Analysis of Performance of a TDMA-based Distributed MAC Protocol in Single-hop Wireless Networks

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***Abstract*— Nowadays, the IEEE 802.11 infrastructure Basic Service Set (BSS) network is the most widely used wireless LAN (WLAN) system. There are growing needs to interconnect Access Points (APs) of separate BSSs to create an IEEE 802.11 Extended Service Set (ESS) mesh network over the wireless medium. Mesh Distributed Coordination Function (MDCF) is a novel Medium Access Control (MAC) protocol, designed for interconnecting a large number of APs to form an efficient wireless multi-hop network supporting quality of service (QoS). Based on that an efficient ESS mesh network can be created. This paper evaluates the traffic performance of MDCF by using the analytical approach. Based on the established mathematical model, the optimal frame parameter settings for MDCF can be precisely determined.**

***Index Terms*—IEEE 802.11 Extended Service Set (ESS) mesh network, Media Access Control (MAC), Mesh Distributed Coordination Function (MDCF), performance modeling, TDMA.**

I. Introduction

The IEEE 802.11 infrastructure Basic Service Set (BSS) [1] formed by an Access Point (AP) and its associated stations is the most widely used wireless LAN (WLAN) system. There are growing needs to interconnect APs of BSSs by radio to form an Extended Service Set (ESS) mesh network. APs thereby become mesh points (MP) of an ESS mesh network and may deliver data packets by means of multi-hop relaying from a source MP to a destination MP. Only few MPs provide access to distributed systems like the Internet. Fig. 1 shows an example. An MP represents a BSS in the ESS and meshes with the other MPs, whilst a station is associated to an AP in a BSS. Sometimes an MP can be a small device and simply put in a place for relaying and increasing mesh connectivity. Obviously, the creation of an ESS mesh network leads to cost reduction in operating and deploying WLANs, and brings more convenience to both operators and end-users.

In the ESS mesh networking, designing the Medium Access Control (MAC) protocol for interconnecting APs to form an efficient multi-hop network supporting quality of service (QoS) is a challenging work [7]. Mesh Distributed Coordination Function (MDCF) [5], [6] is a novel MAC protocol, designed for the use in the scenario. It is able to run on a single frequency channel on top of the IEEE 802.11 Physical Layers (PHY). MDCF is based on Time Division Multiplex Access/Time Division Duplex (TDMA/TDD) technology, operating under distributed control, concurrently to legacy stations on the same

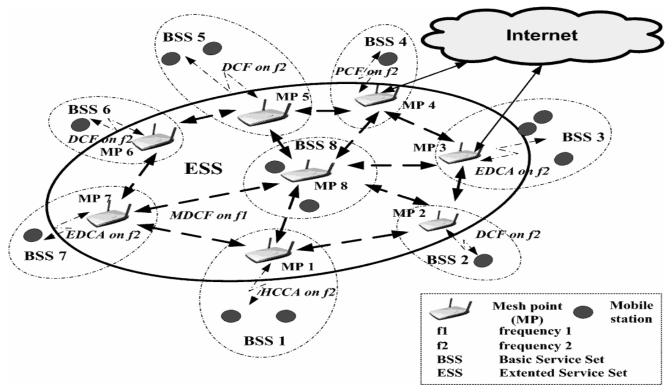

Fig. 1. An ESS mesh network.

channel. It is well designed to properly handle high loaded situations, hidden and exposed stations, and capture in mesh. As results, MDCF is capable of efficiently exploiting channel capacity, fairly distributing bandwidth and supporting multi-hop relaying of a large number of concurrent various traffic services in an ESS mesh network. An ESS network can be created as shown in Fig. 1: MPs form a MDCF multi-hop network on one or several frequency channels, while an 802.11 station is associated and communicates with an AP in a BSS on one of other frequency channels. An AP controlling a BSS may be co-housed with an MP. The BSS traffic to and from the AP can be relayed by the co-housed MP over the mesh network.

This paper builds up an analytical model to study the traffic performance of MDCF by using the queueing network theory [4]. Based on that, the optimal frame parameter settings for MDCF can be precisely determined.

The rest of the paper is organized as follows. After shortly reviewing the operation mechanism of MDCF in Section II, we establish an analytical model for single-hop MDCF networks in Section III. In Section IV, we evaluate the traffic performance of MDCF by using the established model in comparison with the simulation result. Finally we conclude in Section V.

