Cognitive Wireless Mesh Network without Common Control Channel Evaluated in NS-3

Dick Carrillo
Research and Development Center from Brazil - CPqD
Campinas, Brasil
dickm@cpqd.com.br

***Abstract*—The CPqD Cognitive Mesh Network (CCMN) has been developed with traditional cognition elements, such as energy detection based sensing and with the ability to switch the data channel to take advantage of any available channels on a given radio-electric spectrum band. Many of the solutions that utilize cognitive mesh networks are based on the fact that it uses a common control channel (CCC) to manage the system. Therefore the *Multi-Channel - One Interface Manager* (MC-OIM) algorithm was developed to maximize channel usage with a system that does not depend of any CCC . The MC-OIM algorithm was evaluated using network simulator ns-3 and simulation results were validated with testes that were done in a real scenario.**

I. Introduction

Since the beginning of this century, there was a great development in wireless telecommunications industry. 2G (Mobile Second Generation) provided the possibility to increase the number of simultaneous phone calls sharing the same RF spectrum. 3G technology (Mobile Third Generation) increased the data rate transmission and improved the quality of voice services. In recent years, some standards, such as the 3GPP Release 8 (Long Term Evolution - LTE) and 802.16e/m (Worldwide Interoperability for Microwave Access - WiMAX), improved the spectral efficiency of wireless channel using OFDM (Orthogonal Frequency-Division Multiplexing).

The 5G tries to address the accelerated evolution of mobile applications and system services, for example: 3D multimedia, HDTV (High Definition TV), VoIP (Voice over IP), gaming, e-Health, and Communication Car to Car. The 5G seeks to achieve, comparing to 4G (Mobile Fourth Generation), 1000 times higher volume of data traffic in the mobile network per unit area, and a number of 10-100 times greater connected mobile devices. The 5G also increases data rate transmission for each user and the time of cell phone battery life to about 10 times reducing also latency in 5 times. It is postulated that data rate in 5G scenarios should achieve values in the order of 10 Gbps [1].

The mass development of wireless applications will generate a great diversity in characteristics of wireless communication systems. LTE-B, for example, has as a target to complement cellular service with Wi-Fi (Wireless Fidelity - IEEE 802.11) to further increase the overall traffic capacity. The integration between LTE and Wi-Fi is currently supported on the core network, but considering that public Wi-Fi deployed by cellphone operators is becoming more popular, it will be demanded a new integration between these two radio technology access. Thus, a 5G requirement is to ensure coverage using hot spots in areas with high users density. To get this target it is suggested to use Dynamic Wireless Mesh Networks -DWMN [2]. The DWMN network is a WMN (Wireless Mesh Networks) that includes in its architecture cognitive radio concepts.

Considering that sudden spectrum demands may occur in dense and congested cities this paper presents the results of a DWMN implementation in a real world scenario and simulation done using ns-3 (Network simulator 3), it could potentially be used, in a future solution, by any telecommunication system covering 5G. This DWMN is named as CPqD Cognitive Mesh Network (CCMN).

CCMN could be simulated using ns-3 if several changes are done in its network layers. For example, a device needs multiple wireless interfaces to transmit, receive and negotiate with neighboring nodes. The PHY need to be able to sense and detect PUs, the medium access control (MAC) needs to decide and initiate hand-off to another available channel when a PU is detected, and the routing protocol needs to exchange the neighboring node's current listening channel. In [3] some ns-3 modules were developed in order to fully realize a cognitive radio (CR) extension for ns-3. Our main contribution is to complement that CR extension with some detailed features to test scenarios in which is not considered a common control channel. In addition CCMN is developed, installed and tested at CPqD facilities.

In CCMN is implemented the Multi Channel - One Interface Manager (MC-OIM) algorithm , which allows the control channel management without depending of a common control channel (CCC). This feature provides an important gain in all system throughput.

In literature [4]–[6] there are some contributions aimed to optimize the performance of cognitive mesh networks considering that there is no common control channel. All of these articles achieve a throughput similar to this article although all of them only show results obtained through simulation.

