Performance Evaluation of a Medium Access Control Protocol for IEEE 802.11s Mesh Networks

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***Abstract*— This paper presents a performance evaluation study for the Common Control Channel (CCC) protocol, a medium access control protocol suitable for wireless mesh networks. This protocol was submitted in July 2005 to the IEEE 802.11 Task Group s, which is responsible for developing a mesh-networking standard. CCC extends the distributed IEEE 802.11e MAC protocol to multi-channel operation for single- and multiple-radio devices, and enables additional valuable features. As demonstrated by the simulation results, CCC achieves impressive delay and aggregate throughput performance, and thus offers distributed channel access for backbone meshes with delay properties suitable for VoIP and other QoS-sensitive applications[1].**

I. INTRODUCTION

In order to sustain the explosive growth of IEEE 802.11-compliant wireless local area networks (WLANs) experienced in enterprise, public spaces, and residential applications, mesh networks have become important. They enable interconnection of numerous access points in an efficient and cost-effective manner, especially in environments where physical cabling is expensive or not permitted by code. Mesh networks are also important in settings where telecommunication facilities must be installed quickly, as in disaster recovery or in combat, and in areas where a large coverage footprint is desirable, as in campus and municipal WiFi networks [1]. In general, a wireless mesh network may convey either traffic loads comparable to those carried by a single access point but spread out farther, or traffic aggregated by several access points and transported wirelessly. We refer to the latter as a backbone mesh network. The IEEE 802.11s Task Group was formed to address these needs and develop an amendment to the 802.11 standard for mesh networking [2]. The standard is expected in 2007 [3].

Among the medium access coordination proposals presented to the IEEE 802.11s Task Group is the Common Control Channel (CCC) mesh medium access coordination (MMAC) protocol [4] [5]. In this paper we present performance evaluation results for this protocol, which show that CCC provides the superior throughput and delay performance required in next generation mesh networks. Moreover, the CCC MMAC protocol enables additional valuable features, including the operation of multiple-radio mesh devices.

The paper is organized as follows. First, the CCC protocol is briefly introduced in Section II. Related work is reviewed in Section III. The performance evaluation study is described in Section IV, and the corresponding simulation results discussed in Section V. Conclusions and future work appear in Section VI.

II. THE CCC PROTOCOL

The Common Control Channel protocol defines a flexible medium access coordination architecture that works with arbitrary mixtures of devices having one, one-and-a-half and several radios per node and accessing different numbers of channels [4] [5]. The protocol can be used on the backbone of a wireless mesh network, among others. The backbone of a mesh network consists of a collection of nodes that are either access points - each serving a collection of stations in a BSS, stations, or relay points. The nodes can all forward traffic across the mesh and, when other functional differentiation is not relevant, they are simply referred to as 'mesh points'. The mesh medium access coordination protocol addresses channel access control across a link between two mesh points. The path traversed by traffic forwarded across the mesh is determined by the routing mechanism. The MMAC protocol is independent of the routing mechanism and compatible with a variety of routing protocols.

The CCC protocol is based on distributed prioritized contention-based medium access. It reduces to the IEEE 802.11e EDCA MAC protocol for single-channel (and single-radio) mesh devices. As such, it can be regarded as the natural EDCA extension that enables multi-channel and multi-radio use. An additional radio (receiver) enables a mesh point to monitor the activity on all channels carrying mesh traffic. Multi-radio mesh devices will become necessary in large meshes in order to provide the transport capacity needed by the core mesh backbone. Therefore, the following discussion will concentrate on the protocol detail for multiple-radio mesh platform.

IEEE 802.11 has been allocated multiple non-overlapping channels. (i.e., 3 channels are available in the 2.4 GHz ISM RF band for 802.11b/g and 12 in the 5 GHz U-NII RF band for

[1]Some results contained herein have been previously presented at IEEE 802.11 standard meeting in September 2005 as a part of Avaya's proposal for IEEE 802.11s [6]. Zhifeng Tao worked on this study while visiting Avaya Labs Research, Basking Ridge, NJ.