II. Brief Review of Mesh Distributed Coordination Function

MDCF is a MAC protocol applying fully distributed control to a radio channel based on TDMA/TDD technology. Data transmission is in periodic time slots and MPs need to be syn-

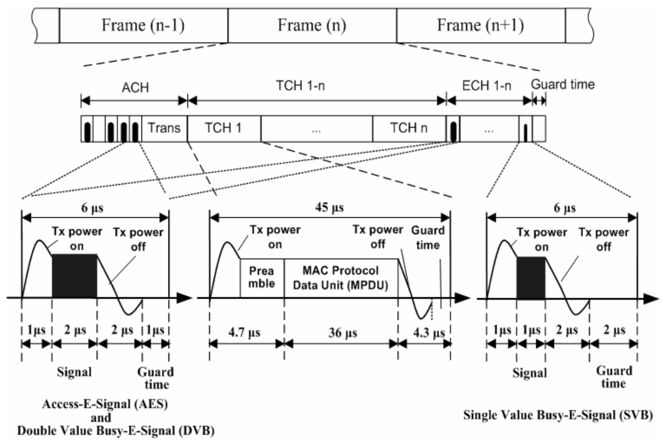

Fig. 2. TDMA frame and energy signals.

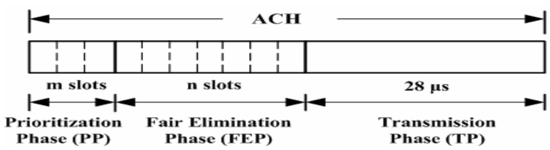

Fig. 3. ACH structure.

chronized for TDMA operation. An algorithm for synchronizing MPs in multi-hop environments is reported in [5]. A transmission pair in MDCF networks contends for channel access to reserve a number of traffic slots for user data transmission, according to the traffic requirement. If successful, the reserved time slots form the link to connect two MPs in TDD mode of operation, to multiplex all packets having the link in their route.

In this Section, we simply describe the operation mechanism of MDCF. For details, please refer to [5], [6].

A. MAC Frame and Energy Signals

Energy signals, in-band busy tones [8], play important roles in MDCF, each occupying a short time slice, e.g. 6 µs. Fig. 2 shows the frame structure and waveforms of energy signals.

Each TDMA frame contains a number of time slots. Time slots are logically grouped into 4 types. The first type is the Access Channel (ACH), in which slots energy signals are used to implement a prioritized and fair channel access. The second type is called Traffic Channel (TCH), each being able to carry one MAC protocol data unit (MPDU) per TDMA frame. The length of MPDUs suitable for a TCH depends on the PHY mode in a given PHY. The third one is the Echo Channel (ECH). An ECH slot is paired with a TCH slot. The number of ECH slots in a TDMA frame is same as that of TCH slots. An energy signal is transmitted by a receiving MP in an ECH slot to notify its nearby MPs that the paired TCH of the ECH is in use. The last slot is guard time with duration less than an energy signal, used to avoid time synchronization errors.

The energy signals transmitted in the ACH are called Access-E-Signals (AES), whereas those transmitted in ECHs are called Busy-E-Signals (BES). BESs are categorized as Single Value Busy-E-Signals (SVB) and Double Value Busy-E-Signals (DVB) according to the signal length. An AES has the exact waveform of a DVB. A SVB is transmitted by a receiving MP merely for informing its nearby MPs of the use of a specific TCH. The receiving MP may transmit a DVB instead of a SVB in the TCH to request the reverse transmission opportunity, besides to notify the use of the TCH.

B. Prioritized Access

An ACH slot has three phases: Prioritization Phase (PP), Fair Elimination Phase (FEP) and Transmission Phase (TP), as shown in Fig. 3. A number of binary AESs are transmitted in the contention slots in PP and FEP to implement a prioritized and fair channel access. Each contention slot is one AES long. PP is the QoS related contention phase, whilst FEP is used to guarantee a high probability of only one winner in each channel contention and to ensure fair channel access. When an MP wants to reserve TCHs for use, it shall contend in the ACH for transmitting a request packet in the TP.

The contention process is as follows: an MP first determines a QoS related contention number and then checks the number bit by bit. When the bit is 1 it sends an AES, for 0 it listens. The most significant digit is transmitted first. During a listening period, if it hears an AES, it must cancel its pending AESs and quit the contention. If surviving in the PP, the MP shall contend again in the FEP with a number set in favor of last losing MPs. If the MP wins in the above phases, it is allowed to transmit in the TP. If losing, it contends again in the next TDMA frame.

