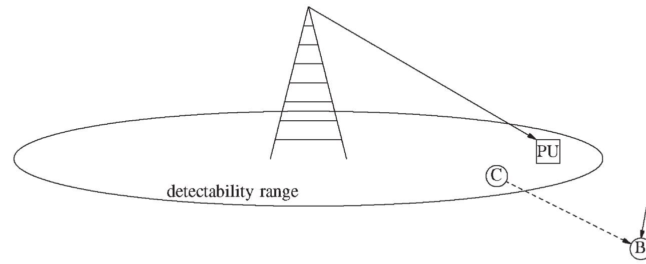


Fig. 2. Distributed sensing can solve the hidden PU problem. Node C informs the communication pair A–B that they might be interfering with a PU.

A. *Network Scenario*

The emerging CR scenario is of interest because of the potential for order-of-magnitude gains in spectral efficiency and network performance [32]. In this paper, we assume the following hierarchical scenario: The policy specifies that a certain technology, i.e., *the primary technology*, has the rights for interference-free communication in certain bands. When unused by the primary technology, these bands can be used for CR communication. The CRs that interfere with a PN have to vacate a channel as soon as possible after the PN has started communicating on the channel.

The CRs measure which frequencies are currently used by PNs. They navigate their communication to avoid channels where they could cause interference to the PNs. The transmission range for the CRs can be larger than the detectability range (e.g., when the transmission range for a PU is small or adaptive). Since these PUs cannot be detected by every CR, *distributed sensing* (i.e., the CR nodes collaborate to get a common spectral view) is needed. In Fig. 2, we see that when node A transmits to node B, a PN is interfered. However, as they are outside the detectability range, they have no way of knowing this. If station C, which is inside the detectability range, notifies node B, then the communication between A and B can be stopped or moved to another channel to avoid interference with the PN.[3] In the remainder of this paper, we make abstraction of the specific implementation of the sensing technique. For distributed sensing, the OR rule is assumed. Here, a channel is declared occupied if at least one terminal sees the channel as occupied [33].

B. *Proposed Radio and Sensing Implementation*

Reconfigurable radios, in particular SDRs, are often considered as key enablers for implementing CRs due to their inherent flexibility. In this paper, we consider the low-power SDR described in [16], which combines reconfigurable analog front-end (AFE) blocks [29] and a heterogeneous multiprocessor system-on-chip SDR-based baseband platform [30], [31].

All radios are assumed to have an interface dedicated for sensing purposes. Communicating and sensing can be done

[3]As we assume that PNs are not cooperating with CRs, node C does not know whether a transmission from A or B might interfere with the PN. This can lead to suboptimal spatial reuse. However, as the prime concern of the CR network should be to protect the primary user, node C needs to make sure that the PN is protected in all circumstances. Meeting this strict constraint requires trading off CR performance.

TABLE I
POWER TABLE OF IMEC SDR

	Analog	Digital	$\sum$
Doze	0mW	10mW	10mW
Idle	120mW	11mW	131mW
Receive	120mW	370mW	490mW
Transmit	600mW	300mW	900mW

in parallel (on different communication channels of course), which significantly reduces the impact of sensing.

Radio-level sensing aspects are tackled by the combination of analog and digital front-ends (DFEs). The AFEs include power amplifier, tunable filtering, tunable matching, and microelectromechanical switches. As we have a dedicated sensing engine, this requires a separate AFE. The DFEs perform automatic gain control and time synchronization on the samples provided by the AFEs. In case of burst-based signal reception, detection functions have a high duty cycle and, hence, need ultralow power implementation. By making the duty cycle of high-power states as low as possible, power consumption can be significantly reduced.

Regarding sensing at system level, we will distinguish two sensing mechanisms (as is done by the 802.22 WG): 1) fast sensing (e.g., energy detection) that can be done very fast (under 1 ms/channel) and 2) fine sensing (e.g., 25 ms in the case of field sync detection for digital TV systems) [6].

In Table I, the power figures for IMEC-SDR are presented. When a radio is in the doze state, it cannot receive any packet. The power consumption of fast sensing is assumed to be the same as that of the idle state. This means the AFE is on but the digital receive functions are not activated. In this state, limited sensing, such as energy detection, can be performed. The power consumption for fine sensing is assumed to be equal with that of the receive state since a coherent detection technique is assumed.

Once again, the results proposed in this paper are not limited to the considered radio implementation.

V. NEW MULTICHANNEL MEDIUM-ACCESS CONTROL-COGNITIVE RADIO

In this section, we introduce the novel MMAC protocol that enables opportunistic spectrum sharing. By borrowing licensed spectrum, this protocol enables significant throughput increase, delay decrease, as well as a potential energy decrease. Since borrowing licensed spectrum has to be done with care, the protocol is designed to protect PUs from CR interference even in hidden terminal situations. The timing structure used here is similar with that of the 802.11 PSM (see Section III-B). Before describing the protocol in detail, we first summarize our assumptions.

A. Assumptions

1) $C + 1$ channels are available for use, and all channels have the same bandwidth. None of these channels overlap, so the packets transmitted over different channels do not interfere with each other. This is (approximately) true for orthogonal techniques like orthogonal frequency-division multiplexing.
2) One of the channels is a Common Control Channel (CCC). This channel is assumed to be free of PU interference. Several groups have stated the need for such a control channel in a CR context [34]–[36].
3) The active period of the PUs is substantially longer than the length of the CR beacon interval. Within the IEEE 802.22, where a TV station stays active for more than a few hours, this is certainly true. In other cases, we can adapt the beacon interval to achieve this.
4) The interfaces are capable of dynamically switching their channel.
5) A node cannot sense a channel used for CR communication because this communication could mask PU signals. A radio can thus only scan a silenced channel, i.e., a channel where CR communication has been temporarily forbidden.

TABLE II
PROS AND CONS OF USING A COMMON CONTROL CHANNEL FOR CR NETWORKS

⊕	⊖
ease of deployment	unreliable when CCC is licensed channel
easy broadcast	CCC starvation
allows distributed sensing	prone to jamming

B. Common Control Channel

The proposed MMAC protocol uses CCC. Here, we evaluate this design decision using Table II.

Several MMAC protocols exist, which do not rely on a CCC. These protocols have the advantage that they do not suffer from control channel starvation, which has specifically been observed for the DCA protocol [10]. In this starvation problem, the CCC can become a bottleneck when too much control information is being sent over this channel. All nodes need to contend for access to the control channel, and the data channels remain underutilized. MMAC [15], which is the core of the presented protocol, is, however, less prone to this problem. As only one handshake on the CCC is needed per connection during the beacon interval, the control information is reduced as compared with the DCA protocol, where one handshake per sent packet is required.

A CCC is however very suited for CR networks [34]. Indeed, the amount of control information sent in a CR network is substantially larger than in traditional wireless networks. This control information has to be shared with, i.e., broadcast to, all neighbors. Traditionally, broadcasting has been overlooked by many of the non-CCC-based MMAC protocols. Using a CCC, broadcasting can be done very efficiently. Hence, when the amount of broadcast traffic increases, as is the case in CR networks, CCC-based MAC protocols become interesting.

