EM-MAC: An Energy-Aware Multi-Channel MAC Protocol for Multi-Hop Wireless Networks

Akhil Sivanantha*, Bechir Hamdaoui*, Mohsen Guizani†, Xiuzhen Cheng‡, Taieb Znati◇

*Oregon State University, sivanana@onid.orst.edu, hamdaoui@eecs.orst.edu
† Qatar University, mguizani@ieee.org
‡ George Washington University, cheng@gwu.edu
◇ University of Pittsburgh, znati@cs.pitt.edu

Abstract— **We propose an energy-aware MAC protocol, referred to as EM-MAC, for multi-hop wireless networks with multi-channel access capabilities. EM-MAC relies on iMAC's efficient channel selection mechanism to resolve the medium contention on the common control channel, enabling wireless devices to select the best available data channel for data communication. Our protocol saves energy by allowing devices that have not gained access to the medium to switch to doze mode until the channel becomes idle again. Simulations results show that EM-MAC reduces energy consumption when compared with iMAC.**

I. Introduction

Cognitive radios [1] empower wireless devices with the capability of switching among multiple spectrum bands, thus enabling multi-channel access. Such a capability needs to be complemented with the required software/protocols in order to effectively use and share the available multi-channel access opportunities. The focus of this paper is on developing an energy-efficient medium access control (MAC) protocol for multi-hop wireless networks by leveraging the conventional IEEE 802.11 CSMA MAC design [2, 3] to accommodate multi-channel access and energy awareness.

The popular IEEE 802.11 CSMA MAC protocol prevents nodes/devices from communicating while their neighboring nodes are involved in active communications. This reduces collision and avoids interference. However, it also yields unnecessary energy consumption at the neighboring nodes which, even though are not involved in active communications, they are kept in idle listening state, overhearing the communication that is taking place. Being in an idle listening state forces these neighboring nodes to consume energy. The IEEE 802.11 Power Saving Mode (PSM) [2, 3] does propose a method to save energy of those neighboring nodes that are not involved in data communication but for single-channel access networks. Our goal in this paper is to propose an energy-aware MAC protocol for multi-channel access networks.

Many MAC protocols have been proposed for wireless networks with multi-channel access capabilities during the last few years [4–11]. Most of these proposed designs designate one of the channels to serve for communicating control traffic needed for e.g. for selecting the best available data channel and updating nodes with current channels' states. This control channel is often referred to as common control channel (CCC). The rest of channels, referred to as data channels, are to be used for data communications. Although most approaches assume single, half-duplex transceiver (e.g., [5, 11]), others assume that wireless devices are equipped with two transceivers, one to be always tuned to CCC while the other is tuned to the data channel being selected for communication (e.g. [4]). When only one transceiver is assumed, devices are required to be periodically tuned onto CCC for an interval of time during which source-destination pairs negotiate and select their new data channel. Unlike in [4, 5, 11], the authors in [8] present a MAC design that requires one channel to be designated for CCC while the rest of channels are grouped into data-busy tone channel pairs. Here, each data channel is associated with a busy tone channel, where busy tone channels are used by receivers to prevent nearby transmitters from interfering with them. This MAC design, however, requires that each wireless device be equipped with one extra half-duplex transceiver, so as to sense busy tones while data is communicating.

Unlike the MAC design of [8], OS-MAC [11] solves interference/collision among nodes through CSMA-like mechanisms. OS-MAC does not require that nodes be equipped with two receivers, and hence, does not require extra hardware to be employed. It enables multi-channel access-capable users to seek and exploit channel opportunities effectively by dynamically adapting its operating parameters to network conditions. Although OS-MAC is shown to improve spectrum utilization through IEEE 802.11 CSMA/CA-like mechanisms, it is suitable for single-hop networks only. To tackle this, iMAC [12] has been proposed, which enables effective multi-channel access and sharing in multi-hop wireless networks. Both OS-MAC and iMAC are energy unaware, however.

This paper proposes an energy efficient multi-channel MAC protocol, referred to as EM-MAC, that uses the channel selection mechanism of iMAC [12] to effectively access and share multiple channels. EM-MAC saves energy by forcing nodes that are not active in data communications to switch

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to doze mode instead of staying idle. In data channels, nodes which are communicating stay active, while all neighboring nodes of sender and receiver switch to doze/sleep state. EM-MAC defines, specifies, and coordinates when and how nodes need to stay in active or in doze/sleep state. It also provides nodes with equal opportunities for communication on the data channels. We evaluate EM-MAC using simulations, and compare its achievable performances in terms of energy savings with those achievable with iMAC. Our results show that EM-MAC reduces energy consumption under various network parameters.