C. TCH Reservation and Transmission

When an MP wishes to transmit packets, it firstly checks the TCH status. If the amount of available TCHs observed at its location meets the traffic need, it contends in the ACH for transmitting a request packet in the TP. A request packet contains the receiving MP's address, QoS-related traffic specification (QTS) and a list of proposed TCHs for transmission. On receiving the request packet, the requested MP checks the free TCHs at its location, and then performs Admission Control (AC) algorithm to evaluate whether to accept the request. It transmits SVBs in the paired ECHs of the accepted TCH(s) if it accepts the request. From the SVBs, the requesting MP knows that the related TCHs have been reserved, whereas nearby MPs know that the TCHs are in use right now. Fig. 4 illustrates the process. Later on, transmission takes place in the reserved TCHs.

Assume that two MPs reserve several TCHs in a TDMA frame, on each of which the sending MP transmit its MPDUs. No matter whether the receiving MP receives an MPDU in a reserved TCH or not, it transmits a SVB in the paired ECH of the TCH, to signal the use of the TCH in its location. If the receiving MP has MPDUs to send back, it transmits a DVB instead of a SVB in the paired ECH of a reserved TCH. When the sending MP senses the DVB, from the next MAC frame on, it stops transmission in the TCH and starts to transmit energy signals in the paired ECH. From the same MAC frame on, the receiving MP starts to send its MPDUs in the TCH. This is called On-Demand-TDD, which is illustrated in Fig. 4.

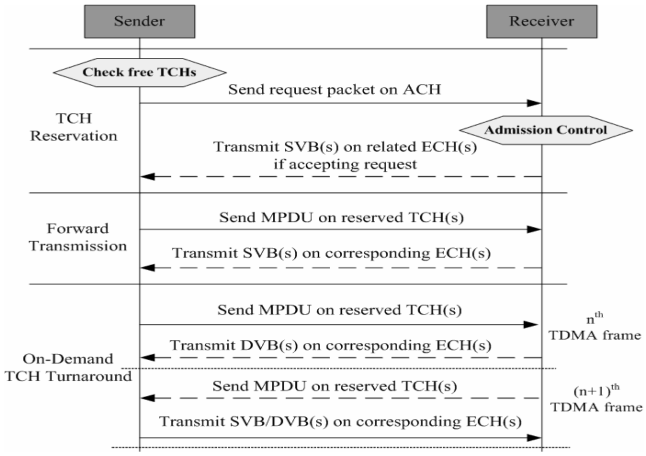

Fig. 4. TCH reservation, transmission and on-demand-TDD.

D. *Service Mode*

MDCF offers two transfer services to the upper layer: Unacknowledged Mode (UM) for connectionless point-to-point, multicast and broadcast applications, and Acknowledged Mode (AM) for reliable point-to-point applications. A higher layer packet is fragmented into MPDUs for transmission in TCHs using UM/AM, and reassembly is performed at the receive MP. A Selective Repeat Automatic Request (SR-ARQ) protocol provides error and flow control under the AM.

E. *TCH Release*

A TCH is freed if no MPDU is in the TCH transmit buffers at both sides of a link over the system wide specified hang-on time, which is a certain TDMA frames long.

F. *Packet Multiplexing and Multi-hop Operation*

A multi-hop link consists of multiple one-hop links in tandem that each independently operates. A TCH reserved between two MPs is used to multiplex any MPDUs transmitted on the route. The MPDU transmitting sequence is according to the QoS requirement.

III. Performance Analysis

Note: 1) due to the limited space, we only model and analyze the traffic performance of single-hop MDCF networks; 2) for simplicity, the frame guard time is neglected.

A. *System model: Scenario and Assumptions*

All MPs are assumed in a free space area and in mutual transmission range.

1) Each MP generates packet groups, all in the same QoS level. A *packet group* consists of a number of packets, starting with a request packet (REQ) which is followed by m MPDUs, as shown in Fig. 5. The REQ is transmitted on the TP in the ACH, whereas m MPDUs are transmitted on a TCH.
2) The traffic source consists of a large number of MPs which collectively form an independent Poisson source with a mean packet group generation rate of λ_{pg} packet groups/s. Obviously, the aggregate mean MPDU generation rate λ_{MPDU} is $m \times \lambda_{pg}$ MPDUs/s.
3) The number of ACH and TCHs in a TDMA frame is 1 and N, respectively.
4) The channel access is assumed to be absolutely eliminated, i.e. only one winner in each ACH contention.
5) Transmissions are under the UM. No packet is lost during transmission. On-demand-TDD is not used.
6) The hang-on count is started on the completion of transmission of the last MPDU in a packet group on a TCH. The TCH is considered free on the expiration of the hang-on time, which is h TDMA frames, and can be reserved again from the next TDMA frame on.