Another benefit of a CCC is the ease of deployment. This is the main reason why commercial players are proposing CCC-based MAC protocols (e.g., C-MAC [17]).

A last benefit is the ability to distributed sensing correctly, i.e., using all neighbors rather than only transmitter and

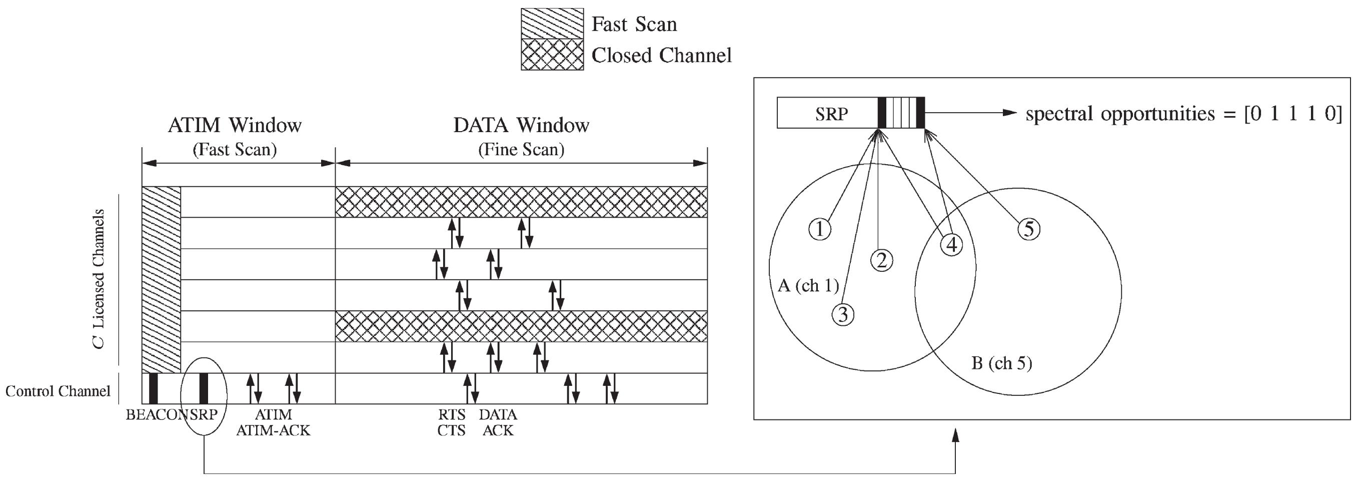


Fig. 3. Proposed MMAC-CR. This protocol uses a dedicated sensing engine that enables scanning and communicating in parallel on different channels. The minislot protocol provides fast and efficient data sharing [28]. In the presented example, nodes 1–5 learn that two PNs (A and B) are active on channels 1 and 5.

receiver. We refer to Fig. 2. Here, station C needs to signal A and B that they might be interfering with a PN. However, it cannot transmit on the channel used by A and B, as it will interfere with the PN. A CCC allows the CRs to share information about their environment without interfering with PNs.

The use of a CCC can however result in unreliable communication due to the appearance of PUs. This can be avoided by asking to allocate a dedicated band for commercial CRs, which is supported by [4] and [34]. Another option is to establish the CCC in the unlicensed ISM bands, which can be done at short term. However, using this approach, the CRs will have to share the CCC with unlicensed devices, increasing the probability of CCC starvation. A last option is to select a new CCC for each beacon interval in the licensed band using a hopping sequence. This reduces the interference toward the primary and makes it less prone to jamming attacks. As previously mentioned, we assume a CCC that is free of PUs. The protocol can, however, be easily extended to have a more dynamic CCC.

C. Data Structures

Each CR maintains two data structures: one is called the spectral image of PUs (SIP) vector, and the other is the secondary users channel load (SCL) vector.

The SIP vector contains the nodes' local view on the spectrum. It has the following three types of entries.

1) No PU is active on channel c ($\text{SIP}[c] = 0$).
2) A PU is active on channel c ($\text{SIP}[c] = 1$).
3) The spectral image of channel c is uncertain ($\text{SIP}[c] = 2$).

When a node joins the network, it performs a fast scan for every channel in the ATIM window. The outcome of these scans is stored in the SIP vector. After this initial sensing, the SIP values are updated using the scan results. The SIP vector is used to determine if the network can use a certain channel for DATA communication. Additionally, it is used to determine whether the node needs to schedule a feature scan during the DATA period. This is needed when the SIP value of a channel is set to uncertain.

The SCL vector is used for choosing the communication channel. It contains the expected load of CR communication on each channel. When a node wishes to transmit, it picks the spectral opportunity with the lowest SCL.

D. Operation

Fig. 3 shows the timing structure of our proposed protocol, as stated in [20]. The global time is divided into fixed-length beacon intervals in which we can distinguish two phases: 1) the ATIM window and 2) the DATA window. During the ATIM window, the nodes perform fast scans and exchange control information. The DATA window is used for data exchange and fine sensing.

1) ATIM Window: During the ATIM window, the nodes participate in the following:

1) the synchronization algorithm;
2) scanning the licensed channels (fast scan);
3) retrieving the network-wide spectral opportunities;
4) ATIM handshakes (two way).

The synchronization algorithm used is the timer synchronization function (TSF) of the IEEE 802.11 MAC protocol [25]. After the start of the ATIM window, nodes compete to transmit their beacon frame, which is carrying their local time, on the control channel. Following the TSF, a node only updates its time if the time carried in a received beacon frame is faster than its own local time. When a node receives a beacon frame, it drops its own beacon frame.

The ATIM window is also used for sensing the licensed channels. The nodes randomly select one of the channels to perform a fast scan. This scan is used to update the SIP value of the scanned channel. It will either confirm the present SIP value or not. If it is confirmed, then no further action is taken. Otherwise, the SIP value is updated to 2, which stands for uncertainty. The protocol is also capable of supporting other channel-selection strategies (see Sections VI-B and C).

During the ATIM window, nodes learn the network-wide spectral opportunities by listening to C minislots, which is a procedure also used in [18], [19], and [28]. This minislot protocol (see Fig. 3) is initiated after the transmission or reception of a scan result packet (SRP) on the control channel. The function of the packet is to ensure tight synchronization. A node will transmit a busy signal in the corresponding minislot for every channel where the SIP is not 0. If a minislot is sensed busy, then the corresponding channel is excluded for CR communication. Every node that either received or transmitted the SRP frame now knows the spectral opportunities. Basically, the minislot protocol is an efficient physical OR implementation, since it avoids all MAC overheads as compared with the case where every node has to transmit its own SIP in a packet. The goal of this protocol can be twofold. First of all, if a PN is detected ($\text{SIP}[i] = 1$), then the channel needs to be closed to avoid interference with the PN. A second reason why the channel can be closed is when uncertainty exists about the presence of a PN ($\text{SIP}[i] = 2$). Quieting the channel is now needed to perform a fine scan in this channel. To integrate this minislot protocol in a legacy 802.11 network, the SRP frame can be masked as an RTS frame so that all legacy nodes defer their transmissions for the duration of the minislot protocol. All nodes will try to send an SRP frame using the DCF rule, but if an SRP frame is received, then a node will drop its own SRP frame.

