INVESTIGATING THE EFFECTS OF THE COMMON CONTROL CHANNEL CHALLENGE IN MULTICHANNEL COGNITIVE NETWORKS WITH HYPOTHETICAL SPECTRUM HOLE

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ABSTRACT

Multichannel MAC protocols have become a design choice of wireless access networks as they increase the achievable throughput. However, the implementation of a common control channel has been a challenge. The common control channel challenge has not been investigated in opportunistic networks where the availability of medium is temporary and unpredictable. The uncertainty of the availability of the channel coupled with the common control channel challenge makes this area an interesting research topic. Unfortunately, this challenge requires further investigation in Cognitive Radio Ad Hoc Networks (CRAHN), a promising next generation technology. The challenge makes an interesting study in CRAHN given the opportunistic access and use of channels. Given a hypothetical spectrum hole of any size coupled with the implementation of a control channel in a multi-channel environment, how much of good put can be realized and be effectively utilized for data transmission. We investigate the common control channel challenge in CRAHN through network simulations. The opportunistic nature of CRAHNs in the presence of the common control channel challenge is investigated. The simulation results show that the combination of the control channel challenge and the size of the spectrum hole degrade gracefully the network. Furthermore, the size of the spectrum hole has a bearing on good put. The results show that a big hole improves performance. Unfortunately, the opportunistic attribute of CRAHNs does not guarantee desirable spectrum holes.

KEYWORDS

Common Control Channel Challenge, CRAHN, Multi-Channel MAC

1. INTRODUCTION

The paper examines the effects of the common control channel and the size of the spectrum hole Cognitive Radio Ad Hoc Networks (CRAHN). The multi-channel approach is envisioned as one of the possible strategies which can be employed to increase the achievable bandwidth. On the other hand, the implementation of CRAHN addresses the scarcity and inefficient utilization of spectrum. The two techniques do complement each other in availing the much needed bandwidth in the wireless next generation networks (WNGN). However, the implementation and the saturation of the control channel is a challenge which requires further investigation. The common control channel is perceived to be a system bottleneck which degrades wireless access networks. The impact of the common control channel is expected to be huge when a small spectrum hole is smaller as compared to bigger ones. The paper explores and presents an in-depth analysis of the

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performance of the common control channel in congested networks. Extensive simulations show that the capacity of the control channel degrades the performance of networks with high traffic loads. The size of the spectrum hole has also an effect on the performance of the networks; A small hole constrains the network while a bigger one avails more data transmission opportunities. The common control channel challenge is investigated in scenarios with different number of channels ranging from 2 to 15 data channels. For each scenario, the number of nodes was increased steadily from 4 to 30. The following scenarios in terms of t he number of nodes were considered: 4, 6, 8, 10, and 30.

The paper is structured as follows: summery of multi-channel MAC schemes in CRAHN is presented in Section II. The related work is analyzed in Section III. Section IV and V, presents the simulation design and simulation results. The paper is concluded in Section VII.

2. MULTI-CHANNEL MAC SCHEMES

Multichannel MAC protocols increase the capacity of existing wireless access networks. Multi-channel MAC protocol designs have demonstrated some encouraging results. The schemes have shown an increase in achievable throughput is possible. As a result, multichannels have been considered in CRAHNs. Unfortunately, the emphasis has been on capacity. The common control channel challenge has not been investigated in opportunistic networks. This challenge requires further investigation in the context of CRAHNs. The common control channel challenge is investigated and how the size of the spectrum hole impacts on network performance. The size of the spectrum hole is also considered in relation to the achievable throughput.

There are a few configurations of multichannel systems which have been considered in research, for example multi-radio multi channel networks and single radio and multichannel networks. A single radio multichannel network is considered in the context of CRAHNs in this paper. The impact of the common control channel has been investigated elsewhere however; to the best of our knowledge its impact on opportunistic CRAHNs with varying sizes of spectrum holes has not been investigated. We explore the common control channel challenge in CRAHNs and investigate the saturation problem in detail, in different possible network scenarios. The paper contributes to the e implementation of multichannel CRAHNs networks.

3. RELATED WORK

The implementation of a common control channel in CRAHNs presents a number of design challenges. The control channel scheme leads to the saturation problem cited in [1] and [2]. In addition, the design of a global control channel is another option in CRAHNs. However, due to the opportunistic use of spectrum, the existence of such a global channel may be a design challenge. As a result, local control channel and switchable schemes have been proposed as possible solutions. However, despite the challenges of the global control channel approach, such a design challenge is preferred. The global control channel facilitates network connection and provides a secondary user (SU) with a platform to detect a PU and share sensing information. The information on PU activities can be determined and shared in a distributed manner subject to challenges cited in [3] and [4] through the control channel however, an always on control channel is desired and its reliability facilitates the discovery of neighbouring nodes in the CRAHNs [3]. In [5] the implementation of the control channel is subject to high signaling cost; however, though it saturates, its design is significant in network setup and in the exchange of control messages and in the sharing of the spectrum information.

One of the design challenges of CRAHNs is the optimization of sensing and transmission durations which impacts negatively on the achievable throughput. The shorter sensing times are desired however the PU detection accuracy should not be compromised. Such optimization relies on the availability of network wide sensing information and network cooperation [5]. The sharing of the sensing information can be possible given the availability of a global control channel which also facilitates cooperation among nodes in a distributed manner. This shows the significance of the control channel in CRAHNs which should be designed to address the saturation challenge.

As noted in [2], the design of a global control channel is a challenge however; the local control channel design approach can addresses the need for local observation, cooperative sensing and the sharing of spectrum information sharing at a local level. This facilitates cooperation in spectrum sensing and sharing [6]. Furthermore, the localization of the sensing activities in a cooperative manner can be considered as a design option which addresses mobility challenges.

Global control channel schemes are also proposed in [7], [8],[9], and [10]. However, the schemes do require global synchronization which is a challenge in wireless networks. In [11] and [12] it is envisioned that synchronization may be possible in a localized environment at the expense of higher overheard costs due to the need to coordinate local sensing and information sharing. This overheard leads to common control channel challenge which is examined in this paper.

In [13], [14], and [15] schemes implementing local control channels are proposed. Techniques such as clustering are employed in the design of a local control channel.