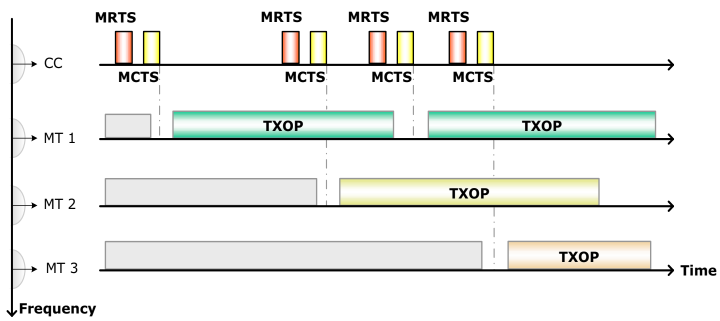


Fig. 1: The CCC MAC protocol with three MT channels

802.11a). The CCC protocol defines a Control Channel (CC), over which all mesh nodes will exchange control and management frames through a dedicated radio, the 'control radio'. The rest of the channels, called Mesh Traffic (MT) channels, are used to carry the mesh data traffic, which comprises traffic forwarded by mesh points. Accordingly, the radios tuned to the MT channels are called 'MT radios'. Reservations of the various MT channels are made by exchanging control frames on the CC channel.

Figure 1 illustrates the concept of CC and MT channels, as well as the basic channel access mechanism. In the illustrated example, the mesh points have access to three MT channels and the control channel. The CCC protocol observes the rules of EDCA (that is, the distributed random access protocol of IEEE 802.11e) for channel access and virtual carrier sensing [7]. As extensions of the legacy RTS and CTS messages, the Mesh RTS (MRTS) and Mesh CTS (MCTS) are exchanged on the control channel in order to reserve an MT channel for the time it takes to transmit a Transmission Opportunity (TXOP). A TXOP is a sequence of frames (and their respective acknowledgments) transmitted serially, immediately following a single successful contention-based channel access attempt, as prescribed by the IEEE 802.11e standard. The particular MT channel selected for transmission of the TXOP is indicated in a special field on the MRTS/MCTS. A mesh point keeps track of the time each MT channel has been reserved based on the value of the $Duration$ field of the MRTS/MCTS.

The CCC protocol enables a small number of MT radios to better leverage the capacity available in a pool of MT channels. The MRTS/MCTS handshake procedure facilitates dynamic channel allocation without entailing any additional signaling overhead, and thus obviates the need for a separate channel assignment algorithm. In addition to the basic access coordination mechanism is provides, the CCC protocol also defines a rich set of new features that enables it to address special problems, such as multi-radio mesh points and the associated adjacent channel interference, the hidden terminal problem, and the exposed node problem. These features are described in references [4] and [5].

III. RELATED WORK

Even before the establishment of IEEE 802.11s task group, mesh networking in general had already gained attention in the research community. Existing literature has touched upon many crucial aspects of mesh networking, ranging from exploiting novel physical layer technologies to routing protocol innovations. Among the papers focusing on medium access control, [8] proposes to move the contention resolution overhead to a separate control channel. However, the discussion therein is limited to only the two-radio two-channel scenario, and thus does not fully quantify the potential capacity made possible by additional available channels. It does not address the control channel bottleneck potential, either.

The protocol evaluated in this paper bears some resemblance to the multi-channel MAC protocol defined in [9]. The CCC protocol, however, comprises additional features needed in mesh networks. This paper presents capacity and delay performance results of multi-channel common control channel access protocols, which have not been covered elsewhere. The CCC MMAC proposal and the corresponding evaluation are specifically designed and optimized for the 802.11-based mesh network.

A different control channel approach is proposed in [10], where two narrow-band busy tones are used on the control channel to indicate whether a node is transmitting RTS packets or receiving data packets. Since the tones on the control channel do not encode any information bits, they are not intelligent enough to fulfill the more complex functionality of the MRTS/MCTS exchange.

IV. PERFORMANCE EVALUATION APPROACH

The objective of the study described in this paper is to evaluate the aggregate throughput and delay performance of a mesh network under the CCC protocol. Sensitivity of these statistics to the physical transmission rate and TXOP size was measured.

Performance was measured by considering several independent traffic streams occurring along mesh links. The links were assumed to be situated sufficiently close so as not to permit channel re-use. It was further assumed that the mesh points at the end of these links can hear all transmissions. Two major scenarios were examined, comprising 4 or 8 independent traffic streams, respectively.

Each mesh point is equipped with one control radio and one MT radio. Both radios operate in the 802.11a 5 GHz band. The control traffic is transmitted at 6 Mbps. The rate at which mesh data traffic is delivered varies. It is either 24 Mbps or 54 Mbps.

Mesh traffic is transmitted in TXOPs, which are groups of frames sent contention-free immediately following a single successful contention-based channel access attempt. Grouping mesh traffic into TXOPs is reasonable to assume, since mesh traffic is the aggregate of traffic generated by one or more BSSs and forwarded by mesh access points and other mesh points. The TXOP size varies in the simulation scenarios. Table I presents the key MAC and traffic parameters, while Table II provides a summary of the key PHY parameters.