Traffic is indicated with two-way handshakes. Nodes that have buffered packets indicate traffic by sending ATIM frames on the control channel during the ATIM window. In the ATIM frame, a node will insert the preferred channel for data transmission, i.e., the one with the lowest SCL, and its queue status. Each node that overhears the ATIM frame accordingly updates its SCL vector. If the receiving node agrees with the selected channel, then it replies with an ATIM-ACK frame. After the ATIM window, the nodes that have exchanged ATIM frames stay awake until they have completed data exchange. The nodes that neither transmitted nor received ATIM frames enter a doze state until the next beacon interval.

2) DATA Window: The DATA window is used for data exchange and fine sensing. Nodes that have set the SIP to *uncertain* perform a fine scan of the corresponding channel, which is now free of CR traffic. This can be done in parallel with communication on another channel as we have assumed that the CRs have a dedicated sensing engine. The SIP value for this channel is updated to the outcome of the fine scan. Data exchange follows the normal DCF procedure from IEEE 802.11 with RTS/CTS exchange. An additional feature is that nodes are allowed to enter a doze state when they complete data exchange in the DATA window (i.e., if the transmit queue is empty).

E. Multihop Networks: Problems and Solutions

Compared with our earlier work on single-hop networks [20], a few additions need to be introduced to ensure correct operation in a multihop environment.

1) Channel Reservation: As noted in [15], a three-way ATIM handshake is necessary to ensure correct operation in a multihop setting. As stated in Section V-D, the transmitter sends an ATIM frame to indicate its desire to set up data communication. In the ATIM frame, it inserts a list of its spectral opportunities. The receiver compares this list with its own list and selects the common opportunity with the lowest SCL if it still has an unscheduled interface. If all its interfaces are scheduled, then the receiver selects the common opportunity with the lowest SCL, where it already has an interface scheduled. The selected channel for data communication is then inserted in the ATIM-ACK frame. To inform the neighbors of the transmitter that were not able to hear the ATIM-ACK frame, the transmitter sends an ATIM-RES frame, which includes the selected data channel.

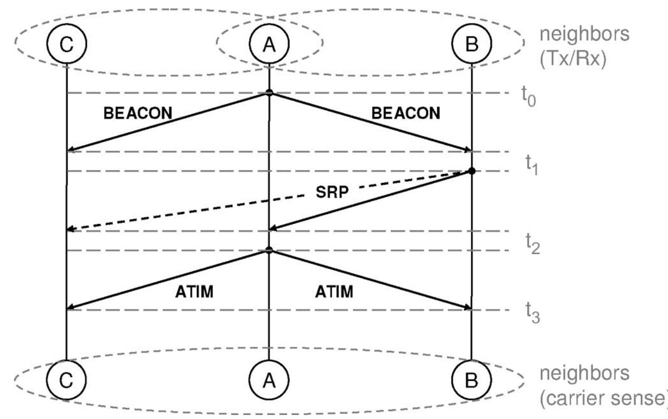


Fig. 4. In a multihop network, ATIM exchanges can be received before the spectral opportunities are known. In this example, node C receives an ATIM frame before it has been able to receive or transmit an SRP frame. This happens when node C waits for the transmission of node B but does not receive the SRP frame.

2) (Re)Scheduling Based on Correct SIP Information: Another problem faced in multihop networks is that the order beacon/SRP/ATIM is no longer guaranteed (see Fig. 4). To solve this, we adapt the DCF rule using the priority scheme presented in [37]. The traffic is split into two classes (high priority and low priority). High-priority packets can select a backoff $w \epsilon [0, \text{CW}/2)$, and low- priority packets have to select a backoff $w \epsilon [\text{CW}/2, \text{CW})$. This operation is similar to the quality-of-service extension of 802.11 (802.11e). However, the backoff value is reset each time a packet is transmitted to provide preemptive prioritization. The high-priority access is used for beacon and SRP frames, whereas ATIM handshakes will use the low-priority access. Since the ATIM handshake now takes place after updating the spectral view, the nodes can select a data channel based on correct information. The order between beacon and SRP frames does not have to be guaranteed, as these present different functions.

Sometimes, nodes still set up communication based on incomplete information. For instance, Fig. 5 shows an illustrative example. The colored nodes (1, 8, 9, and 16) have sent an SRP frame. This means that all nodes have either sent or received an SRP frame, and no further SRP frames will be sent in the network. The only SRP frame node 2 will receive is that of node 1, since nodes 8, 9, and 16 are out of range. Node 2 will thus not have participated in a minislot protocol with node 3 or 7, which is needed to obtain a full spectral image. In the situation that a PN is present at A, node 2 will not get the information that it will interfere with this PN. Although this situation will not occur often in a more dense network, precautions need to be taken.

We can let every node send an SRP frame, which will give an excellent coverage (only collisions might interfere). However, as this introduces a large overhead, we opted to keep the system introduced in Section V-D. To counter a wrong decision based on an incomplete view on spectral opportunities, we enable

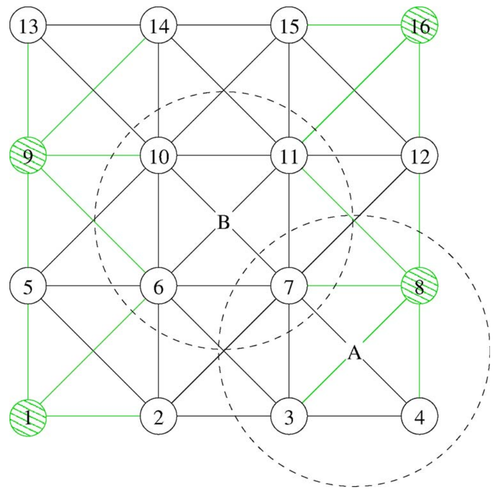


Fig. 5. Multihop networks pose additional challenges that have to be overcome to ensure the PUs from interference-free operation. The view on the spectral opportunities can be incorrect (node 2 only received an SRP frame from node 1), or the CVT can be slow (to effectively protect network B in this scenario, nodes 6, 7, 10, and 11 should all have detected it).

nodes to reschedule their transmission if they do receive an SRP frame after an ATIM handshake. Hence, nodes send an extra SRP frame after a conflicting ATIM, ATIM-ACK, or ATIM-RES frame has been received to update the incorrect spectral image of their neighboring node. For instance, if node 2 has scheduled a communication on channel 4 and receives an SRP frame after which it decides that channel 4 needs to be closed down, then node 2 needs to reschedule. Since its spectral image is now updated, it no longer suggests channel 4. The SRP frame that node 2 receives is generated by both nodes 3 and 7 when they overhear the ATIM handshake for channel 4. This also indicates that the ATIM-RES frame is necessary to allow a node to keep track of which channels its neighbors will be using for data transfer. Once again, to avoid overhead, if node 3 is faster to send the SRP frame, then node 7 will drop its SRP frame.