A number of multi-channel MAC schemes have been designed to address different challenges. They are designed to address the following challenges, throughput, Hidden Terminal problem, and the Missing. The scheme in [16] addresses the HTP. The common control channel challenge was not investigated. In [17] a scheme optimized for capacity oriented scheme is proposed however the common control channel challenge was also not investigated. A reconfigured version of this protocol is proposed in [18]. The scheme does not examine the impact of the common control channel challenge on network performance. The two protocols are capacity based and the impact of the common control channel challenge was not investigated.

A common control channel protocol is proposed in [19], with its improved version is proposed in [20]. The two schemes are capacity oriented; the common control channel challenge was not examined. There is therefore a need to common control challenge in the context of capacity or of improving the end-to-end throughput. The performance and capacity of the common control channel challenge has an effect on network capacity. Furthermore, the saturation challenge may be explored in access networks such as the CRAHNs. The CRAHNs is the promising candidate of the WNGN. Our paper analyzes the impact of the size of the spectrum hole and the capacity of the network in the CRAHNs through analytical and network simulations. To this end, we investigate the saturation challenge in different network scenarios.

In [21] a single transceiver scheme is proposed, however, it does not implement the common control channel. Works in [22], [23] and [24] implement similar capacity based schemes. The optimization of upper bound capacity requires attention as its design impacts on the performance of the network.

The scheme in [25] implements a common control channel with a single transceiver. The saturation problem was investigated in the absence of channel switching costs. Furthermore, the saturation challenge was not rigorously examined in different network scenarios. The switching cost effects network performance as two switching costs are involved. The switching penalty is set to a maximum value of 224µs [26], [27], [28], and [29]. The total switching cost for the penalties – for the two channel switching delays, to and from a given data channel is 448µs, which is a significant cost. We added the two channel switching delays in our simulation environment. Furthermore, the common control channel challenge in the context of CRAHNs in different network scenarios is investigated.

Different approaches are proposed in [30] to [37], schemes which implement random home channels [31], the quiescent channels [32], the default channels and, the fixed and the switchable transceivers [35]. The schemes partition the network. Furthermore, a temporary control channel is implemented in these schemes; as a result high channel switching cost is incurred due to frequent channel switching. The protocols however, do not investigate the common control channel challenge in multichannel MAC schemes and the implementation of upper bounds schemes.

4. ANALYTICAL MODEL

Cognitive networks are characteristic with the co-existence of primary and secondary spectrum users. The primary user (PU) is the owner of the spectrum and its usage of the spectrum should not be interfered with. The PU enjoys an uninterrupted usage of the spectrum every time is in session. An idle PU has to be protected and given uninterrupted access to the spectrum when it decides to utilize the spectrum. This means that the PU requires protection when it is using, and when it is not using the spectrum. The most critical one is when the PU is not using the spectrum. This critical in the sense that when a PU appears, other users are expected to vacant the spectrum and make sure they do not interrupt it. On the other hand the secondary user (SU) is an opportunistic user of the spectrum. It is a user who does not own the spectrum but would want to use it as and when it is not in use. The design issue is the positive identification of a PU and ability to differentiate the activities of a PU from other SUs.

The opportunistic usage of the spectrum by SUs and their coexistence with PU is depicted in Fig 1. The SU has to identify spectrum holes, which are durations in which the PU is idle. When the PU is not active, the spectrum lies idle. The SU then utilizes the spectrum during these inactive periods. When the PU begins transmitting the SU has to vacant the spectrum immediately and move to the next vacant spectrum. In fig 1, there are three spectrum holes which are available to the SU. As indicated by the arrows, the SU will transmit first in the first spectrum hole. When it detects the PU, it jumps into the hole in the next frequency band. While in the next band, when the PU appears, the SU has to jump into the third hole to continue it transmission. However, Fig 1 assumes that these holes are big enough to allow the SU to engage in meaningful transmission. This is the general assumption which may not always be the case. If the hole is not big enough, the SU not fail to complete its transmission resulting in the wastage of bandwidth and the need to retransmit packets.

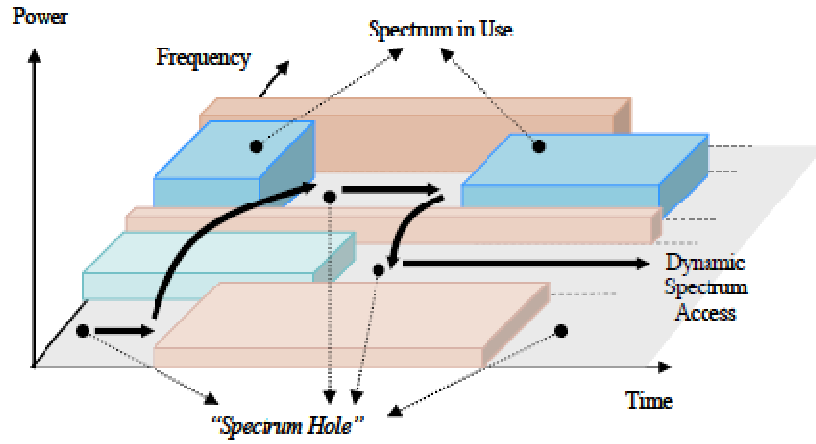


Figure 1. Opportunistic utilization of spectrum holes by secondary users during the absence of the primary users [39]

We characterize the effect of the size of the spectrum hole in Fig 2. The model clearly shows that he size of the spectrum hole matters; otherwise it may cause a number of retransmission and network congestion.