TABLE I: Key MAC and traffic parameters

CWMin	CWMax	AIFS	TXOP Size (frames)	Payload (bytes)	Interarrival Time Distribution
31	1023	DIFS	1, 10 or 15	1500	Exponential

TABLE II: Key PHY parameters

Control Channel	Traffic Channel	Number of Control Radios	Number of Traffic Radios
802.11a band 6 Mbps	802.11a band 24 Mbps or 54 Mbps	1	1

Simulations were conducted by using the OPNET Modeler modeling platform. New 'node' and 'process' models were developed in order to evaluate the performance of the CCC protocol.

V. RESULTS AND DISCUSSIONS

A. Capacity

Figures 2(a) and 2(b) show the network capacity, achieved by 4 and 8 traffic streams, respectively, for the scenarios specified in Section IV. The capacity is compared for different physical transmission rates for mesh data traffic and different TXOP sizes. Two physical transmission rates were considered for the MT channels: 24 Mbps and 54 Mbps. TXOP sizes of 10 and 15 frames were used.

The simulation results show that the network capacity (i.e., the aggregate throughput for all the independent traffic streams considered) increases linearly with the number of MT channels available. The maximum capacity is attained when the number of MT channels available is the same as the number of traffic streams. It reaches approximately 280 Mbps when 8 MT channels are deployed. The maximum traffic that can be carried by a wireless mesh using EDCA is 19 Mbps. This clearly shows that EDCA cannot be used in backbone mesh networks, which carry typically traffic from multiple BSSs.

The linear increase of capacity to the number of MT channels suggests that the control channel is not a bottleneck, as saturation of the control channel would have resulted in a diminishing rate of capacity increase.

The concern about the control channel becoming a bottleneck is further allayed by observing that capacity improves minimally when the TXOP size increases from 10 to 15 frames, which represents a 33.3% decrease in control traffic.

Finally, we can see that the control channel is not a bottleneck by examining the difference in the capacity attained with 4 and 8 traffic streams, given the same ratio of MT channels to traffic streams. Even though the control traffic in the latter case is twice the magnitude of the former, the capacity difference is negligible. Had the control channel been a bottleneck, a lower capacity per traffic stream and per channel would be observed in the latter case.

It is worth noting that the aggregate throughput improvement of CCC over EDCA or the legacy 802.11 MAC is achieved with a single MT radio per mesh point. Since the capacity of a full channel is available to each node, more radios would be needed at the mesh points in order to achieve a higher link/node capacity. Issues relating to multiple-radio mesh points are addressed in reference [11].

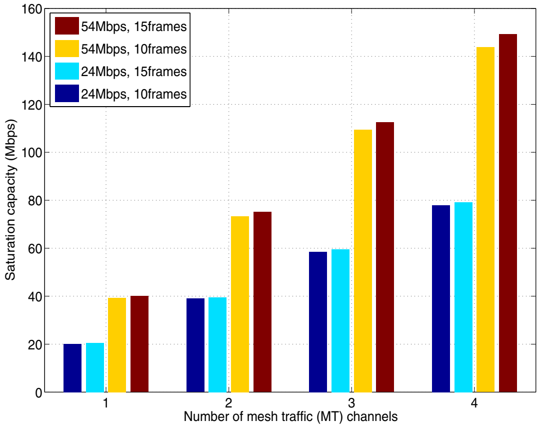
B. Delay

In order to examine the delay performance of the CCC protocol, independent traffic streams were simulated at the mandatory data transmission rate of 24 Mbps. A number of traffic streams access MT channels, numbering from 2 upward, through the CCC protocol. Two TXOP sizes are examined: 1 and 10 frames per TXOP. One frame per TXOP would be more common in lightly loaded meshes, carrying the equivalent of the traffic of a BBS, and used to extend range of communication through multiple-hop transmissions. Longer TXOPs would be typical of mesh backbone networks conveying BSS traffic aggregated at different mesh APs.