The paper is organized as follows: in Section 2 is made description of the cognitive mesh network architecture. Section 3 describes the architecture of CPqD Cognitive Mesh Network (CCMN). Section 4 discusses the existing CR extension for ns-3 and contributions done to it in order to test scenarios that does not consider CCC. Description of the experimental network which is used to validate the algorithms and the evaluation of the results are presented in Section 5. In Section 6, is described the conclusions. Finally we present some observations for future work.

ISSN 2305-7254

II. Cognitive Wireless Mesh Network

This section describes the cognitive wireless mesh network architecture, also describes the routing and switching channel process.

A. Architecture of cognitive wireless mesh network

The elements of a cognitive wireless mesh network are mainly cognitive mesh routers which coexist with primary users (PUs). These PUs can be, for example, IEEE 802.11 access points, as well as devices based on Bluetooth or Zigbee. In urban areas with a high user density, experimental results show that these devices occupy most of the spectrum in the ISM (Industrial, Scientific and Medical) band [7].

Cognitive mesh routers are wireless devices equipped with multiple Wi-Fi radio interfaces (other air interface technology beyond Wi-Fi could be used either). One of those interfaces is used to exchange control messages between routers [8] and other interfaces are used to receive and transmit packages in different channels. A particular case of this architecture was developed in [9], in which the cognitive network has a Wi-Fi interface on each router, this interface is used to transmit and receive data packets on 4 different channels, those channels are being exploited opportunistically using cognitive network rules. The interface used to exchange control messages is fixed to a common control channel (CCC) to disseminate routing information and update the channels status information.

B. Routing and switching channels of cognitive wireless mesh network

Routing protocols enable routers to discover multiple paths toward gateway or any other specific destination. Then use alternative routes when the initial path is not available or in cases that the path is congested due to traffic from other routers or under the PU presence.

There are routing protocols on-demand [10], [11] which uses ETX (Expected Transmission Count) metric [12], other using the ETT (Expected Transmission Time) metric or WCETT (Weighted Cumulative ETT) [13] metric, which are not appropriate when the path between two routers is fixed and the link quality is modified by PU activity. In [14] is described an algorithm called Urban-X that implement a forwarding mesh structure. In this algorithm, the message is transmitted between routers. This message contains information of the next route path candidate.

C. Designation techniques in scenarios with multiple channels and multiple interfaces

In [15] it is presented various scenarios with many communication channels, however the number of available interfaces is considerable small. In literature, there are strategies used to designate interfaces, these strategies are organized into:

1) Static assignment: this strategy assigns each interface a specific channel for a long period of time [16], [17].
2) Dynamic assignment: This type of strategy allows any interface to be assigned to any channel and to be changed from one channel to other. In this strategy, it is critical to use a coordination mechanism to ensure that the interfaces are on the same channel [18], [19].
3) Hybrid assignment: this strategy combines the previous two strategies. In this case, it is applied static assignment for some interfaces and dynamic assignment to others. In [20] it is showed an example of a hybrid approach.

III. CCMN - CPqD Cognitive Mesh Network

A. Architecture of CCMN

The CPqD Cognitive Mesh Network (CCMN) has two types of cognitive routers, each one equipped with multiple Wi-Fi radio interfaces. These routers were named Management Cognitive Mesh Router (MCMR) and Forwarding Cognitive Mesh Router (FCMR), these routers are described below:

1) MCMR: It is constituted by three radio interfaces (R1, R2 and R3). R1 is a Wi-Fi interface that operates in frequency range of sub-1 GHz. R2 is a RF interface responsible for spectrum sensing. R3 is another Wi-Fi interface that operates in 2.4 GHz frequency band.
2) FCMR: constituted by two RF interfaces (R1 and R3). These interfaces retain the same characteristics of MCMR interfaces.

R1 interface is responsible for transmission of data between FCMRs and MCMR. This interface operates on a channel that is dynamically adjusted according to PU activity.

R2 interface is basically composed by an antenna which operates in the frequency band sub-1GHz. The signal received by R2 is used as the signal input for energy detection algorithm in order to check spectrum signal only outside the band, in contrast of what is traditionally done in the literature(in-band and out-band sensing simultaneously) [9].

R3 interface is responsible for creating connectivity between the network sub-1 GHz and devices operating in the commercial 2.4 GHz band (smart-phones, tablets, etc.).