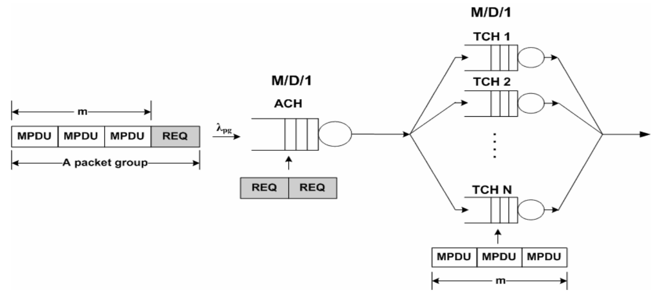

Fig. 5. A queueing model of the single-hop MDCF network.

B. *Overview and Definitions*

The MDCF system can be modeled as an open queueing network [4]. Fig. 5 shows the model. The queueing network consists of 1 ACH queue and N identical TCH queues. It works as follows:

MPs having pending packet groups first contend in the ACH if at least one free TCH queue is available. The ACH queue handles REQs. Clearly, the arrival of REQs to the ACH queue is Poisson process with a mean rate of λ_{pg} REQs/s. Since no collision happens in the TP of the ACH (assumption 4), a REQ is served per TDMA frame, i.e. the service rate of the ACH queue is 1 REQ/TDMA frame if there is a free TCH queue. However, the ACH queue stops to handle REQs if no free TCH queue is available. When this happens, the service rate of the ACH queue is lower than 1 REQ/TDMA frame. Based on above analysis, the ACH queue can be modeled as M/D/1 queue, whose service rate is dependent on the availability of free TCH queues.

After the REQ of a packet group is served by the ACH queue, its followed m MPDUs are transferred into a free TCH queue for being served. Thus, the arrival rate of MPDUs to a TCH queue is $(m/N) \times \lambda_{pg}$ MPDUs/s. Under the assumption 5, it is clear that the service rate of a TCH queue is 1 MPDU/TDMA frame. Obviously, a TCH queue needs m TDMA frames to complete the service for all MPDUs in a packet group. After that, the TCH queue starts to hang on and will not serve any MPDU before it is freed. Clearly, a TCH queue can also be modeled as M/D/1 queue. The following definitions will be used later:

$\boldsymbol{D_M^{1\text{-}hop}}$: One-hop mean MPDU delay;
$\boldsymbol{D^i}$: Delay of the i^{th} MPDU in a packet group, $i \in [1, m]$.

$Q_{Acc}^{1\text{-}hop}$: One hop access delay of a packet group. It is the sum of the service time and waiting time in the ACH queue.
X_{ACH}: Service time of the ACH queue.
ρ_{ACH}: Utilization factor of the ACH server.
W_{TCH}^{i}: Waiting time of the i^{th} MPDU in a packet group at a TCH, $i \in [1, m]$.
P_{TDMA}: The length of a TDMA frame in ms.
$Th_{pg}^{1\text{-}hop}$, $Th_{MPDU}^{1\text{-}hop}$: One-hop (packet group, MPDU) throughput.
T_{Tran}: Transmission delay of an MPDU on a TCH.
Λ: Mean time difference between the start of the ACH and the starts of the TCHs in a TDMA frame.
T_{ACH}, T_{TCH}, T_{ECH}: Duration of a (ACH, TCH, ECH) slot.
$max(x)$: Upper bound of an uncertain value x.