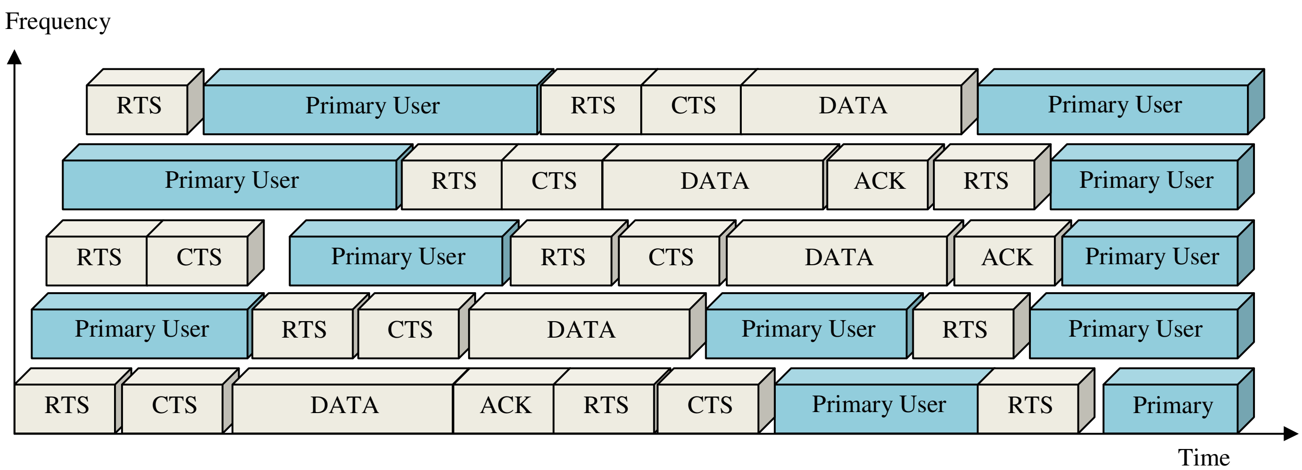


Figure 2. Utilization of spectrum holes

Assuming that frequency x, has five frequency bands counting from bottom up and that we have two spectrum holes in the first band. Given the first hole, an SU would be able to successfully transmit a single packet which going to be positively acknowledged. The second attempt will not succeed because the PU will appear after the exchange of RTS and CTS packets. An attempt to jump into the hole in band two would succeed given that it is already occupied by another SU. The SU-2 in band-2 fails to receive a positive ACK packet as a result the bandwidth would be wasted necessitating the need for retransmission. The second spectrum holes in both bands 1 and 2 accommodate only an RTS packet which also wastes bandwidth.

The first hole in band-3 allows the SU to exchange only the RTS and CTS packets before the PU appears while the second hole is big enough for the successful transmission of one data packet. Band-4 hole accommodates only data transmission and the second attempt ends with only an RTS packet having been transmitted. Lastly, band-5 has two holes which are not big enough for data transmissions to be scheduled in them.

The model demonstrates that the size of the spectrum hole is significant. The availability of the spectrum is not fundamental but their size. SUs can still fail to utilize the available hole due to their size. Depending on the activities of other SUs, a given SU may not be able to hop from one spectrum hole to another to complete its transmission. Having occupied the first hole, when it fails to access the next one, it wastes bandwidth which may also lead to numerous retransmissions. On the other hand retransmission may lead to the congestion of the frequency bands. Finally, when these scenarios are considered in the light of the common control channel challenge, a severe degradation of the performance of the network is expected. These may cause SUs to fail to transmit successfully in holes which they have done so in the absence of the common control channel challenge. There is therefore need to analyze the performance of cognitive networks in the presence of these challenges. The correctly detection of the activities of PUs and the available spectrum holes do not address these challenges.

5. SIMULATION MODEL

The simulated scenarios were investigated in the NS 2 network simulator. The simulation was based on the IEEE 802.11 standard implemented in NS 2. The details of the simulation parameters are depicted in table 1. Five main networks were evaluated and in each of the five fourteen scenarios were examined. The networks were categorized by size in terms of the number of nodes in a network. The number of nodes range from 4 to 30. The simulation environment consist of one common control channel set aside for signaling purposes and the rest where earmarked for data transmission. Furthermore, all the channels were assumed to be two Mbps. The table below depicts all the parameters and their associated values which were considered in the evaluation.

The saturation challenge was investigated in an NS 2.28 simulation environment. The environment had a multi-channel patch installed. For routing purposes the No Ad Hoc (NOAH) routing protocol was used. The network scenarios consisted of one control channel and one radio. The multichannel switching cost was set to 224µs. The number of data channels was increased steadily from 2 to 15 resulting in 14 different network scenarios. Given these network scenarios, the saturation challenge was well investigated

Table 1. MAC Layer and other Parameter Settings

	Parameter	**Value**	
	SIFS	10 µs	
	DIFS	50 µs	
	EIFS	364µs	
	CIFS	56 (µs)	
	Slot time	20 µs	
	Data rate	2 Mbps	
	Basic rate	2 Mbps	
	Channels	2,3,4,5,6,7,8,9,10,11,12,13,14,15	
	Switching time	224µs	
	Packet size	1000 bytes	
	CW_{max}	1023	
	CW_{min}	7	
	Short Retry Limit	7	
	Long Retry Limit	4	
	PLCP Length	192 bits	
	PLCP rate	1 Mbps	
	RTS	20 bytes	
	CTS	14 bytes	
	ACK	14 bytes	
	MAC Header - Data	28 bytes	
	MAC Header rate	Basic rate	
	Routing Agent	NOAH	
	Network Sizes	4,5,6,8,10 and 30 nodes	

The channels were assumed to be orthogonal for experimentation purposes. The different network sizes were designed to evaluate the impact of the control channel saturation challenge. General network topologies which were fully connected were considered in the simulations. For each scenario, at least 10 simulations were run each for 300 seconds, the simulation time. The results presented in the next Sections are averages of these simulations which were run to effectively investigate the effects of the common control channel challenge. The x axis depicts the number of data channels which were considered for the 14 different networks in terms of the number of data channels involved.

6. SIMULATION RESULTS

We present and analyze simulation results in this Section. The simulation environment was modeled according to Table.1 and its detailed description was presented in Section IV. The effect of the common control channel challenge was investigated as the number of data channel was increased from 2 to 15. Furthermore, different network sizes and scenarios were examined. The different scenarios were designed to adequately investigate the common control channel challenge. Figure 3 depicts the performance of a network with 4 nodes.

Fourteen scenarios with different number of nodes were investigated. The data channels were increased from 2 to 15. The first network had two data channels, and thereafter, they were increased steadily to 15. The largest network had 15 data channels. In Fig 3, the network performance kept on fluctuating between 5.42 and 5.45 Mbps as the data channels were increased steadily from 2 to 15 data channels. A recurring pattern was observed between two and ten channels. The achieved throughput increased from the data channels added to four data channels. Thereafter, it decreased when the data channels were increased to five. This same pattern was then repeated between six and ten channels. The achieved throughput however, was the same in networks with eight and nine data channels. After the 10th data channel, it increased marginally before decreasing and exhibiting signs of saturation.