In [14] it is being presented a cognitive multi-radio architecture based on principles of dynamic spectrum access to improve throughput in mesh networks. It also contemplates the use of an algorithm that optimizes the allocation of traffic channels when there is any PU.

Whereas there is no possibility of using a CCC, the control information will be transmitted on the data channel. So we need to ensure that all routers in the mesh network always commute to the same channel, even having a PU with high channel occupation that could harm the connection between routers. This technique is known as Frequency *Rendez-Vous* [21]. To reduce the effects of scenario described above, it is developed the algorithm called Multi Channel - One Interface Manager (MC-OIM), which is detailed later.

B. Spectrum sensing

The CCMN spectrum sensing is done with a energy detector sensor implementation. Energy detector sensitivity ensures protection of PU [22].

To implement the energy detector algorithm which is used to estimate the presence of the PU, it is used a Software Defined Radio (SDR). The SDR calculates the statistic of samples collected by R2 interface. This signal is represented by $r(n)$, so average power is estimated using the relationship of equation 1, in which, M is the number of samples used by SDR.

$$Z_{DE}(n) = \frac{1}{M}\sum_{n=0}^{M-1}|r(n)|^2 \tag{1}$$

The average power represented by Z_{DE} is compared with a threshold called λ, which is dynamically calculated based on a given value of false alarm probability. The optimal λ calculation details are outside the scope of this article.

The threshold λ is used to decide if the channel is occupied or unoccupied according to nexus defined in equation 2.

$$if\ Z_{DE} > \lambda \rightarrow H_0 \tag{2}$$

$$if\ Z_{DE} =< \lambda \rightarrow H_1 \tag{3}$$

in which, H_0 and H_1 represent a hypothesis that channel is being occupied by the PU and the channel is not being occupied, respectively.

Based on information of equations 1 and 2, the MCMR will calculate the average power for all available channels. This occupation statistic is represented by the variable Z_j.

Equation 4 is used to select the channel with less occupancy from the group A. This group A represents all available channels.

$$i = arg\max_j \frac{1}{Z_j}, j \in A \tag{4}$$

Equation 4 is used by MCMR to select the best channel and pass this information to all other routers through the channel that is being shared by control and data plane. Thus, each router is always updated with the ranking of the best channels calculated by cognitive controller.

C. Multi Channel - One Interface Manager (MC-OIM)

The MC-OIM algorithm was developed due to necessity of using a system without a common control channel, in that way at system level the scenario is summarized to a system with one interface and multiple channels.

MC-OIM is described in algorithm 1: step 1 uses the process called ping-pong, which will be responsible for defining the connectivity status between routers. This algorithm basically consists in broadcasting permanently beacons among all routers, when this beacon is received, the variable $IsAlive$ switches to 1, otherwise it switches to 0. Thus, the algorithm contemplates two possible states for variable $IsAlive$:

- $IsAlive = 1$, the communication link between routers is working normally.
- $IsAlive = 0$, the communication link between routers has any fault.

The step 2 is done in order to validate the channel based in two well defined parameters:

$$P_i \rightarrow Datatransmission\ flow \tag{5}$$

$$Z_i \rightarrow Ocupancy\ of\ channel\ i \tag{6}$$

The parameter P_i is calculated by taking advantage of MAC layer algorithm that controls data rate on IEEE 802.11 standard. This algorithm is called Minstreal [23]. Minstrel algorithm classifies transmission rates using integer numbers [0,1,2,3,4,5,6,7,8,9]. For example, if data transmission flow is too low, Minstrel will use a rate equal to zero, in the same way, if the data transmission flow is too high, the Minstrel will use a rate equal to nine.

The parameter Z_i, which was defined in Equation 1, represents the channel occupation. The calculation of this statistic depends on spectrum sensing quality to determine if a channel is in occupied or non occupied state. Details about calculation of this statistics are beyond the scope of this article. After the previous steps, it is applied product operation between parameters P_i and $\frac{1}{Z_i}$. This operation is repeated in all available channels in order to obtain the vector Q.

The Step 3 uses as the primary input the vector Q , which has been calculated in the previous step. Thus, the vector elements are arranged in descending order and the first element of this vector indicates the channel with greater chance of being taken as the transmission channel (best channel).