Next sections are organized as follows. EM-MAC design is provided in Section II, evaluation results are given in Section III, and concluding remarks are given in Section IV.

II. EM-MAC Protocol

We now describe the EM-MAC design. EM-MAC uses iMAC's channel selection mechanism to select the best available channels, and leverages medium access features and power saving techniques from IEEE 802.11's CSMA/CA and PSM designs. Like iMAC, EM-MAC's common control channel (CCC) is used by wireless nodes, every time they are not involved in active communications on one of the data channels, to listen and receive updated information regarding the multi-channel system load. Neighboring nodes wanting to communicate agree upon the data channel to be used for data communication on CCC, prior to switching to the chosen data channel for data communication. Once switched to the agreed upon data channel, nodes invoke the energy savings mechanism to save energy while communicating their data.

A. Common Control Channel (CCC)

It is in CCC where nodes invoke the channel selection mechanism to decide on the best data channel to use for data communication. This section describes the control frames, the data structures, and EM-MAC's operations in CCC.

1) Control Frames and Data Structures: We begin by introducing and defining the control frames and the data structures used in CCC.

iMAC's Request To Send (IRTS). Figure 1 shows the structure of IRTS. Most of the fields contain information similar to that of IEEE 802.11 CSMA/CA's RTS. Frame Control (FC) is unchanged and contains information about the version of the protocol, message type, details about fragmentation, power management, and privacy information. Duration field is modified to hold the time taken to send an ICTS, a Channel Selection Message (CSM), and 2 Short Inter Frame Spacing (SIFS) intervals. Receiver Address (RA) holds the address of the receiver, and Transmitter Address (TA) holds the address of the sender; both remain unaltered. Channel List holds an ascending ordered list of data channels which the sender proposes to the receiver for data communication. This list is constructed based on the load (number of nodes) the sender estimates in each of the data channels (construction of this structure is described later). Frame Check Sequence (FCS) remains unaltered.

FC	DURATION	RA	TA	CHANNEL LIST	FCS

Fig. 1. iMAC's Request To Send (IRTS) [12]

iMAC's Clear To Send (ICTS). Figure 2 shows the structure of ICTS. As in the case of IRTS, ICTS also contains information similar to that of IEEE 802.11 CSMA/CA's CTS frame. Frame Control (FC), Receiver Address (RA), and Frame Check Sequence (FCS) are unchanged. Transmitter Address (TA) holds the address of the receiver. Channel Identifier (Channel ID) holds the selected channel by the receiver. Duration field is modified to hold the time taken to send a Channel Selection Message (CSM) and a SIFS interval. This informs the neighbors of the receiver about the data channel that the receiver has chosen for data communication.

FC	DURATION	RA	TA	CHANNEL ID	FCS

Fig. 2. iMAC's Clear To Send (ICTS) [12]

Channel Selection Message (CSM). Figure 3 shows the structure of CSM. Frame Control (FC), Receiver Address (RA), Transmitter Address (TA), and Frame Check Sequence (FCS) fields are similar to those of IRTS and ICTS. Channel Identifier (Channel ID) holds the ID of the chosen data channel for data communication. It informs the neighbors of the sender about the data channel that the sender has chosen to communicate on.

FC	CHANNEL ID	RA	TA	FCS

Fig. 3. Channel Selection Message (CSM) [12]

Channel Information Table (CIT). Table I shows the structure of CIT, which is maintained by each node. It indicates the current estimated load of the channels; i.e., the number of communicating node pairs in each data channel. It holds the ID of the node (nodeID) and the time (t) at which the corresponding node moved to the chosen data channel.

TABLE I
Channel Information Table (CIT) [12]