3) Triggering Additional Energy Scans: The channel vacate time (CVT) is a vital criterion for CRs, since it defines how well PUs can be protected. It is defined as the time it takes for all CR terminals that can interfere with the PN to close down the channel after this PN is activated. In a single-hop environment, all nodes close down the channel if one of the nodes that is able to detect the PN detects the PN. In a multihop environment, this is not true. For instance, if PN B started transmitting on channel 2 (see Fig. 5), nodes 6, 7, 10, and 11 all need to detect the PN before PN B is guaranteed to operate interference free, assuming all nodes interfere with the PN. To speed up this process, we have added the following feature: If a node sees that a channel is closed down, while it was open in the previous beacon interval, then it performs an additional energy scan on this channel during the ATIM window. This introduces an extra energy overhead but substantially speeds up the PN detection.

VI. System Analysis

In this section, we present a detailed system analysis of the proposed protocol. In Section VI-A, we describe the false alarm and the missed detection probabilities in a CR network. In Section VI-B, we present the modeling of the CVT. The channel opening time (COT) is defined and modeled in Section VI-C. The activity of PUs is modeled in Section VI-D. Finally, we compute the throughput for a single-hop CR network in Section VI-E. All the parameters used here and in Section VII can be found in Table III.

TABLE III
Simulation Parameters

Datarate	24Mbps	PLCP datarate	6Mbps
CW_{min}	15	t_{ATIM}	10ms
CW_{max}	1023	t_{BI}	100ms
l_{BEAC}	14 bytes	l_{ATIM}	14 bytes
l_{ACK}	14 bytes	l_{RTS}	20 bytes
l_{Hdr}	28 bytes	l_{PLCP}	40 bits
SIFS	16 μs	σ	9 μs
λ_{ON}	40s	λ_{OFF}	40s

A. False Alarms and Missed Detections

Here, we model the false alarms and missed detections in the network. The individual missed-detection probability is denoted as $p_{\text{md}}^{(i)}$. We define M as the number of CRs inside the detectability range of the considered PN and N as the number of CRs in the network $(M \leq N)$. As only the CRs inside the PN detectability range have the ability to scan the PN, the missed detection will only impact these terminals. A CR outside the detectability range of any active PN might mistakenly decide that a PU signal is present. We assume that these false alarms are only due to the noise power, which is assumed to be the same for all CRs in the network. Hence, all CRs in the network are affected by false alarms. The individual probability of a false alarm is denoted as $p_{\text{fa}}^{(i)}$. As the energy scan is largely responsible for false alarms or missed detections, $p_{\text{fa}}^{(i)}$ and $p_{\text{md}}^{(i)}$, respectively, denote the false alarms and the missed detection probability from the energy scan.

Because we use an OR rule (see Section IV-A), and nodes randomly select one channel to scan (i.e., the probability of selecting a channel is equal to $1/C$), the network-wide $p_{\text{fa}}^{(n)}$ and $p_{\text{md}}^{(n)}$ can be derived as

$$p_{\text{fa}}^{(n)} = 1 - \left(1 - p_{\text{fa}}^{(i)}\right)^{N/C} \tag{1}$$

$$p_{\text{md}}^{(n)} = \left(1 - \frac{1}{C}\left(1 - p_{\text{md}}^{(i)}\right)\right)^{M} \tag{2}$$

where C is the number of licensed channels, N is the number of CRs in the network, and M is the number of CRs within the detectability range of the considered PN.

Increasing the number of nodes in the network increases the number of false alarms in the network. This results in capacity loss for the licensed channels (see Fig. 6(a) for a 200-s simulation). With more channels, the relative loss of losing a single channel for communication reduces. Hence, increasing the number of channels decreases the capacity loss due to false alarms.

The probability of a network-wide missed detection exponentially decreases with the number of CRs capable of detecting a PN. Of course, if no CR is within the detectability range of

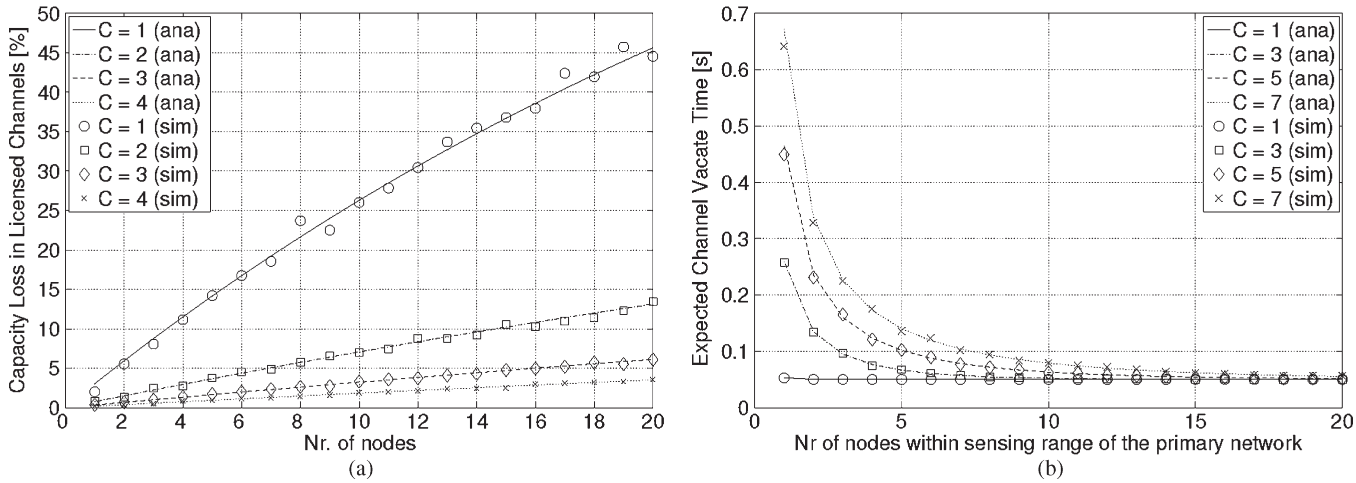


Fig. 6. Comparison between analytical and simulation results for the capacity loss and the CVT. (a) The capacity loss due to $p_{\rm fa}^{(n)}$ rises with the number of scanning nodes and dropping with the number of channels used. (b) The expected CVT exponentially decreases with the number of nodes able to detect the PN.

the PN, then interference cannot be avoided. The probability of incorrectly opening a channel when a channel has been declared to be occupied is negligible as a channel is only opened when the fine scanning agrees with the fast scanning that no PN is present and when all nodes inside the detectability range of the PN have declared the channel free. A PN is thus only interfered at startup. Here, the most important factor is the CVT, which we derive in Section VI-B.

B. CVT

Here, we derive the expression for the CVT. As we have previously mentioned, a channel is only vacated if at least one CR inside the detectability range performs a correct scan on the channel. Hence, the expected value of this CVT is derived as

$$\mathrm{E[CVT]} = \frac{t_{\rm BI}}{2} + \sum_{k=1}^{\infty} \left(p_{\rm md}^{(n)}\right)^k t_{\rm BI}[\mathrm{s}] \tag{3}$$

$$= \frac{t_{\rm BI}}{1-p_{\rm md}^{(n)}} - \frac{t_{\rm BI}}{2}[\mathrm{s}] \tag{4}$$

where $t_{\rm BI}$ is the length of the beacon interval. We assumed here that, on average, the PN activates in the middle of the beacon interval. In Fig. 6(b), it can be seen that, even with random channel selection, the expected CVT is below 150 ms with only five CRs able to detect the PN. This can further be lowered by more frequently scanning the open channels than the closed channels (defensive strategy).