C. Performance Modeling for Single-hop Networks

From the queueing model shown in Fig. 5, it is clear:

$$D^i = Q_{Acc}^{1-hop} + W_{TCH}^{i} + \Lambda + T_{Tran} \qquad i \in [1, m] \tag{1}$$

where

$$W_{TCH}^{i} = i \times P_{TDMA} \qquad i \in [1, m] \tag{2}$$

Note that Λ can roughly reflect the time differences between the start of the ACH and the start of a TCH if a TCH for transmission is randomly selected. We have:

$$\begin{aligned} D_M^{1-hop} &= \frac{1}{m} \times \sum_{i=1}^{m} D^i \\ &= \frac{1}{m} \times \left[m \times (Q_{Acc}^{1-hop} + T_{Tran} + \Lambda) + P_{TDMA} \times \sum_{i=1}^{m} i \right] \\ &= Q_{Acc}^{1-hop} + T_{Tran} + \Lambda + P_{TDMA} \times \frac{m+1}{2} \end{aligned} \tag{3}$$

As the ACH queue can be modeled M/D/1 queue, then [3]:

$$Q_{Acc}^{1-hop} = X_{ACH} \times \left[1 + \frac{\rho_{ACH}}{2 \times (1 - \rho_{ACH})} \right] \tag{4}$$

Delivery of m MPDUs needs $m+h$ TDMA frames (consider the hang-on time), whilst reservation of N TCHs in a TDMA frame needs N TDMA frames. Then, if $m+h \leqslant N$, even when the ACH server is fully utilized, there are still N-m-h free TCH queues. Under this, the service time of the ACH queue is 1 TDMA frame. But if $m+h > N$, when the arrival rate of packet groups is high enough, all N TCH queues may be on service at a time. If so, the ACH queue stops working until at least one TCH queue becomes free again. Under this condition, the service time of the ACH queue can be looked as $(m+h)/N$ TDMA frames to match the process capability of the N TCH queues. Based on above analysis, we have,

$$\begin{cases} X_{ACH} = P_{TDMA} & m+h \le N \\ X_{ACH} = \dfrac{m+h}{N} \times P_{TDMA} & m+h > N \end{cases} \tag{5}$$

It is known that [3]:

TABLE I
KEY PARAMETER SETTING USED FOR PERFORMANCE ANALYSIS

Number of contention slots in the PP (ACH)	2
Number of contention slots in the FEP (ACH)	10
Duration of a contention slot used in the ACH	6 µs
Duration of the TP in an ACH	28 µs
Duration of a TCH	45 µs
Duration of an ECH	6 µs
Number of TCHs/ECHs in a TDMA frame	16
Duration of a TDMA frame	916 µs
Hang on period (unit: TDMA frames)	6

$$\rho_{ACH} = \lambda_{pg} \times X_{ACH} \tag{6}$$

Substituting Eqs. (5) - (6) into Eq. (4) yields:

$$\begin{cases} Q_{Acc}^{1-hop} = P_{TDMA} \times \left[1 + \dfrac{\lambda_{pg} \times P_{TDMA}}{2 \times (1 - \lambda_{pg} \times P_{TDMA})} \right] & m+h \le N \\ Q_{Acc}^{1-hop} = \dfrac{m+h}{N} \times P_{TDMA} \times \left[1 + \dfrac{\lambda_{pg} \times ((m+h)/N) \times P_{TDMA}}{2 \times (1 - \lambda_{pg} \times ((m+h)/N) \times P_{TDMA})} \right] & m+h > N \end{cases} \tag{7}$$

Since no packet is lost in the queueing network, then:

$$Th_{pg}^{1-hop} = \lambda_{pg} \tag{8}$$

From Eq. 6, we have $max(\lambda_{pg}) = 1/X_{ACH}$. It is evident that,

$$\max(Th_{pg}^{1-hop}) = \begin{cases} \dfrac{1}{P_{TDMA}} & m+h \le N \\ \dfrac{N}{(m+h) \times P_{TDMA}} & m+h > N \end{cases} \tag{9}$$

IV. PERFORMANCE EVALUATION

The IEEE 802.11a PHY [2] at 5.2 GHz is assumed. For validation purpose, the analytical results are compared with the results achieved in a simulator, which is built based on all system assumptions. Table I shows the parameter settings used for performance analysis. Note that the assumption 4 is relaxed in the simulation, since the number of contention slots in the FEP is 10, which guarantees a highly but not a fully eliminated channel access.

A. Performance of Single-hop MDCF Networks

Note in the following graphs, the analytical results are plotted with solid lines while simulation results with points.

Due to limited page, only MPDU delays are plotted. However, $max(Th_{pg}^{1\text{-}hop})$ and $max(Th_{MPDU}^{1\text{-}hop})$ can be derived by observing the delay: in a given condition, a λ_{pg} value causing a significant high delay is almost equal to $max(Th_{pg}^{1\text{-}hop})$, see Eq. (7). Similarly, when a λ_{MPDU} value leads to a very high delay, the value of λ_{MPDU} is very close to $max(Th_{MPDU}^{1\text{-}hop})$.