Channel ID	Nodes(Node ID, Time)
Channel 1	(X,t1), (Y,t2)
⋮	. . .
Channel n	· · ·

2) Operation: When in CCC, nodes use the channel selection mechanism and the control frames and data structures discussed earlier to select the best available data channel. Firstly, the sender node computes/updates its CIT, for an ascending ordered list of channels, based on the load estimated in the data channels. This CIT list is then sent by the sender as part of the IRTS. Now the receiver also updates its CIT based on the load in the channels that the receiver observes, and finds the first channel from the sender's list having the highest rank based on its own ranking list of channels. When some channels reflect the same information, then the highest ranked channel from the sender's list is taken. Once selected, the receiver sends an ICTS to inform the sender as well as its neighbors about the selected channel. Once the ICTS is received by the sender, the sender sends a CSM to inform its neighbors about the chosen data channel. In addition to informing the neighbors of receiver and sender by means of ICTS and CSM respectively, this handshaking also helps nodes to update their CIT. Whenever an ICTS or CSM is transmitted, the corresponding neighbors update their CIT accordingly. In order to keep CITs up to date, nodes are forced to switch back to CCC after being in the data channel for a duration of length T (a system-wide constant time), which is the maximum time nodes can spend on the selected data channel. These frames also help in solving the hidden node problem at CCC. IRTS and ICTS function as a way to control access to CCC, so neighboring nodes which receive an IRTS or ICTS set their Network Allocation Vectors (NAVs) to the duration specified in the corresponding frame, and defer access to CCC until this duration expires. The exponential backoff mechanism of IEEE 802.11 [2, 3] is used on data channels to reduce collision.

B. Data Channel (DC)

Once node pairs select their best data channel, they switch to it to communicate their data. It is while communicating in their data channels, nodes invoke the power savings mechanism to save energy. This section describes the new control frames added to save energy, and illustrates EM-MAC's operations in data channels.

1) Control Frames: We begin by introducing the control frames used in data channels.

Energy-Aware Request-To-Send (EARTS). Figure 4 shows the structure of EARTS. The fields contain information similar to that of IEEE 802.11 CSMA/CA's RTS. Frame Control (FC) is unchanged and contains information regarding the protocol's version, message type, details about fragmentation, power management, and privacy information. Power management bit is set to 1 in order to indicate that our power saving mode is on. Duration field is renamed as Energy-Aware Interval (EAI) and modified to hold the time for Energy Aware Interval. Receiver Address (RA) holds the address of the receiver, and Transmitter Address (TA) holds the address of the sender; both remain unaltered. Frame Check Sequence (FCS) remains unaltered. It helps in informing the neighbors of the sender about the energy aware interval.

FC	ENERGY AWARE INTERVAL	RA	TA	FCS

Fig. 4. Energy-Aware Request-To-Send (EARTS)

Energy-Aware Clear-To-Send (EACTS). Figure 5 shows the structure of EACTS, which is similar to that of IEEE 802.11 CSMA/CA's CTS. Frame Control (FC), Receiver Address (RA), and Frame Check Sequence (FCS) remain unchanged. Power Management bit is set to 1 in FC in order to indicate that power saving mode is on. Duration field is renamed as Energy-Aware Interval (EAI) and modified to hold the time for Energy Aware Interval. It helps in informing the neighbors of the receiver about the energy aware interval.

FC	ENERGY AWARE INTERVAL	RA	FCS

Fig. 5. Energy Aware Clear To Send (EACTS)

System Wide Time Constant (T). This is the duration during which nodes can stay on the data channel. At the end of each period, nodes must switch to CCC to update themselves with the current load of channels. It helps nodes maintain the latest information about the channels' load.

Energy-Aware Interval (EAI). Figure 6 shows the Energy-Aware Interval (EAI) and its constituents: the Energy-Aware Active Window (EA-AW) and the Energy-Aware Doze/Sleep Window (EA-D/SW). EA-AW informs communicating nodes about the length of their communication period; i.e., a window or period during which nodes stay in active or idle state based on whether the node is a communicating node or a neighboring node. EA-D/SW informs non-communicating nodes about the length of their doze or sleep state; i.e., a window or period during which neighbors of the communicating nodes stay in doze or sleep state.

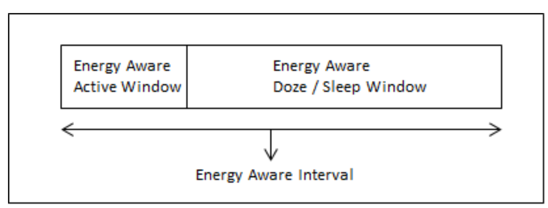

Fig. 6. Energy Aware Interval (EAI)

2) Operation: Figure 7 depicts EM-MAC's operations. Nodes are equipped each with a single, half-duplex transceiver, and hence, when they are communicating on data channels, they end up not updating their CIT. Thus, they might not have the most up to date channel information. During their stay in the selected data channel, nodes follow a