C. COT

Another impact factor is the COT, which we derive in this section. The COT is defined as the time it takes to open up the channel after a PN has stopped its communication. As we are using the OR rule, false alarms occur more frequently, and channels are declared open more slowly.[4] This is why the COT is typically larger than the CVT. As a starting point, we assume that all nodes have detected the channel as occupied. The COT can then be derived as follows. To further simplify our analysis, we assume that CRs do not have false alarms after they detected that the PN stopped transmitting. Hence, our approximation will be more valid with a few CRs in the network. We denote the number of scans that an individual CR needs to detect the channel free as $s^{(i)}$. The probability distribution of $s^{(i)}$ can then be found as

$$p\left(s^{(i)}=x\right) = \frac{1-p_{\rm fa}^{(n)}}{C}\left(\frac{C-1}{C}+\frac{p_{\rm fa}^{(n)}}{C}\right)^{x-1}, \quad x \in \mathbb{N}_0^+. \tag{5}$$

All CRs need to detect the channel free before it is opened for communication. We denote the number of scans the network needs to detect the channel as free as $s^{(n)}$ to differentiate from $s^{(i)}$. The COT can then be derived as

$$p\left(s^{(i)}<x\right) = \sum_{k=1}^{x-1} p\left(s^{(i)}=k\right), \quad x \in \mathbb{N}_0^+ \tag{6}$$

$$p\left(s^{(n)}=x\right) = \sum_{m=1}^{m}\left[\binom{M}{m} p\left(s^{(i)}=x\right)^m \times p\left(s^{(i)}<x\right)^{M-m}\right], \quad x \in \mathbb{N}_0^+ \tag{7}$$

$$\mathrm{E[COT]} = t_{\rm BI}\left(\sum_{k=1}^{\infty} x p(s=x)\right) + \frac{t_{\rm BI}}{2}[\mathrm{s}]. \tag{8}$$

D. Modeling PU Activity and Channel Availability for CR Communication

The PU activity is modeled as a (dual) Poisson process. The length of the ON and OFF periods are exponentially distributed with parameters $\mu_{\rm ON}$ and $\mu_{\rm OFF}$, respectively. We approximate the influence of CVT and COT by altering the arrival parameters as

$$\mu^{\star}_{\rm CLOSED} = \left(\frac{1}{\mu_{\rm ON}} + \mathrm{E[COT]} - \mathrm{E[CVT]}\right)^{-1} \tag{9}$$

$$\mu^{\star}_{\rm OPEN} = \left(\frac{1}{\mu_{\rm OFF}} + \mathrm{E[CVT]} - \mathrm{E[COT]}\right)^{-1}. \tag{10}$$

[4]One could devise an explorative strategy by more frequently scanning the closed channels. However, as CRs are only borrowing spectrum, protection of the PNs should be the prime concern.

Here, we assume that $\mu^\star_{\text{CLOSED}}$ and $\mu^\star_{\text{OPEN}}$ are positive, which is the case in a well-designed system.

The probability that a channel is free for CR communication can then be derived as

$$p_{\text{free}} = \frac{\frac{1}{\mu^\star_{\text{OPEN}}}}{\frac{1}{\mu^\star_{\text{OPEN}}} + \frac{1}{\mu^\star_{\text{CLOSED}}}}. \tag{11}$$

E. Throughput of the Single-Hop CR Network

To simplify our analysis, we assume that one PN is present on each channel (except on the control channel). All of the CRs in the saturated single-hop network are assumed to be inside the detectability range of the PNs (i.e., $M = N$). The network is a peer-to-peer network, where each communication link has a dedicated transmitter/receiver pair (i.e., where L denotes the number of links, $L = N/2$). All CRs are assumed to have succeeded scheduling their transmissions during the ATIM window. As the proposed MMAC protocol uses the IEEE 802.11 MAC protocol on a channel, we can use the model presented in [38, eq. (1)–(13)] to calculate the throughput on a channel as a function of the number of links using this channel. We denote the throughput estimation of this model as $S_c(n_c)$, where n_c is the number of links on the channel. Previously, we mentioned that a link selects the channel that has the lowest SCL. In a saturated network, however, a link selects the channel that has the least links scheduled. The total throughput of the CR network S_t (with C licensed channels and one control channel) can thus be derived as

$$\begin{aligned} S_t = \sum_{i=1}^{C+1} \Bigg[\binom{C}{i-1} \left[p_{\text{free}} \left(1 - p_{\text{fa}}^{(n)}\right)\right]^{i-1} \\ \times \left[1 - p_{\text{free}}\left(1 - p_{\text{fa}}^{(n)}\right)\right]^{C+1-i} \left(\frac{t_{\text{BI}} - t_{\text{ATIM}}}{t_{\text{BI}}}\right) \\ \times \Bigg([L - \text{mod}(L,i)]\, S_c\left(\left\lfloor \frac{L}{i} \right\rfloor\right) \\ + \text{mod}\,(L,i) S_c\left(\left\lfloor \frac{L}{i}\right\rfloor + 1\right)\Bigg)\Bigg] \end{aligned} \tag{12}$$

where $\lfloor x \rfloor$ is the flooring operator, and $\text{mod}(x, y)$ is the modulo operator. In Fig 7, we show the performance of the proposed protocol. The simulated throughput closely matches the modeled throughput. The model slightly overestimates the throughput. This can be explained by the fact that we ignore the effects of reclosing the channel due to false alarms in the expression of the COT. In the next section, we more thoroughly analyze the proposed protocol using a simulation-based approach.

We also see that the maximum throughput is obtained for a low number of direct neighbors in the network. Although the number of neighbors in the network can be kept low using power control, this still results into low scalability. The cause of this low scalability is the defensive OR rule [see Fig. 6(a)]. As mentioned in [39], this can be overcome by selecting qualified radios (i.e., radios with a good channel to the primary) from unqualified ones. This can easily be implemented in the presented protocol but requires some additional control information.

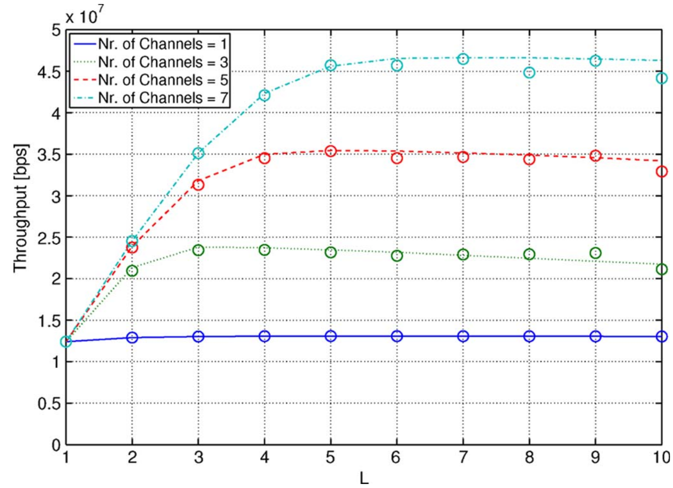


Fig. 7. We see that the simulated throughput closely matches the modeled throughput. Throughput increases with an increasing number of channels. The throughput declines after a rapid increase due to an increase in false alarms and the resulting capacity loss.