Algorithm 1 Main step by step of MC-OIM algorithm

STEP 1: Message transmission between MCMR and FCMR to check link communication between routers

Check $IsAlive_{jk}, j \neq k, \{j,k \in G\}$

STEP 2: Getting metric to be used as trigger decision

for $i \in F, F \rightarrow Set\ of\ Channels$ **do**
    $Q \leftarrow \frac{P_i}{Z_i}$
end for

STEP 3: Ranking channel update

while $Q \neq 0$ **do**
    $C \leftarrow descendingOrder(Q)$
    $i^* \leftarrow C[0]$
    if $ActualChannel = 0$ **then**
        $switch\ to\ channel\ i^*$
        if $ActualChannel = 0$ **then**
            $i^{**} \leftarrow C[1]$
            $switch\ to\ channel\ i^{**}$
        end if
    end if
end while

D. Routing and switching channel

Whereas implementation of CCMN focuses on network performance evaluation in cognitive scenarios, the distribution of routers is made so that the routing protocol is fixed between routers to ensure that the routing table is always the same.

The channel switching scheduling is based on information of channel ranking provided by equation 4. The resource manager details of cognitive network deployed at CPqD campus are beyond the scope of this article but they are detailed in [9].

The difference of MC-OIM algorithm in relation to practical implementations of cognitive networks [9] is that it does not run any in-band sensing process (in-band sensing is not done). When PU and WMN use the channel at the same instant of time, the channel switching is performed to the channel i^*, considering that synchronization is a crucial factor on this algorithm, if routers can not synchronize, each WMN will switch to channel i^{**}, called emergency channel.

A key element in practical implementation of MC-OIM algorithm is that all routers need to be synchronized, therefore all cognitive routers run a NtpClient-based script to ensure network synchronization. So, WMNs Channel are changed in cases there is a new best channel. The idea is that, in contrast of what was proposed in [9] Wi-Fi interfaces are not turned off at any moment.

IV. NS-3 SIMULATOR MODEL FOR CCMN

In this section, we present the architectural model of ns-3 extension proposed in [3]. It is described the building blocks of the extension, followed by an explanation of the needed changes at some network layers to simulate the CCMN in a non CCC environment.

A. Building blocks for the simulator

The spectrum management global block serves as a black box to the other modules in ns-3. Different layers in the network simulator keep a reference to the spectrum Manager instance and tie their cognitive functionality via exposed APIs and hooked listeners. The Spectrum manager block contains several sub-modules that map to the cognitive cycle, which are briefly described next.

- Spectrum Sensing/Database Query. This block is responsible for checking whether a PU exists in a given channel within s specified period of time.
- Spectrum Decision. In this block, several policies are implemented, for example: a policy to determine whether a hand-off should be performed and a policy to determine which channel a hand-off should happen.
- Spectrum Mobility. This block initiate the hand-off protocol in the current node.
- Spectrum Sharing. This sub-module uses the built-in carrier sensing MAC 802.11 standards in ns-3 to make sure that the available spectrum is shared in a collision-free manner between the CR nodes that chose to transmit on the same channel.

More detail information of Spectrum Manager block, please refer to [3]

B. modifications to ns-3 for non CCC scenario

The main contribution related to ns-3 environment is that we included two main differences in comparison to [3]. One of these differences is at *link and Physical layers*, here a CR node may define any number of these cognitive interfaces. Each interface constitutes of three separate MAC-PHY, if this node is a MCMR, or two separate MAC-PHY, if this node is a FCMR. The third MCMR interface is a typical 802.11 operating at a commercial 2.4GHz band (it represents R3 interface described at section III). The R1 interface implementation at ns-3 simulator is to transmit data messages to neighboring nodes (TX) and this same interface is used to transmit check link communication called $IsAlive_{jk}$ between nodes as it was described in 1. This interface is switchable between different channels to transmit queued data packets that are destined to different nodes. Other difference is R2 interface R2 which is a switchable receiving interface, which senses for PU activity to perform out band sensing to populate the ranking channel information detailed in algorithm 1. The sensing state in the PHY layer uses the Spectrum Manager APIs. See FCMR Cognitive Interface block in Fig. 1.