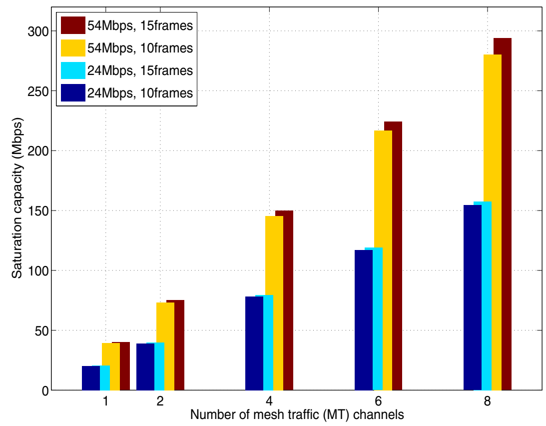
A total traffic load of 15 Mbps was spread across 8 traffic streams when TXOPs of a single frame were simulated. A total load of 19 Mbps was considered across 8 traffic streams for TXOPs of 10 frames long. Note that a load of 19 Mbps approaches the saturation capacity of an 802.11a channel when EDCA is used. The channel access delay and queuing delay are compared with the same delays experienced when all MT radios share a single channel using EDCA. Figure 3 shows the distribution of channel access delay and queuing delay for 1 and 10 frames/TXOP, respectively. Table III summarizes the average delays for the two TXOP sizes considered.

The delays observed when EDCA is used as the MMAC protocol are shorter when TXOPs consist of a single frame than multiple frames, while CCC consistently results in significantly lower delays. When using mixed priorities, EDCA assures the high priority portion of the traffic load delay performance acceptable for QoS-sensitive applications if the TXOP consists of a single frame, as seen in performance analysis of the IEEE 802.11e MAC protocol [12]. When the entire traffic load has QoS requirements, however, the 31.9 millisecond average delay experienced per hop by a 15 Mbps traffic load with EDCA would be too long. Using CCC as the MMAC protocol with just *two* MT channels would lead to acceptable delays - e.g., 1.2 millisecond average delay per hop, for such a traffic load. For traffic loads in excess of 19 Mbps, EDCA is not even a feasible option.

As the TXOP size increases, simulations show that access and queuing delays experienced with EDCA grow rapidly,

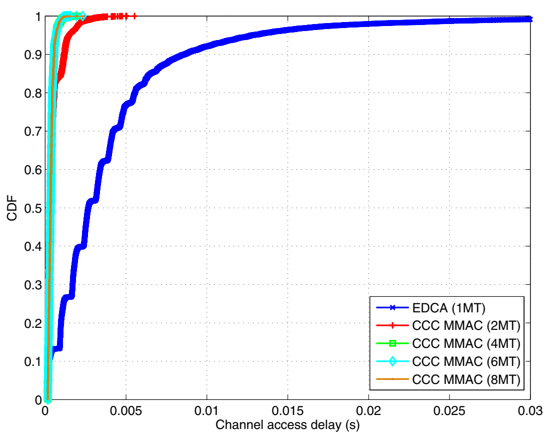


(a) Saturation capacity for 4 streams

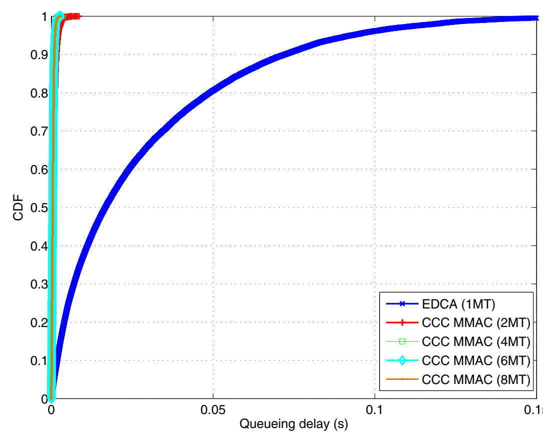


(b) Saturation capacity for 8 streams

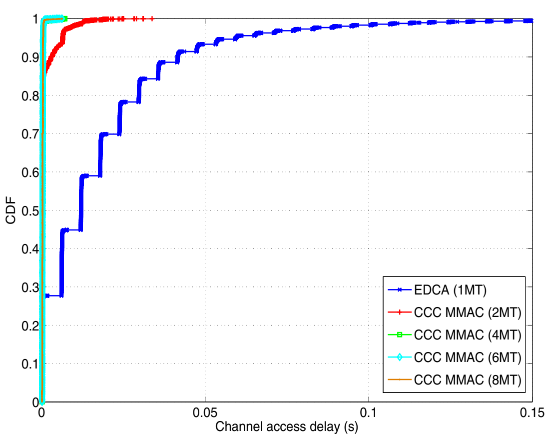
Fig. 2: Saturation network capacity for CCC MMAC