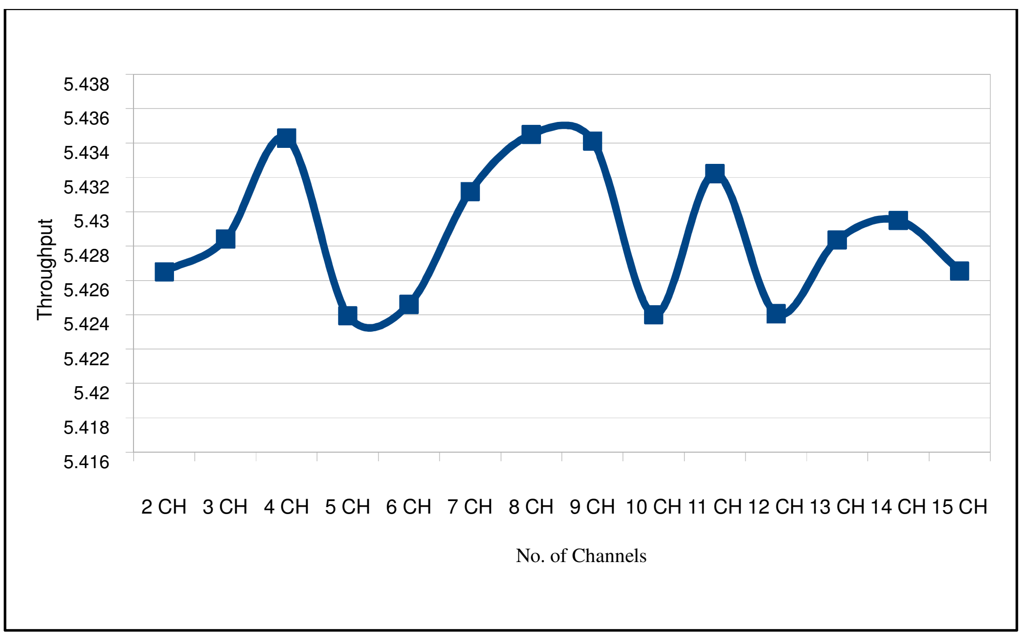


Figure 3.Achievable Network Throughput in a Network with 4 terminals

The saturation problem was noticeable from the ninth data channel. The achievable throughput began decreasing until the fifteenth data channel. This shows that the effect of the saturation problem becomes more severe in overloaded and congested networks. In the following results in Fig 4, we further investigate common control channel challenge. In this case, we investigate the performance of the buffer queues in the presence of the saturation challenge in similar set up.

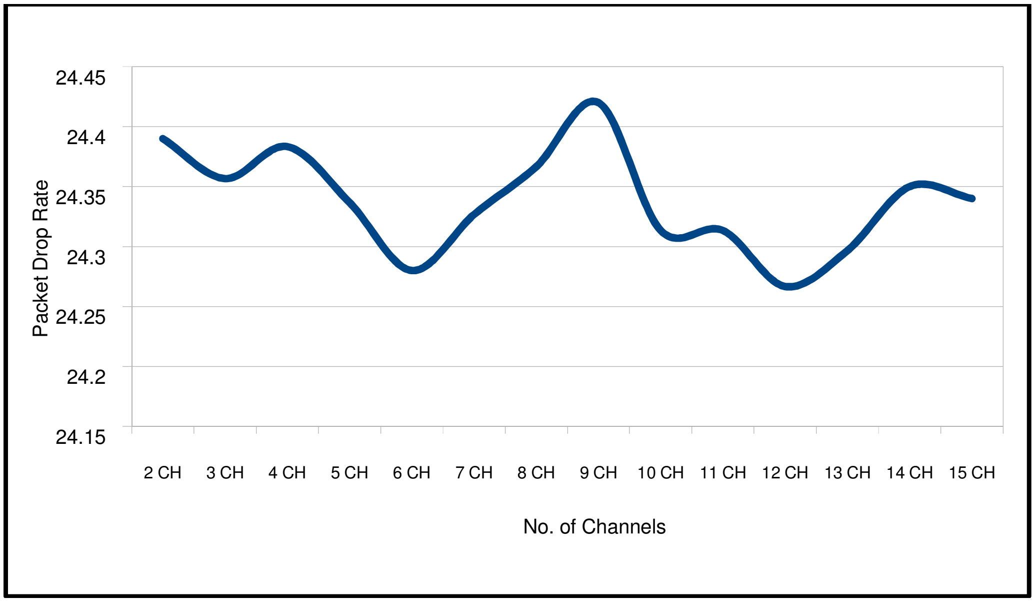


Figure 4. Investigating the effect of the saturation on Packet Drop Rate

As it can be seen in Fig 4 above, the packet drop rate kept improving from the two channels to sixth data channels. From seven channels to nine data channels it worsened, before improving again. In general, the effects of the saturation problem are not as evident as in the achievable throughput results. The results of the packet drop rate in general, seem to be improving. In the next set of results, the network was increased to 6 nodes.

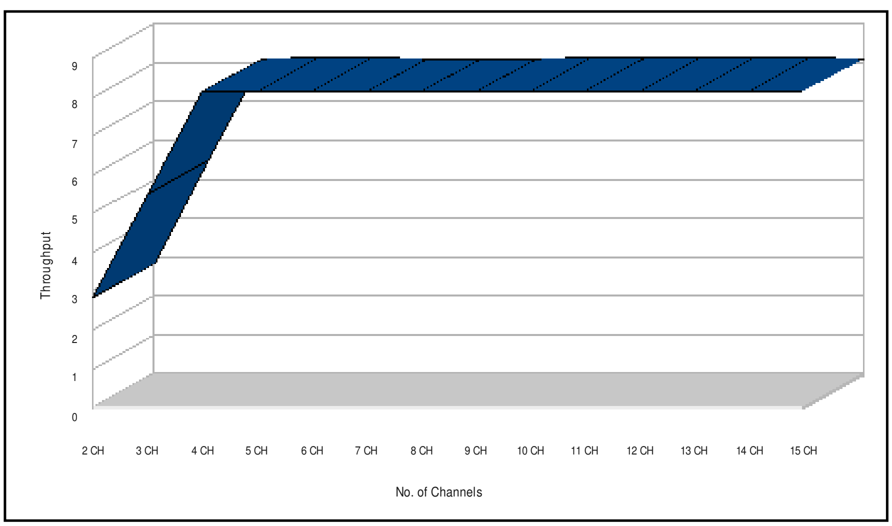


Figure 5.Achievable Network Throughput in a Network with six nodes

The achievable throughput did plateau at 8 Mbps between the fifth and the fifteen data channels after it had increased from 3Mbps in the second data channel. The effect of the saturation problem causes the control channel to fail to coordinated and schedule more data transmissions, as a result, it causes a system bottleneck. The number of channels does not increase the achievable throughput when the control channel had saturated. The results of the packet drop rate in Fig 6 show a similar behaviour. Its performance improves and then remains unchanged just below a packet drop rate of fifty packets per second. However, this is higher than the drop rate observed in Fig 4. This depicts that the network size and the amount of traffic has an effect on the saturation problem. The severity of the saturation problem increases with the increase in congestion.