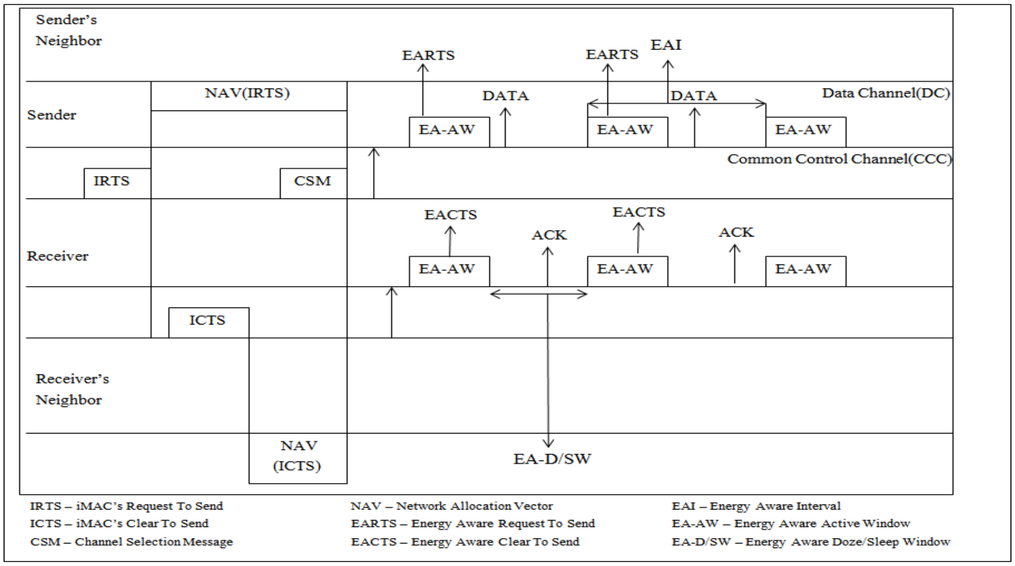

Fig. 7. EM-MAC's operations

mechanism combining IEEE 802.11's CSMA/CA and PSM features. As described in previous sections, EARTS and EACTS are introduced in addition to the normal DATA and ACK frames to help resolve the medium contention. Duration fields such as the EAI field defined earlier helps in informing the neighboring nodes to switch to active state and try to access the medium for its communication after every such an interval.

Nodes wanting to communicate contend with neighboring nodes for gaining access to the chosen data channel once all move to the data channel. For this, prior to sending its data, a sending node sends an EARTS control frame, which has information about the sender, receiver, as well as about the energy aware interval. Once they overhear the EARTS, all neighbors of the sender switch to a doze/sleep state after the EA-AW and restrict themselves from being part of any communication. Once the receiver receives an EARTS, it responds by sending an EACTS. Like in the case of EARTS, once they overhear the EACTS, neighbors of the receiver switch to doze/sleep state after the EA-AW and restrict themselves from being part of any communication. Neighboring nodes of the sender and the receiver stay in doze/sleep state for the entire duration of the energy aware interval, as indicated in EARTS and EACTS. When the energy aware interval expires, all nodes become active and nodes wanting to communicate contend with each other again through the EARTS/EACTS message exchange, in order to gain access to the medium for their data communication. The exponential random backoff mechanism, similar to that of IEEE 802.11, is used to further reduce collisions. Data is discarded by the sender after retransmitting EARTS seven times after failure to receive an EACTS. Nodes joining the data channel stay idle for a duration of length equaling the sum of EA-AW and EA-D/SW if they overhear ongoing communications. Once they overhear an EARTS or EACTS, they get aligned to the communication. Nodes which do not receive an EARTS or EACTS follow EA-AW and EA-D/SW for their idle and doze/sleep state durations.

III. Performance Evaluation Results

We now assess the effectiveness of EM-MAC vis-a-vis of its ability to save energy.

A. Simulation Setup

We implement EM-MAC and evaluate its energy savings by varying number of nodes, number of channels, and transmission range. Table II depicts the network parameters used in our simulations. We set the area of the simulated network to 1000x1000, and randomly generate and distribute nodes over this area. Based on the range of transmission, each node determines and creates the set of neighboring nodes. For each node pair communicating on a particular data channel, we measure the energy consumed by the pair under both iMAC and the proposed EM-MAC. For both EM-MAC and iMAC, we measure and compute the total energy consumed by all node pairs across the system. Power consumptions values for idle, send/receive, and doze/sleep are: y equals 3 times x and z equals 0.07 times x, where x is the power consumed by the pair when it is in an idle state [13]. Energy Aware Interval (EAI) is set to 0.1 [3].