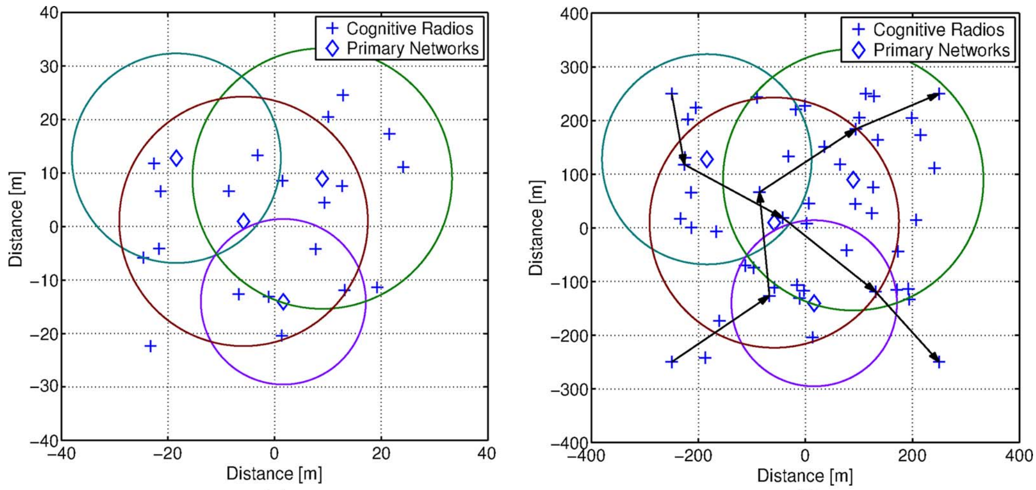
To limit the amount of additional control information, the number of CRs can quite efficiently be estimated with the technique presented in [28]. Here, the authors implement minislots after the beacon frame. At each beacon interval, every terminal randomly selects a minislot to transmit a busy signal. By observing the distribution of the busy minislots, the number of CRs in the network can be estimated. Based on this estimate, the CRs can derive a participation probability that is inversely related with the number of CRs in the network. This participation probability defines whether a CR needs to do an energy scan in the beacon interval. The operator can state that, on average, k CRs should scan one channel within the beacon interval. When the number of CRs per licensed channel is lower than k, the CRs should be capable of sensing multiple channels in parallel. Alternatively, the number of licensed channels that the CR network is allowed to use should be decreased until the CR network is able to scan each channel with k CRs during one beacon interval.

VII. Simulation Results

In this section, we present the simulation results of the proposed protocol. First, we discuss the simulation setup. Then, we present the results for a single-hop scenario. Finally, we evaluate the proposed protocol in a multihop environment. The results show that the performance can significantly be increased by borrowing licensed spectrum (throughput increases almost linearly with the number of available licensed channels). We also show that the protocol protects the licensed systems from CR interference.

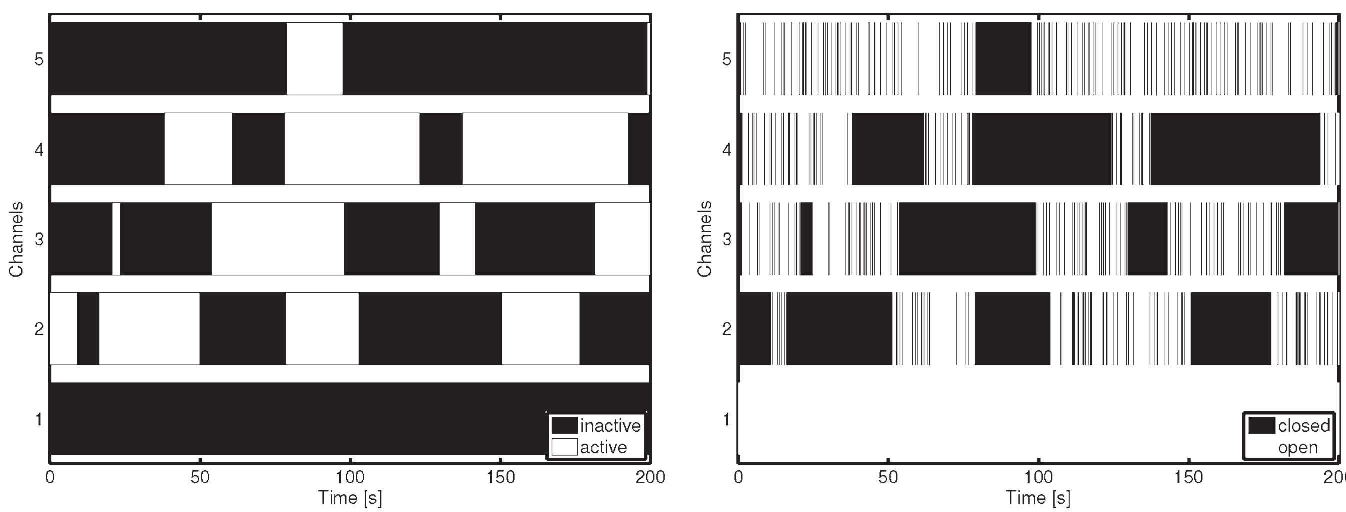
A. Simulation Setup

Extensive simulations were performed using the network simulator ns-2.29 [40]. In Fig. 8(a), the considered scenario is represented. The CRs are randomly deployed and assumed to be within each others' transmission range. The BSs of the PNs are also randomly deployed in this area but have lower



(a) (b)

Fig. 8. Topologies of the highlighted simulation runs. (a) Single-hop scenario. (b) Multihop scenario.



(a) (b)

Fig. 9. Activity of the PUs compared with the CR channel states in the single-hop scenario. The CR network correctly closes a channel when a PN is active on this channel. (a) No PUs are present on the control channel (channel 1). The active period of the PUs is substantially longer (order of minutes) than the length of the beacon interval of the CRs (100 ms). (b) The barcode-like behavior is a consequence of the false alarms for fast scanning.

transmission range than the CRs. This situation is the most demanding scenario for CRs. The circles in Fig. 8(a) denote areas in which the signal from a PN can be detected by the CRs. The hidden terminal problem is thus clearly present in the simulations.

As mentioned in Section IV-B, Table I lists the power figures used in simulations. For fine sensing (feature detection), we assume the scanning interface to be in the receive state for 25 ms, and for fast scanning (energy detection), the idle state is assumed for 1 ms [6]. Other parameters can be found in Table III.

B. *Results for the Single-Hop Scenario*

For the single-hop scenario, we use the randomly generated topology shown in Fig. 8(a). Other results agree with the outcome of this single-hop scenario. We use five channels and consider four PNs. Of the 20 CRs, only ten are communicating. The control channel (channel 1) is presumed to be free of PUs (PUs). The activity of the PNs is randomly generated and can be seen in Fig. 9(a). The CRs are sending 150 packets/s.