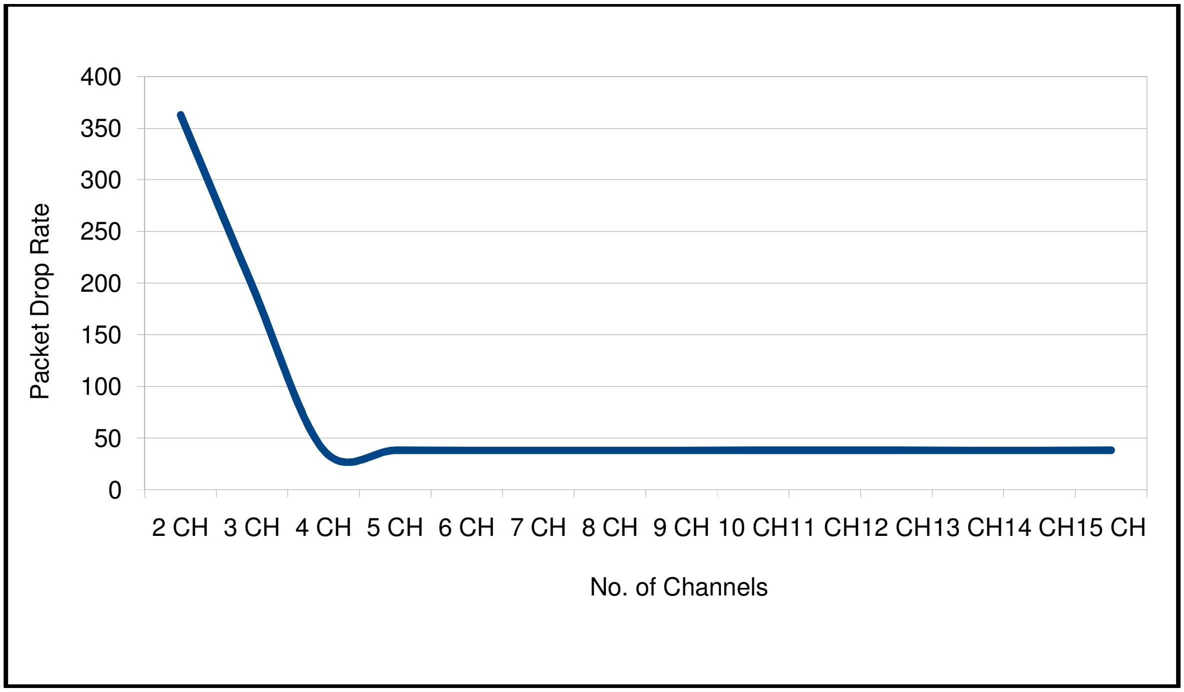


Figure 6.Packet Drop Rate in a Network with six nodes

The results thus far show the effect of the saturation challenge and the congestion of the control channel in overloaded networks. We now summarize the results of the other network scenarios under the similar network configurations.

In Figs 7, 8, and 9, we closely analyze the effect of the saturation problem in large networks which are overloaded. In these three figures, the nodes were increased to 8, 10 and 50 respectively.

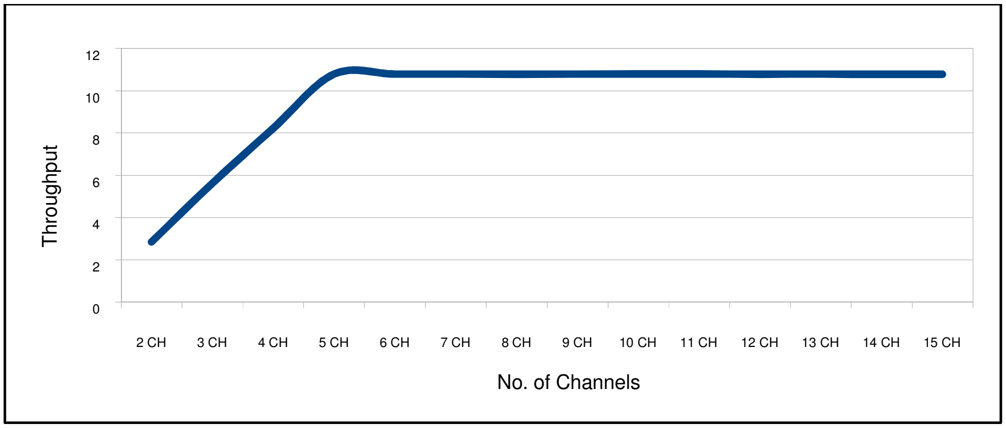


Figure 7.Achievable end-to-end Throughput in a Network with eight nodes

It can be noted that the saturation levels remain unchanged. For example, in Fig 5, the achievable throughput is 4/3 Mbps per each node which is the same average achievable throughput which was realized in Fig 9. However, in Figs 7 and 9 it is lower due to the effects of the saturation problem. The saturation challenge is not severe in Fig 9 due to spatial reuse. There is therefore a need to improve the efficiency of the network through design ingenuity instead of relying on spatial reuse. However, despite the spatial reuse, the effects of the saturation problem are still evident. The network in Fig 9 did plateau after the third channel as opposed to the sixth channel in Fig 8. This clearly demonstrates the effects of the saturation problem.