1) Traffic load of packet groups vs. delay

Eq. 3 is plotted into Fig. 6. It can be seen that under a given

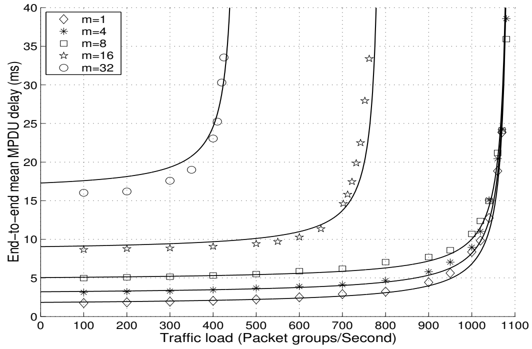

Fig. 6. Traffic load of packet groups vs. delay, N = 16, T_{TCH} = 45 μs.

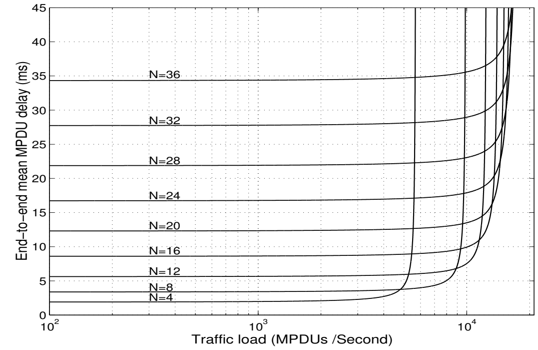

Fig. 8. Impact of N in single-hop networks, where m = N, T_{TCH} = 45 μs.

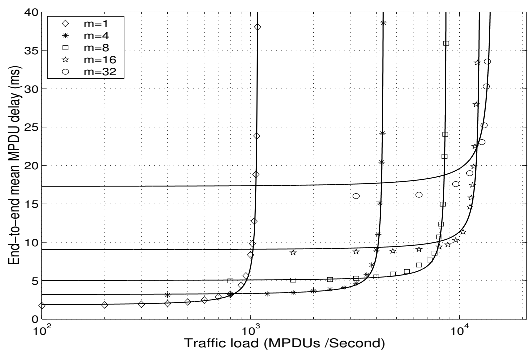

Fig. 7. Traffic load of MPDUs vs. delay, N = 16, T_{TCH} = 45 μs.

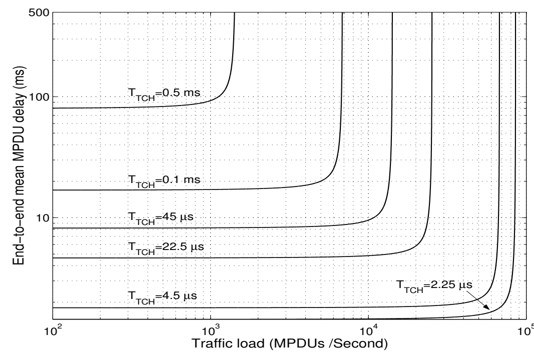

Fig. 9. Impact of T_{TCH} in single-hop networks, where m = N = 16.

traffic load of packet groups, a smaller m leads to a smaller MPDU delay. The reason is obvious: a smaller m results in a smaller traffic load of MPDUs in a network. Under a given m, when λ_{pg} is smaller than a certain value, the delays are almost same. A network under this is considered lightly loaded where delays are mainly attributed by $\Lambda+P_{TDMA}\times(m+1)/2$. In contrast, when λ_{pg} is larger than the value, the delay shall increase very sharply and a network tends to be highly loaded where delays is mainly due to the access delay $Q_{Acc}^{1\text{-}hop}$. Note $\lambda_{pg} \in [0, max(Th_{pg}^{1\text{-}hop})]$. It can be seen from Fig. 6 that a single-hop network is lightly loaded as long as $\lambda_{pg} < 80\% \times max(Th_{pg}^{1\text{-}hop})$. The value of $max(Th_{pg}^{1\text{-}hop})$ is dependent on the relative value of $m+h$ to N: Given $m+h > N$, the higher m, the smaller $max(Th_{pg}^{1\text{-}hop})$.