B. Impact of Number of Nodes

We first study the impact of number of nodes on energy consumption. For this, we set a=1000x1000, b=100, x=0.75, y=2.25, z=0.0525, n=5, A=0.025 and B=0.075, and calculate

TABLE II
SIMULATION SETUP PARAMETERS

Symbol	Parameter Description
a	Simulated network setup area
b	Transmission range
N	Number of nodes
M	Number of channels
A	EA-AW interval
B	EA-D/SW interval
x	Idle state power consumption
y	Send and Receive (together) power consumption
z	Doze/Sleep state power consumption
n	Number of energy aware intervals

the total consumed energy by iMAC (referred to as E^{iMAC}) and EM-MAC (referred to as E^{EM-MAC}). Here, N is varied from 10 to 500. Figure 8 shows the consumed energy as a function of the number of nodes for M=5 and M=10 (M is the number of channels). When N increases, E^{iMAC} and E^{EM-MAC} increase as well. Observe that E^{iMAC} and E^{EM-MAC} when M=10 are greater than when M=5, but in both cases E^{EM-MAC} is smaller than E^{iMAC}. The figure shows that the higher the N, the greater the energy savings. Given that the transmission range is fixed, as N increases, the per node average neighboring nodes also increases, which in turn increases contention on data channels. Under EM-MAC, nodes that do not gain access conserve energy by switching to doze/sleep state. This is not the case for iMAC, where nodes stay in idle listening state when they are not communicating, which consume more energy than when they are in doze/sleep state as in EM-MAC.

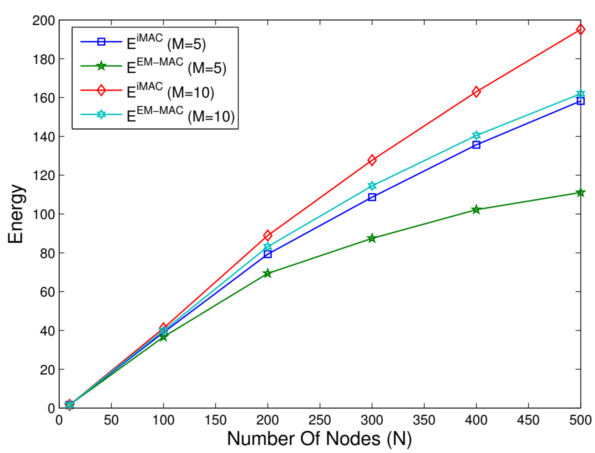

Fig. 8. Energy consumption when varying the number of nodes

C. Impact of Number of Channels

To study the impact of the number of channels, we fix a=1000x1000, b=100, x=0.75, y=2.25, z=0.0525, n=5, A=0.025 and B=0.075, and vary M from 1 to 10. Figure 9 plots consumed energy for N=100 and N=500. Observe that E^{iMAC} and E^{EM-MAC} when N=500 are greater than when N=100, but E^{EM-MAC} is smaller than E^{iMAC} in both cases. Increasing the number of channels gives the nodes more options to pick for data communication and hence reduces contention on the data channels. This can be seen from the figure where the gap between iMAC and EM-MAC decreases as we increase the number of channels. Our results show that EM-MAC consumes less energy when compared with iMAC.

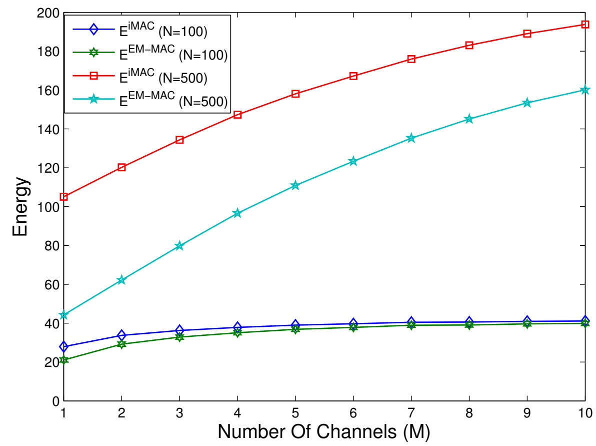

Fig. 9. Energy consumption when varying the number of channels

D. Impact of Transmission Range

To study the impact of the transmission range, we fix a=1000x1000, N=500, x=0.75, z=0.0525, n=5, A=0.025 and B=0.075, and vary the transmission range b from 50 to 150. y depends on the transmission range here. Figure 10 plots the consumed energy for various numbers of channels. Observe that an increase in b results in an increase in E^{iMAC} and E^{EM-MAC}. The figure also shows that E^{iMAC} and E^{EM-MAC} when M=10 are greater than when M=5. As the transmission range increases, the number of neighbors increases, which in turn results in an increase in the contention on the data channels, as well as the possibility of nodes being in idle listening state (for iMAC) and in doze/sleep state (for EM-MAC), which led to a decrease in the energy consumption when EM-MAC is used instead of iMAC.