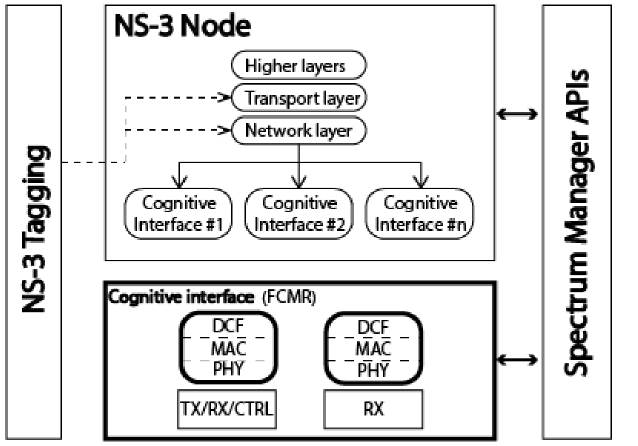

Fig. 1. FCMR Cognitive Interface block architecture considered at ns-3 implementation

V. EXPERIMENTS WITH CCMN

This section presents details and results of the experiment done with the CCMN at CPqD facilities.

A. CCMN configurations

As stated in Section 2, the CCMN is composed by two types of cognitive routers: MCMR and FCMR. In this section, these routers will be described, focusing on issues related to simulation and implementation of CCMN.

The experimental network simulated with ns-3 and installed at CPqD consists of one MCMR and two FCMR.

MCMR is basically composed by an embedded system responsible for running MC-OIM algorithm using information from the following sources:

1) The power detector, which provides the information that will be used to calculate occupation channel, this detector energy runs on a SDR.
2) The mesh router, which provides data rate information related Minstreal algorithm. Here is made a cross-layer in Wi-Fi standard architecture(MAC / PHY) to perform the channel switching sequences and also the algorithm that determines the status of the variable $IsAlive$.

The FCMR router has the same components used in MCMR, it only differs from MCMR because it does not consider any SDR device responsible for implementing energy detection (no spectrum sensing in this router).

The communication between routers (MCMR and FCMRs) is made by Wi-Fi Mesh interface, switching between frequency channels 763 — 768 — 773 — 778 MHz. The network topology was designed in a way that communication between routers located in building 11 (point 1) and CPqD Tower (point 2), is possible only through routing using router located in

Building 12 (point 3), as shown in Fig. 2. In every router (all of them) is possible to use Wi-Fi technology operating at 2.4 GHz to access Internet because each router has two WiFi interfaces, one operating at 1 GHz sub-frequency band and the other operating in 2.4 GHz frequency band.

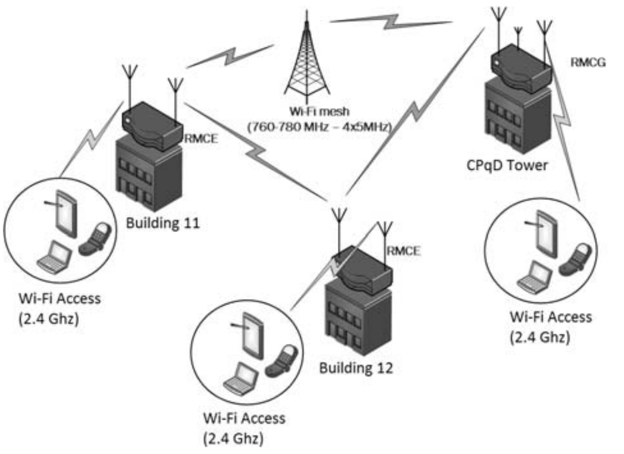

Fig. 2. Experimental network topology of CCMN installed at CPqD facilities

B. Primary user model

To emulate the primary user spectrum occupancy an OFDM transmitter is used. Automatic switching of PU follows an arbitrary sequence, this sequence could be:

1) PU sequential mode: the primary user has an incremental change in channel operation, for example: $CH1 \rightarrow CH2 \rightarrow CH3 \rightarrow CH4$
2) PU random mode: the primary user has a random pattern to perform exchange channel, for example: $CH3 \rightarrow CH1 \rightarrow CH2 \rightarrow CH4$

The PU is generated in frequencies that correspond to sub-1 GHz frequency bands, according to the following characteristics:

- PU signal generation is done only in one of the four available channels, it means that it was not generated simultaneous in two or more channels.
- PU is generated using a low SNR, it is typically greater than 3 dB.
- PU uses OFDM with BPSK modulation, a typical data rate of 2.5Mbps@5MHz BW — FFT 512 — CP 128.