2) *Traffic load of MPDUs vs. delay*

The traffic load in a network can be reflected by λ_{MPDU}. Clearly, $\lambda_{MPDU} = m \times \lambda_{RP}$. Applying this into Eq. 7 yields the relation between $Q_{Acc}^{1\text{-}hop}$ and λ_{MPDU}. Based on that, the relation of $D_M^{1\text{-}hop}$ and λ_{MPDU} is plotted in Fig. 7. It shows that a bigger m value leads to a higher $max(Th_{MPDU}^{1\text{-}hop})$. But when $m+h > N$ (m = 16 and m = 32), the values of $max(Th_{MPDU}^{1\text{-}hop})$ are very close. In lightly loaded situations, given an input λ_{MPDU}, a bigger m causes a higher delay. However, using a smaller m makes a network more likely to be highly loaded, where $D_M^{1\text{-}hop}$ is high.

From the above analysis, it is clear to see that m has great impact on the achievable throughput, delay and range of λ_{MPDU} under which a network is lightly loaded. To obtain a better performance in the first and third aspects, m should be as high as possible, which is however adverse to the performance in the second aspect. It can be found that a good trade-off is achieved when $m = N$, i.e. $m = 16$. Under that, the value of $max(Th_{MPDU}^{1\text{-}hop})$ is close to the maximum value N/P_{TDMA}. Accordingly the range of the λ_{MPDU} leading to a lightly loaded network is wide enough. At the same time $D_M^{1\text{-}hop}$ is small. In the following, the optimal performance is considered to be achieved when $m = N$.

3) *Impact of number of TCHs in a TDMA frame*

It is evident that:

$$P_{TDMA} = T_{ACH} + N \times (T_{TCH} + T_{ECH}) \tag{10}$$

As already pointed out, the optimal performance is achieved when $m = N$. Applying this and Eq. 10 into Eq. 3 yields the relation between $D_M^{1\text{-}hop}$ and N, as plotted in Fig. 8. It can be seen that a larger N leads to a higher $max(Th_{MPDU}^{1\text{-}hop})$ and also a higher $D_M^{1\text{-}hop}$. However, when $N > 16$, the values of $max(Th_{MPDU}^{1\text{-}hop})$ are almost same. The dependence of $max(Th_{MPDU}^{1\text{-}hop})$ on N can be derived by applying Eq. 10 and $\lambda_{RP} = \lambda_{MPDU} / m$ into Eq. 9:

$$\begin{aligned}\max(Th_{MDPU}) &= \frac{m \times N}{j \times (m+h) \times [T_{ACH} + N \times (T_{TCH} + T_{ECH})]} \\ &= \frac{1}{j} \times \frac{1}{1+\frac{h}{m}} \times \frac{1}{\frac{T_{ACH}}{N} + T_{TCH} + T_{ECH}}\end{aligned} \tag{11}$$

The optimal m value is N. Using $m = N$ yields:

$$\max(Th_{MPDU}) = \frac{1}{j} \times \frac{1}{1+\frac{h}{N}} \times \frac{1}{\frac{T_{ACH}}{N} + T_{TCH} + T_{ECH}} \qquad (12)$$

Eq. 12 shows that when N increases, the values of $max(Th_{MPDU}^{1\text{-}hop})$ are getting close and approaching to $[1/(T_{TCH} + T_{ECH})]$. The above analysis suggests that there exists a range of N values which are appropriated for achieving a high throughput while ensuring a low delay. By carefully checking the figure, we can find that the range is $N \in [16, 20]$.

4) Impact of the duration of a TCH slot

Given a predefined MPDU length in bytes, T_{TCH} is dependent on the PHY data rate. The higher the PHY data rate, the shorter T_{TCH}. The dependence of $D_M^{1\text{-}hop}$ on T_{TCH} is obtained by applying Eq. 10 into Eq. 3. Fig. 9 shows results. It can be seen that a short T_{TCH} leads to a high achievable throughput and a low delay. Therefore, from the perspective of achieving high traffic performance, T_{TCH} should be as small as possible as long as a PHY allows.

V. Conclusion

MDCF is a novel MAC protocol, designed for interconnecting a large number of APs in order to create an efficient ESS mesh network supporting QoS. This paper models and analyzes the traffic performance of MDCF in single-hop wireless networks. Based on the established model, the optimal frame parameter settings for MDCF can be precisely determined. Due to the limited space, we limit our study in this paper on single-hop MDCF networks. The modeling and performance analysis of MDCF multi-hop networks will be presented in a future publication.

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