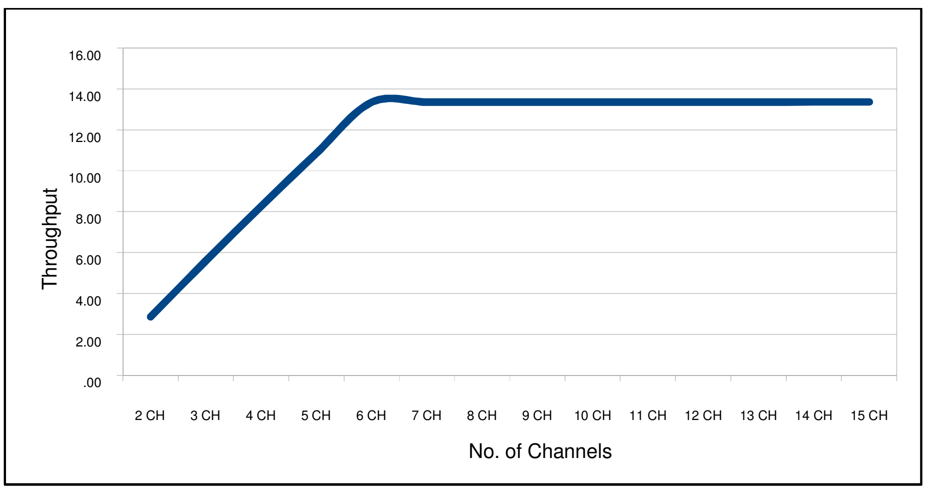


Figure 8.Achievable end-to-end Throughput in a Network with 10 nodes

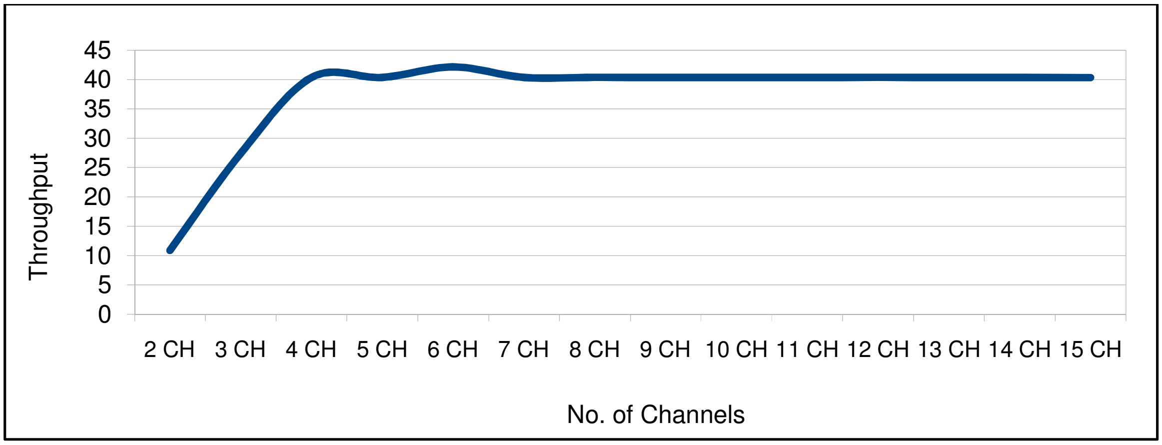


Figure 9.Achievable Network Throughput in a Network with 30 nodes

In the throughput results, with the exception of Fig 3, the achievable throughput increased from its minimum to its maximum as the spectrum hole remained available. The size of the spectrum hole affects the achievable throughput in the sense that if the available transmission time is very short, very few or no packets can be transmitted. The achievable throughput rises from its minimum to its maximum given the availability of the spectrum hole. However, it does not continue to rise due to the effects of the saturation problem. The small spectrum hole therefore constrains throughput, while a bigger one enables nodes to realize more achievable throughput.