1) Channel States: In Fig. 9(b), we see the channel states for the CRs. The CRs clearly close down the channel if a PN is active. During the nonactive periods of the PNs, we see a barcode-like behavior. This is a result of the false alarms from the fast scans, which signal the need to close down the channel for fine scanning.

2) Interference: In Fig. 10, at the left, we see the CVTs for the different PNs. The CVT is the time it takes to close down a channel for CR communication after a PN is activated on this channel. For every PN, the CVT is lower than 200 ms, which is twice the beacon interval length and the CVT specified in the IEEE 802.22 standard.

We also plot the relative time during which the PN is interfered with in Fig. 10(b). We can see that it is low (less than 0.001% for PU 4 on channel 5 and significantly less for the others). The interference time is dependent on the traffic load of the CRs. If the idle times are ignored, then the PNs would be

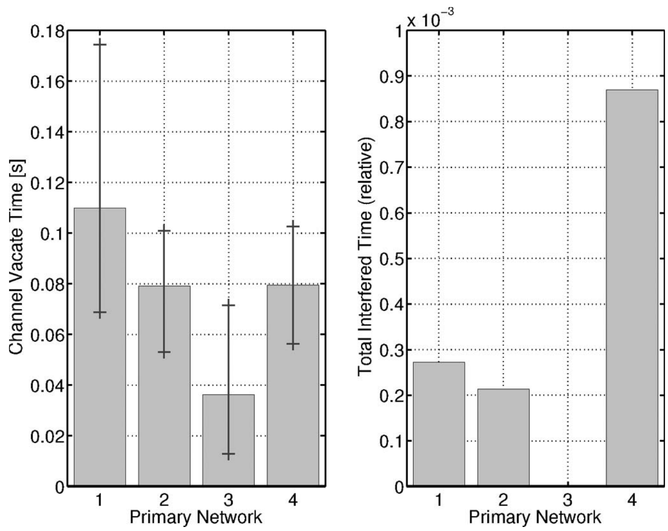


Fig. 10. Average CVTs and total interfered time for the PNs (relative to the active period of the PN). The lines represent the minimum and maximum CVTs that have been seen in simulation.

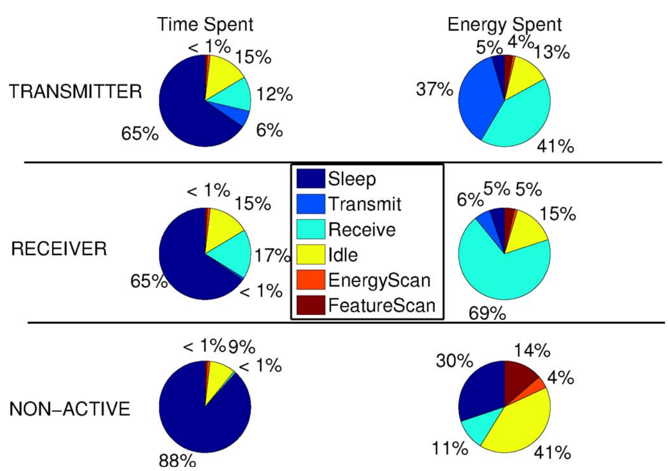


Fig. 11. Time and energy spent for the single-hop scenario.

interfered with by an upper limit determined by the CVT for a saturated CR network. Here, we can also see an additional benefit of sleeping after the last packet in the transmission queue is sent. A CR tries to send his packets as fast as possible and defers packets, generated after the transmit queue is emptied, to the next beacon interval. If a PN happens to be activated, then these packets can be guided to a free channel in the next beacon interval, since the spectral image has then been refreshed.

3) Energy Consumption: Finally, we study the energy consumption for the CR nodes (see Fig. 11). It can be seen that the scanning cost is limited for active CRs (only 3% of the total spent energy). A nonactive radio has a larger share of its consumed energy due to scanning, since this amount stays the same, whereas there is less total consumed energy. However, we see that even in this situation, the scanning energy contributes less than 10% to the total energy consumed.

Transmission energy can be reduced with distributed transmit power control, which can also reduce the interference to PUs. The main contributor to energy consumption is the receive state. This overhearing of nonuseful packets (i.e., when you are not

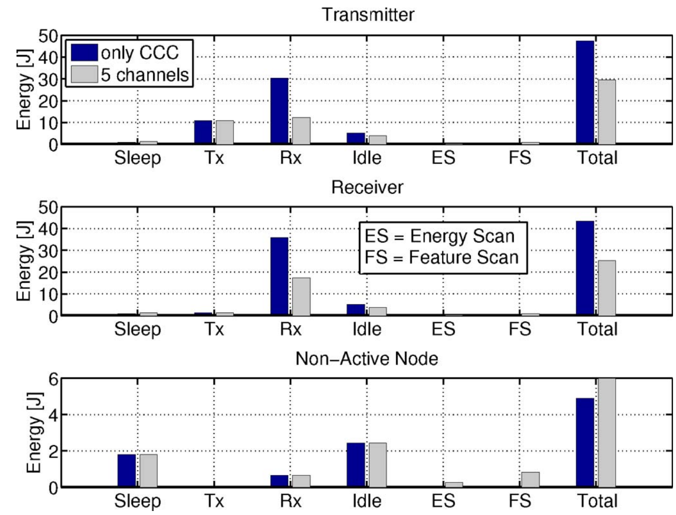


Fig. 12. Energy cost of scanning can completely be compensated. The availability of four licensed channels reduces energy with 40% for active nodes for the reference scenario.

the destination) can be reduced if more channels are available. We see in Fig. 9(b) that only a few channels can be used for CR communication at the same time when the PU activity is high. When more channels are available or there is less PU activity, the communication can be spread across the different channels, and less overhearing overhead is incurred. The total energy cost can hence be reduced by using extra licensed channels. Fig 12 shows the results for the single-hop scenario in the case that only the control channel is used (without scanning) compared with the case where four licensed channels can be used (with scanning). We see a 40% energy cost reduction for sending and receiving node. This indicates that the gain in overhearing energy, by borrowing the licensed spectrum, can cancel out the extra cost for scanning. For nonactive nodes, the energy consumption increases by 15% (i.e., scanning cost) because they do not benefit from a reduced overhearing in the DATA window. For these nodes, the idle state is the most energy consuming. As discussed in Section III-B, this can be optimized by making the ATIM window adaptive to the number of active CR links.

4) Spectrum Opportunities: CR performance depends on the amount of spectrum opportunities in time and frequency. In Fig. 13, we see the throughput for a saturated CR network (20 CR nodes, all communicating) in different scenarios. It can be seen that increasing the spectrum opportunities in time (decreasing the PU activity) or in frequency (increasing the number of licensed channels) results in higher gains compared with only using the control channel. In the best case presented (five extra licensed channels, no PU activity), a factor of more than 5 gain can be made. The relative gain can be larger than the relative added spectrum, as collisions are reduced with an increasing number of channels.