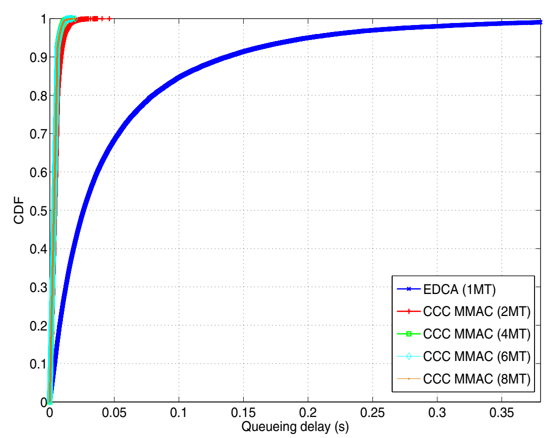
(a) Channel access delay CDF for 1 frame/TXOP



(b) Queueing delay CDF for 1 frame/TXOP



(c) Channel access delay CDF for 10 frames/TXOP



(d) Queueing delay CDF for 10 frames/TXOP

Fig. 3: Delay performance for CCC MMAC with a 24 Mbps data rate and 8 traffic streams

while CCC is not impacted negatively. For instance, using EDCA as the MMAC protocol with a 19 Mbps traffic load would lead to an average delay of 71.6 milliseconds per hop - 18.2 milliseconds of access delay and 53.4 milliseconds of

TABLE III: Summary of Per Hop Average Delay Statistics

Key Simulation Settings	Scenario	Channel Access Delay (msec)	Queueing Delay (msec)	Total Delay (msec)
1 frame/TXOP 15 Mbps load 8 Traffic Streams	EDCA	4.2	27.7	31.9
	CCC with 2 MT	0.5	0.7	1.2
	CCC with 4 MT	0.4	0.5	0.9
	CCC with 6 MT	0.4	0.5	0.9
	CCC with 8 MT	0.4	0.5	0.9
10 frames/TXOP 19 Mbps load 8 Traffic Streams	EDCA	18.2	53.4	71.6
	CCC with 2 MT	1.1	4.4	5.5
	CCC with 4 MT	0.3	3.5	3.8
	CCC with 6 MT	0.3	3.4	3.7
	CCC with 8 MT	0.3	3.4	3.7

queuing delay, when using 10-frame TXOPs, as seen in Table III. Both channel access and queuing delays thus improve significantly when CCC is employed as the MMAC protocol. With 4 traffic channels, use of CCC reduces the observed per hop average delay to 3.8 milliseconds - 0.3 milliseconds of access delay and 3.5 milliseconds of queuing delay.

The improvement in delay jitter is even more dramatic. For 10 frames/TXOP case, as shown in Figure 3(c) and 3(d), the 90 percentile of the queuing delay is 135.6 milliseconds and of the access delay is 42.5 milliseconds, when using EDCA. CCC with 4 MT channels reduces these statistics to 5.8 and 0.4 milliseconds, respectively.

The results above show that EDCA cannot provide delay performance adequate for QoS applications in mesh networks that carry heavy QoS-sensitive traffic. Backbone mesh networks can be described as such because they carry traffic aggregated by multiple access points. In contrast, CCC generates short per hop delays, adequate for all QoS applications. Since delay and jitter play a central role in determining the QoS for applications like voice over IP, a superior delay performance is essential for any mesh medium access coordination protocol to be relevant to mesh backbone networks.

VI. CONCLUSIONS AND FUTURE WORK

This paper reports the performance evaluation conducted for the CCC medium access control protocol, which has been submitted to the IEEE 802.11s Task Group for consideration for inclusion into the new mesh standard as the MMAC. The simulation results presented here indicate that CCC can deliver the capacity and delay performance that meets the requirements demanded by the next generation mesh backbones. No other distributed protocol for backbone mesh channel access is known to deliver delay performance suitable for VoIP and other QoS-sensitive applications. Sharing a single channel through EDCA can produce acceptable delay and jitter, but only with light mixed traffic loads, which, for the entire mesh, should not exceed the traffic load typically seen in a BSS. However, it would be unlikely for a mesh backbone network, which carries traffic to and from several BSSs, to be able to meet QoS requirements while sharing a single channel through EDCA, if it can carry the load at all.

By its nature, CCC provides dynamic channel assignment capability, which significantly simplifies the management and maintenance of mesh networks and facilitates mobile mesh points. In addition, for mesh networks to be able to forward traffic aggregated by mesh APs, multi-radio mesh devices are needed at mesh points near portals or other points of traffic concentration. CCC addresses the adjacent channel interference problem that could arise with multiple-radio mesh points [11]. Finally, CCC introduces a multitude of new features that enable it to address problems like the hidden terminal problem and the exposed node problem [4] [5]. Further performance studies will evaluate these features.

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