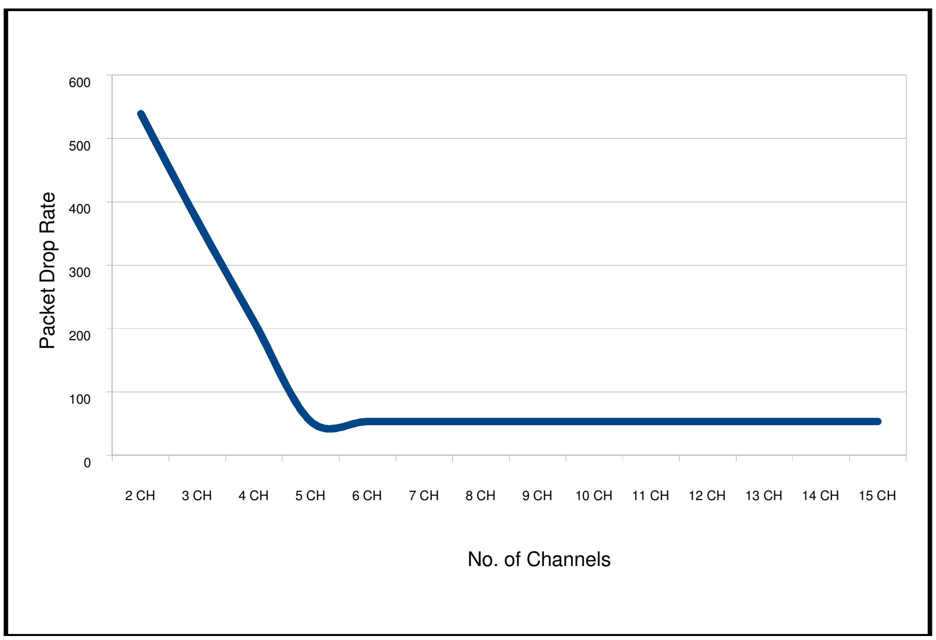


Figure 10.Packet Drop Rate in a Network with eight nodes

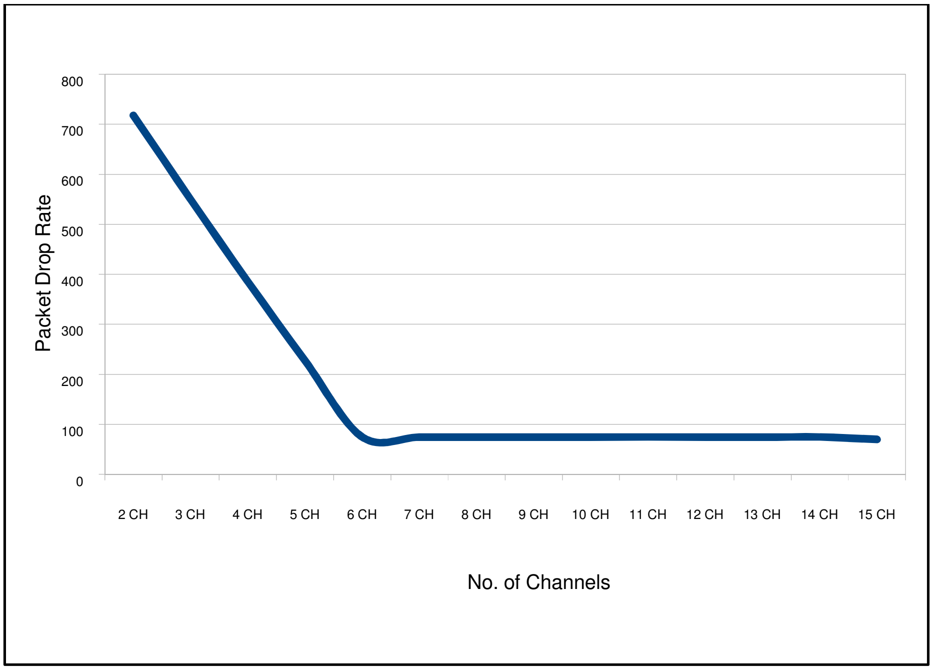


Figure 11.Packet Drop Rate in a Network with ten nodes

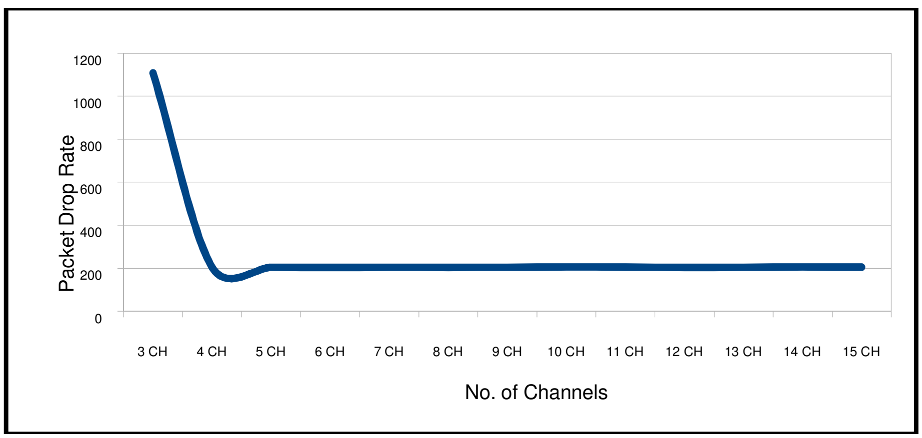
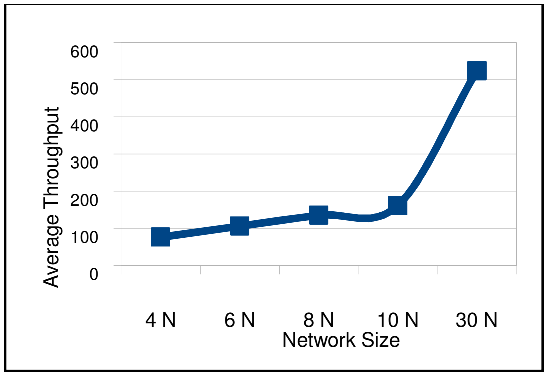


Figure 12.Packet Drop Rate in a Network with thirty nodes

We analyze the effects of the common control channel challenge in Figs 10, 11, and 12, on the network buffers whose negative impact results in the increases the number of dropped packets. In Figs 10 and 11, the packet drop rate, improves (drops) to below 100 packets per second while in Fig 12 it drops down to 200 packets /simulation second. The results in Fig 12 are worse than those in Figs 10 and 11. The poor performance was caused by the by the common control channel challenge which worsens in large networks.



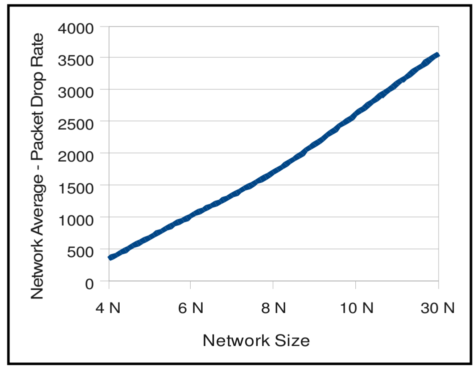


Figure 13(a). Average Achievable throughput in the five network scenarios (b). Average Packet Drop Rate in the five network scenarios

Fig 13 depicts the average results of all the network scenarios which were investigated. Fig 13(a) shows the average achieved throughput in the five different networks investigated in this simulation, while Fig 13 (b) depicts the average packet drop rate in these five network scenarios. In Fig 13(a), the increase in the achievable throughput is not linear to the network size due to the common control channel challenges while Fig 13 (b) the average packet drop rate increases exponentially. The increase in the average packet drop rate at such a fast rate was caused by the common control channel challenge.

7. CONCLUSION

The results of the investigation show that both the saturation problem and the size of the spectrum hole have an effect on the performance of the Medium Access Control protocols. The results show that these two challenges degrade the performance of the networks. The effect of the common control channel challenge is clearly depicted in Fig 13 (b), in which the average packet drop rate worsens at an exponential rate. As the network increases, the packet drop rate degrades gracefully. The degradation of the average packet drop rate is caused by the common control channel challenge in networks with heavy loads or networks with ever increasing traffic loads. On the other hand, the size of the spectrum hole and its effect on the network performance can be correlated with the available transmission time. The network takes time sensing channels and communicating the spectrum sensing information. The transmission time is therefore reduced. Given a small spectrum hole, signalling will constitute a larger percentage impacting negatively on the available bandwidth which can be ear-marked for data transmission. There is therefore a need to reconfigure transmission and sensing times. The effect of the common control channel challenge given a relatively small spectrum hole becomes huge.