C. Results for the Multihop Scenario

For the multihop scenario, we use the randomly generated topology shown in Fig. 8(b). All nodes are in a 500 m $\times$ 500 m square. We generate two traffic streams (150 packets/s) that

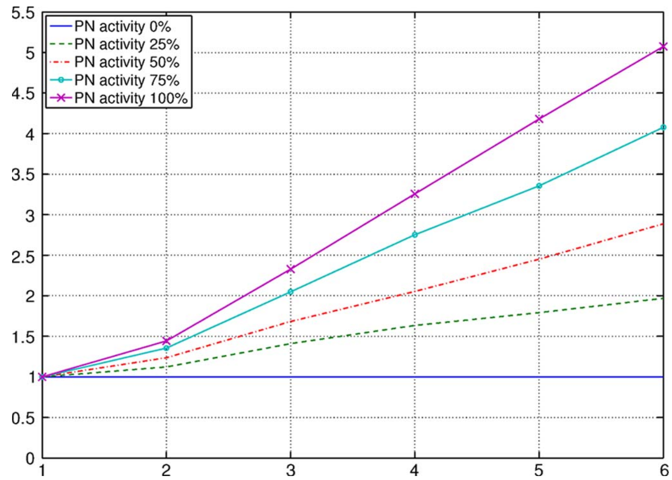


Fig. 13. Gain in throughput for a saturated CR network rises with the amount of spectrum opportunities.

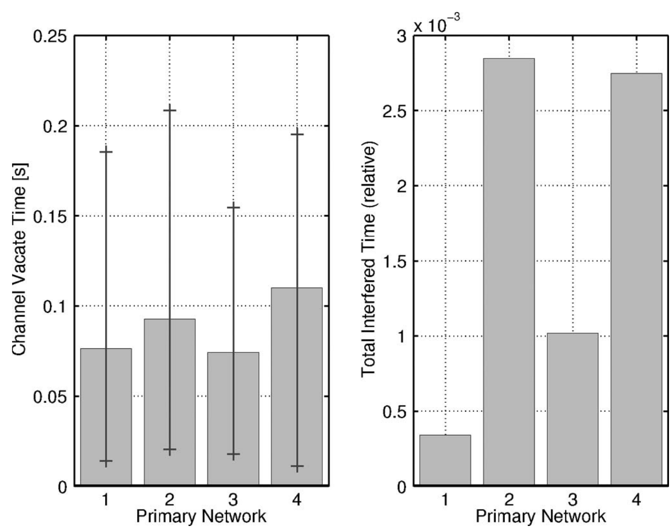


Fig. 14. Average CVTs and total interfered time for the PNs (relative to the active period of the PN) for the multihop scenario. The lines represent the minimum and maximum CVTs seen in simulation.

diagonally cross the network. Resulting from the ad hoc on-demand distance vector routing protocol [41], streams 1 and 2 need three hops to reach their destination.

As in the single-hop scenario, the PN activity is randomly generated. The area in which a CR is able to scan the PN varies from 100 to 200 m. The interference range is taken to be 350 m. If a CR within interference range of a PN sends a packet on the channel of the PN, then it interferes with this PN.

In Fig. 14, we see that the average CVT for the multihop scenario is low (on average smaller than the beacon interval). The PNs are interfered with for a small portion of their active period (around 0.3%). We can hence conclude that the protocol is capable of protecting PNs, even in multihop scenarios.

However, sometimes, it can happen that a CR within interference range of a PN is not covered. A node may thus be unaware of the fact that it is interfering with the PN. If we assume a random deployment of CRs, then we can see in Fig. 15 that the probability for a node to be covered decreases with distance

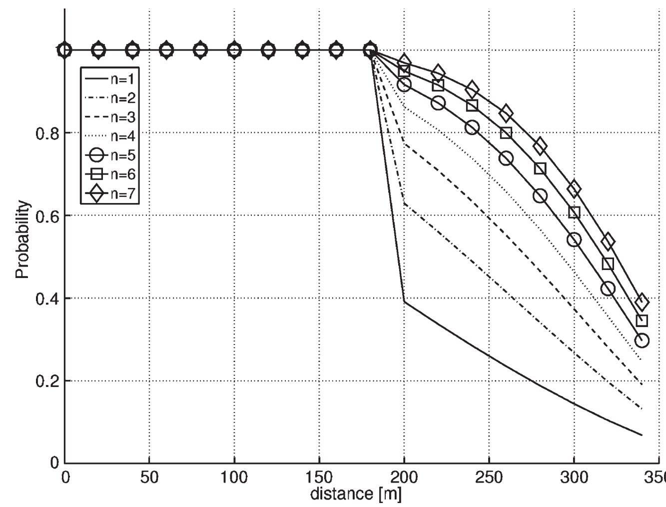


Fig. 15. Probability of coverage for a node in a randomly deployed network as a function of the number of nodes that are able to scan the PN n.

from the PN and increases with the number of nodes being able to scan the PN. Of course, if a node is within detectability range of the PN, then it is always covered, since it can detect the PN itself. The sudden drop at the detectability range is due to the approximation that a node cannot scan the PN outside the detectability range. In reality, the missed detection probability drops more gradually with decreasing SNR. This approximation, however, allows us to evaluate the effectiveness of distributed sensing.

To increase coverage, we can use (a combination of) the following five approaches.

1) The detectability range can be increased. This can be done by taking more samples. Now, the same performance can be achieved at a lower SNR (or equivalently, at a larger distance).
2) The interference range can be decreased. This can be done by lowering the transmission power in the licensed channels. The rate should also be lowered to keep the communication range constant. This way, the neighborhood remains the same, and the MAC layer is transparent for the routing layer.
3) The CR communication range can be increased, i.e., during the ATIM window, a CR should always operate at full power.
4) Several hops can be used. In the extreme case, we can close down a channel for the entire network, but then we risk losing opportunities in the spatial domain. If we predefine the maximum number of hops we would like to use, then we can extend the minislot protocol to support this. For instance, if we want to cover over two hops, we use not one time slot per channel but two. The extra time slot is used to indicate an indirect presence of a PN (i.e., if you hear somebody with a positive scan of a PN). It should be easy to program this so that it can be done within the same minislot protocol. No extra communication overhead is then incurred (apart from doubling the number of time slots in the minislot protocol).

5) We can also deploy extra scan nodes (randomly or not). Their functions could be limited to scanning and participating in the minislot protocol on the control channel. The benefit from this approach is not only an increase in coverage, but guarantees can now be given to the primary technology, since the topology is controlled. The downside is an extra hardware and deployment cost.

VIII. Conclusion

We have proposed a distributed MMAC protocol as enabler for CR networks. Contrary to standard work on MMAC protocols, which assumes all nodes get equal access to the medium, we have developed a protocol with recognition of PUs in the network. The protocol is based on the timing structure from the PSM of IEEE 802.11 and is shown to improve performance by using spectral opportunities in licensed channels. It is shown to effectively protect the PUs from interference. For an active node, the scanning cost was shown to contribute only 5% to the total energy cost. This cost is compensated by a reduction in overhearing cost to achieve a 40% decrease in global energy consumption (for the reference scenario).

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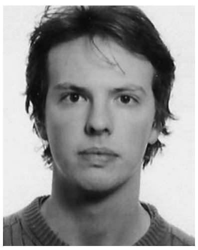

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