IV. CONCLUSION

We propose an energy-aware multi-channel MAC protocol for multi-hop wireless networks, and show that it reduces energy consumption when compared with iMAC via simulations.

REFERENCES

[1] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, and Shantidev Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks*, 2006.

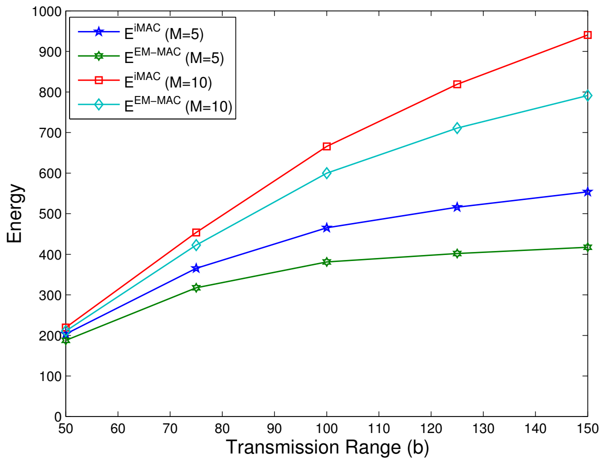

Fig. 10. Energy consumption when varying the transmission range

[2] "IEEE 802.11 Standard Specification," *http://standards.ieee.org/getieee802/download/802.11-2007.pdf*.

[3] Matthew S. Gast, *802.11 Wireless Networks: The Definitive Guide*, O'Reilly, 2005.

[4] S. Wu, C. Lin, Y. Tseng, and J. Sheu, "A new multi-channel MAC protocol with on demmand channel assignment for multi-hop mobile ad hoc networks," in *Proceedings of Inter. Symp. on Parallel Architectures, Algorithms and Networks*, 2000, pp. 232–237.

[5] J. So and N. Vaidya, "Multi-channel MAC for ad-hoc networks: Handling multi-channel hidden terminals using a single transceiver," in *ACM Proceedings of MOBIHOC*, 2004, pp. 222–233.

[6] C. Zou and C. Chigan, "On game theoretic DSA-driven MAC for cognitive radio networks," *Computer Comm.*, vol. 32, no. 18, 2009.

[7] S. Sankaranarayanan, P. Papadimitratos, A. Mishra, and S. Hershey, "A bandwidth sharing approach to improve licensed spectrum utilization," in *IEEE Inter. Symp. on New Frontiers in Dynamic Spectrum Access Networks*, 2005, pp. 279–288.

[8] L. Ma, X. Han, and C. C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks," in *IEEE Inter. Symp. on New Frontiers in Dynamic Spectrum Access Networks*, 2005, pp. 203–213.

[9] Kaveh Ghaboosi, Matti Latva-aho, and Yang Xiao, "A distributed multi-channel cognitive MAC protocol for IEEE 802.11s wireless mesh networks," in *Proceedings of The Third International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, 2008.

[10] M. Timmers, S. Pollin, A. Dejonghe, L. Van der Perre, and F. Catthoor, "A distributed multichannel MAC protocol for multihop cognitive radio networks," *IEEE Tran. on Vehicular Technology*, vol. 59, no. 1, 2010.

[11] Bechir Hamdaoui and Kang G. Shin, "OS-MAC: An efficient MAC protocol for spectrum-agile wireless networks," in *IEEE Transactions on Mobile Computing*, August 2008.

[12] Megha Maiya and Bechir Hamdaoui, "iMAC: Improved medium access control for multi-channel multi-hop wireless networks," *Wireless Communications and Mobile Computing Journal*, 2011.

[13] Daniel de O. Cunha, Lus Henrique M. K. Costa, and Otto Carlos M. B. Duarte, "Analyzing the Energy Consumption of IEEE 802.11 Ad Hoc Networks," *www.gta.ufrj.br/ftp/gta/TechReports/CCD04a.pdf*.