References

1. T. Vamsi Krishna and Amitabha Das. A survey on MAC protocols in OSA networks, computer networks 53 (2009), www.elsevier.com/locate/comnet

2. P. Bhal, R. Chandra, and J Dunagan . SSCH: Slotted Seeded Channel hoping for capacity improvement in IEEE 802.11 ad hoc wireless networks, in proceedings of the ACM MobiCom 2004

3. I.F. Akyildiz, W.-Y. Lee, K.R. Chowdhury, CRAHNs: Cognitive radio ad hoc networks Ad Hoc Networks Journal, Elsevier, 2009. www.elsevier.com/locate/adhoc

4. 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 50 (2006). www.elsevier.com/locate/comnet

5. C Cormio and K.R. Chowdhury (2009). A survey of MAC protocols for cognitive radio networks, Ad Hoc Networks, www.elsevier.com/locate/adhoc
6. I.F. Akyildiz, W.-Y. Lee, K.R. Chowdhury, Cognitive radio ad hoc networks: research challenges, to appear in Ad Hoc Networks Journal, Elsevier, 2009.
7. M. Thoppian, S. Venkatesan, R. Prakash, R. Chandrasekaran, MAClayer scheduling in multi-hop wireless networks, in: Proceedings of the IEEE WoWMoM 2006, June 2006.
8. L. Ma, X. Han, C.-C. Shen, Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks, in: Proceedings of the IEEEDySPAN 2005, November 2005, pp. 203–213.
9. J. Jia, Q. Zhang, X. Shen, HC-MAC: a hardware constrained cognitive MAC for efficient spectrum management, IEEE Journal on Selected Areas in Communications 26 (1) (2008) 106–117.
10. H. Su, X. Zhang, Cross-layered based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks, IEEE Journal on Selected Areas in Communications 26 (1) (2008) 118–129.
11. J. Zhao, H. Zheng, G.-H. Yang, Distributed coordination in dynamic spectrum allocation networks, in: Proceedings of the IEEE DySPAN 2005, November 2005, pp. 259–268.
12. J. So, N. Vaidya, Channelization: multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver, in: Proceedings of the ACM MobiHoc, May 2004.
13. T. Chen, H. Zhang, G.M. Maggio, M. Chlamtac, CogMesh: a clusterbased cognitive radio network, in: Proceedings of the IEEE DySPAN 2007, April 2007, pp. 168–178.
14. A.V. Adamis, K.N. Maliatsos, P. Constantinou, A new MAC protocol with control channel auto-discovery for self-deployed cognitive radio networks, Program for European Wireless 2007, EW 2007.
15. C. Cordeiro, K. Challapali, C-MAC: a cognitive MAC protocol for multi-channel wireless networks, in: Proceedings of the IEEE DySPAN 2007, April 2007, pp. 147–157.
16. J. Deng and Z. Haas (1998). Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks, in Proc. of IEEE ICUPC, Florence, Italy, 1998J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.
17. A. Nasipuri, J. Zhuang and S. R. Das (1999). A Multichannel CSMA MAC Protocol for Multihop Wireless Networks, in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, September 1999.
18. A. Nasipuri and S. R. Das (2000). Multichannel CSMA with Signal Power-based Channel Selection for Multihop Wireless Networks, in Proc. of IEEE Vehicular Technology Conference (VTC), September 2000.
19. S.-L. Wu, C.-Y. Lin, Y.-C. Tseng and J.-P. Sheu (2000). A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks, in Int'l Symposium on Parallel Architectures, Algorithms and Networks (I-SPAN), 2000.
20. W. Hung, K. Law and A. Leon-Garcia (2002). A Dynamic Multi-Channel MAC for Ad Hoc LAN," in *Proc. Of 21st Biennial Symposium on Communications*, April 2002.
21. Jungmin So and Nitin vaidya (2004). Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver. MobiHoc 2004, Roppongi, Japan, ACM.
22. N. Jain and S. Das (2001). A Multichannel CSMA MAC Protocol with Receiver-Based Channel Selection for Multihop Wireless Networks, in *Proc. of the 9th Int.Conf. on Computer Communications and Networks (IC3N), October 2001.*
23. A. Tzamaloukas and J.J. Garcia-Luna-Aceves (2001). A Receiver-Initiated Collision-Avoidance Protocol for Multi-Channel Networks," in Proc. of IEEEINFOCOM, 2001.
24. Ritesh Maheshwari, Himanshu Gupta and Samir R. Das. Multichannel MAC protocols for wireless networks. SECON 2006, Volume 2, Issue , 28-28 Sept. 2006

25. Jingpu Shi, Theodoros Salonidis, and Edward W. Knightly (2006). Starvation Mitigation Through Multi-Channel Coordination in CSMA Multi-hop Wireless Networks, MobiHoc'06, May 22–25, 2006, Florence, Italy.
26. IEEE computer society LAN MAN standards committee: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. ANSI/IEEE Std. 802.11, 1999 Edition, The Institute of Electrical and Electronic Engineers, New York, 1999.
27. IEEE-SA Standards Boards. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, June 2003. http://standards.ieee.org
28. IEEE Computer Society LAN MAN Standards Committee, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Standard 802.11-1997, New York, NY, 1997.
29. IEEE 802.11x family of standards. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4248378&isnumber=4248377
30. Arup Acharya, Archan Misra, and Sorav Bansal (2003). MACA-P : A MAC for Concurrent Transmissions in Multi-hop Wireless Networks. Proc. Of PerCom, March 2003
31. Sudthida Wiwatthanasaranrom and Anan Phonphoem. Multichannel MAC Protocol for Ad-Hoc Wireless Networks. Department of Computer Engineering, Kasetsart University.
32. Hoi-Sheung Wilson So, Jean Walrand, and Jeonghoon Mo. McMAC: A Parallel Rendezvous Multi-Channel MAC Protocol.
33. Jeonghoon Mo, Hoi-Sheung Wilson So, and Jean Walrand (2005). Comparison of Multi-Channel MAC Protocols. MSWiM 2005, 10 – 13 October, Montreal, Quebec, Canada.
34. Jenhui Chen, Shiann-Tsong Sheu (2004). Distributed multichannel MAC protocol for IEEE 802.11 ad hoc wireless LANs. Computer Communications 28 (2005).
35. Pradeep Kyasanur Jungmin So, chandrakanth Chereddi, and Nitin H. Vaidya. Multi-Channel Mesh Networks: Challenge and Protocols. University of Illinois
36. Myunghwan Seo and Joongsoo Ma (2007). Flexible Multi-channel Coordination MAC for Multi-hop Ad hoc Network. Technical Report, January 2007.
37. Chandrakanth Chereddi, Pradeep Kyasanur, and Nitin H. Vaidya (2006). Design and Implementation of a Multi-Channel Multi-Interface Network. REALMAN'06, May 26, 2006, Florence, Italy
38. Mthulisi Velempini and Mqhele E. Dlodlo. Analyzing the effects of increasing data channels and the number of data flows on network performance (Wireless VITAE 2009) – Denmark, 17 – 20 May 2009, ISBN 978-1-4244-4067-2
39. MOZHDEH MOLA & ZAHRA ALAVIKIA (2010). Spectrum Management in Cognitive Radio Networks, Jul 14,2010

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