In the case of ns-3 simulation it is used a database file, exactly the way that is suggested in [3] following the patterns defined above.

C. Experimental results

Tests were run using iperf generating TCP traffic in different scenarios to distinguish system performance in cases MC-OIM algorithm is used for both cases: simulation scenario and real implementation scenario.

Results are shown in Table I: 6 Mbps is used as a throughput reference which is the upper limit (scenario where the mesh network has no cognition algorithm and PU activity is turn off). In all measurements, the average throughput showed a gain when MC-OIM algorithm is considered.

TABLE I. AVERAGE THROUGHPUT WITH TCP TRAFFIC USING MC-OIM ALGORITHM.

Average Throughput [Mbps]		Primary User type	Throughput Gain [%]
with MC-OIM	without MC-OIM		
6	6	Without PU and without cognition	
5.23	4.83	Without PU	8.28%
4.94	4.43	Random PU	11.5%
4.83	3.73	Sequential PU	29.5%
5.5	4.1	Sequential PU simulated in ns-3	34%

VI. CONCLUSION

This paper has presented the architecture of simulation and real implementation of a DWMN network. This DWMN was named CPqD Cognitive Mesh Network (CCMN). It was simulated using ns-3 and developed/implemented in a real scenario within CPqD facilities.

The MC-OIM algorithm was inserted in all routers, this algorithm enabled the management of control channel without the necessity to use a common control channel (CCC). Besides it was not necessary to use a CCC. The algorithm MC-OIM, in both scenarios: simulation scenario with ns-3 and real implementation scenario, also generated an important gain in total throughput because channel capacity were better exploited. Tests performed using the MC-OIM algorithm showed in all cases a greater throughput compared to tests performed without using algorithm MC-OIM.

Validation of ns-3 simulation was done using real implementation result as a reference, in spite that data throughput are not exactly the same, qualitative result indicates that ns-3 cognitive radio implementing MC-OIM algorithm provides a gain. This ns-3 extension could be used to test bigger scenarios without the necessity of extra expenses in building real scenario setups.

FUTURE WORKS

As every radio cognitive project, it is important to validate the effect of interference caused by the MC-OIM algorithm to primary users.

ACKNOWLEDGMENT

The author thank the Ministry of Communications that through the Fund for the Technological Development of Telecommunications (FUNTTEL) finances the RASFA Project at CPqD.

REFERENCES

[1] E. Hossain, M. Rasti, H. Tabassum, and A. Abdelnasser, “Evolution toward 5G multi-tier cellular wireless networks: An interference management perspective”. IEEE M WC, 2014, Vol. 21, no. 3, 118-127.

[2] A. Gohil, H. Modi, and S. Patel, “5G technology of mobile communication: A survey”. *Intelligent Systems and Signal Processing (ISSP), 2013 International Conference on*, 2013, pp. 288-292.

[3] A. Al-Ali, and K. Chowdhury, “Simulating dynamic spectrum access using ns-3 for wireless networks in smart environments.” in *Sensing, Communication, and Networking Workshops (SECON Workshops), 2014 Eleventh Annual IEEE International Conference on*, 2014, pp. 28-33.

[4] Y. Dai, J. Wu, C. Xin, “Efficient Virtual Backbone Construction without a Common Control Channel in Cognitive Radio Networks,” IEEE J PDS, vol. 25, no. 12, pp. 3156-3166, 2014.

[5] J. Zhang and Z. Zhang, “Initial link establishment in Cognitive Radio Networks without common control channel,” in *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*, 2011, pp. 150-155.

[6] Y. Kondareddy, P. Agrawal, K. Sivalingam, “Cognitive Radio Network setup without a Common Control Channel,” in *Military Communications Conference, 2008. MILCOM 2008. IEEE*, 2008, pp. 1-6.

[7] D. Gokhale, S. Sen, K. Chebrolu, B. Raman, “On the Feasibility of the Link Abstraction in (Rural) Mesh Networks,” in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, 2008.

[8] P. Kyasanur, C. Chereddi, and N. H. Vaidya, “Net-x: System extensions for supporting multiple channels, multiple interfaces, and other interface capabilities,” *University of Illinois at Urbana-Champaign, Wireless Networking Group, Urbana, IL, Tech. Rep*, 2006.

[9] D. Carrillo, F. Mathilde, R. Yoshimura, J. Bazzo, “Red experimental cognitiva: Algoritmos y resultados,” in *Communications and Computing (COLCOM), 2013 IEEE Colombian Conference on*, 2013, pp. 1-5.

[10] A. Subramanian, M. Buddhikot, S. Miller, “Interference aware routing in multi-radio wireless mesh networks Wireless Mesh Networks,” in *Wireless Mesh Networks, 2006. WiMesh 2006. 2nd IEEE Workshop on*, 2006, pp. 55-63.

[11] S. Waharte, B. Ishibashi, R. Boutaba, D. Meddour, “Interference-Aware Routing Metric for Improved Load Balancing in Wireless Mesh Networks,” in *Communications, 2008. ICC ’08. IEEE International Conference on*, 2008, pp. 2979-2983.

[12] D. S. J. D. Couto, ; D. Aguayo, J. Bicket, and R. Morris, “A High-Throughput Path Metric for Multi-Hop Wireless Routing”. 2003.

[13] R. Draves, J. Padhye, and B. Zill, “Comparison of routing metrics for static multi-hop wireless networks,” 2004.

[14] W. Kim, A. Kassler, M. Di Felice, and M. Gerla, “Cognitive Multi-Radio Mesh Networks on ISM bands: A cross-layer architecture,” in *Performance Computing and Communications Conference (IPCCC), 2010 IEEE 29th International*, 2010, pp. 34-41.

[15] P. Kyasanur, N. H. Vaidya, “Routing and link-layer protocols for multi-channel multi-interface ad hoc wireless networks,” in *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 10, no. 1, pp. 31-43, 2006.

[16] R. Draves, J. Padhye, and B. Zill, “Comparison of routing metrics for static multi-hop wireless networks,” in *ACM SIGCOMM Computer Communication Review*, vol. 34, no. 4. ACM, 2004, pp. 133-144.

[17] A. Raniwala, K. Gopalan, T.-c. Chiueh, “Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks”. *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50-65, 2004.

[18] J. D. Dunagan, P. Bahl, R. Chandra, “Slotted seeded channel hopping for capacity improvement in wireless networks,” May 27 2008, uS Patent 7,379,447.

[19] J. So and N. H. Vaidya, N. H. “Multi-channel mac for ad hoc networks: handling multi-channel hidden terminals using a single transceiver,” *Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing*, ACM, 2004, pp. 222-233.

[20] S.-L.Wu, C.-Y. Lin. Y.-C. Tseng, and J.-P. Sheu, “A new multi-channel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks Parallel Architectures, Algorithms and Networks,” in Parallel Architectures, Algorithms and Networks, 2000. I-SPAN 2000. Proceedings. International Symposium on. IEEE, 2000, pp. 232-237.

[21] K. Bian, J.M. Park, “Maximizing Rendezvous Diversity in Rendezvous Protocols for Decentralized Cognitive Radio Networks,” in *IEEE J MC, 2013*, vol. 12, no. 7, pp 1294-1307.

[22] A. Chandran, R. Karthik, A. Kumar, R. Naidu, M. Siva, U. Iyer, R. Ramanathan, “Evaluation of energy detector based spectrum sensing for OFDM based cognitive radio,” in *Communication and Computational Intelligence (INCOCCI), 2010 International Conference on.* IEEE, 2010, pp. 163-167.

[23] D. Xia, J. Hart, and Q. Fu, “Evaluation of the Minstrel rate adaptation algorithm in IEEE 802.11g WLANs,” in *Communications (ICC), 2013 IEEE International Conference on,* 2013, pp. 2223-2228.