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Throughput enhancement with a modified 802.11 MAC protocol with multi-user detection support☆

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Abstract

A modification to the traditional CSMA-based media access control protocol, named 802.11-MUD, is proposed in this paper which differs from the IEEE 802.11 in its support of simultaneous transmissions/receptions with multi-user detection (MUD). A joint information and renewal theoretic analysis framework is introduced to study the performance of 802.11-MUD. While the information theoretic part is useful for modeling the increase in sum capacity attributed to MUD, the renewal theoretic part is good for modeling the impact of MUD on alleviating the collision probability and increasing the network throughput. In addition, this analytical framework helps us finetune the 802.11-MUD system (called 802.11-MUD* after the optimal tuning) and achieve significantly enhanced network throughput especially in busy networks.

Keywords: Wireless LAN; MAC protocols; Multi-user detection

1. Introduction

In wireless local area networks (LAN), medium access control (MAC) protocols aim to coordinate the access of wireless client stations to the shared communication medium in an efficient manner. Among many technologies and standards developed so far, the carrier sense multiple-access/collision avoidance (CSMA/CA)-based IEEE 802.11 has emerged as the most popular MAC protocol for wireless LANs. As its goal is to avoid collisions whenever possible, 802.11 attempts to eliminate simultaneous transmissions at any given moment using a random backoff mechanism. This may be a simple and robust solution; however, in a busy network, major resources such as wireless bandwidth and time are wasted significantly during the backoff period.

The restriction on simultaneous transmissions has been a standard assumption for CSMA schemes since the seminal paper of Kleinrock and Tobagi [1]: any two or more simultaneous packet transmissions (or receptions at the receiver) are regarded as a strict sense collision event, which results in the corruption of all transmitted information. Thanks to fast advances in signal processing and multi-user detection (MUD) technologies [2], however, simultaneous transmission and multi-packet reception (MPR) [3–6] are among many recent physical layer technologies getting accepted in practice.

Techniques for simultaneous transmission and reception may range from the passive *capture* operation to the more active space-division multiplexing used in space–time modem [7]. The capture phenomenon occurs when we take into account the diversity of signal strengths at the receiver. Even in the presence of multiple signals, a stronger signal can be

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successfully received provided the ratio of its strength to the combined strength of noise and other signals is greater than a certain threshold. Using antenna arrays, a narrow beam of signals along a certain direction can be formed for transmission as well as for reception. Thus, the antenna array can be used to reduce the signal interference problem. This is a *spatial* domain multiplexing. At the receiver, many signals from different directions can be detected simultaneously. Recently, with the growing interests in mobile ad hoc networks, the impact of using beam-forming antenna array for MANET operation has been studied [8]. Other related work includes Orozco-Lugo et al. [9], who considered the multiple packet reception for MANET. Signature sequences are used for signal modulation and to distinguish between different users when their signals simultaneously arrive at the receiver.

Recently, it has been shown that the low-density parity check coded modulation signals can be separated and detected at the access node using the iterative message-passing decoder for a number of simultaneous users [10,11]. It should be noted that this is done without any traditional explicit multiplexing scheme such as in code-, time-, frequency-, or spatial-division. The channel-code can be used as the means for both spreading and user identification. The traditional approach has been to separate the jobs of channel coding and spreading, the latter of which is used mostly combined with the user identification – code division. However, theoretical analyses [12,13] have shown that the optimal multiple-access channel capacity is achievable when the entire bandwidth is devoted to coding. A suggested approach is to use a very low-rate channel code without spreading, and the signature for user differentiation can be obtained by varying the random interleavers used in each user's coding process [14,15]. This is coined as the interleaver division multiple accessing.

With all these new developments, it is envisioned that the future wireless networks will abound with nodes with MPR capability. This, in turn, spurs an interest in cross-layer design: how the existing media access control algorithms should be changed to better utilize the enhanced physical layer capability.

To date, a handful of works exist in the literature which address the impact of employing capable receivers on multiple-access throughput with capture effect [16,17] and with MPR on a slotted ALOHA framework [4,6]. Modification of ALOHA protocol designed to exploit the MPR capability has been proposed in [6]. In [5], Mergen and Tong propose a distributed random access protocol for MANET, which consists of spread-spectrum-based MPR enabled nodes. Randomly generated seeds are exchanged among local nodes and they can be used to generate the spreading sequences at the pertinent nodes. The authors have shown that the throughput of the new protocol can be made comparable to that of the pure slotted ALOHA system.

While these prior works have shown significant throughput advantage of the MPR capable access node, especially within the ALOHA framework, there has been lack of studies on how the MPR systems can be embraced into the CSMA framework and how the overall system can be optimized for throughput enhancement.

In this paper, we propose an analytical throughput calculation framework for the 802.11 with the assumption that the access node supports simultaneous transmission and reception. A modification to the 802.11 is proposed, named 802.11-MUD in this paper, to maximize the benefit of the MUD capability of the access node. One of our goals is to determine the maximum throughput obtainable by the 802.11-MUD system as compared to that of the conventional 802.11 system. Numerical evaluation of the proposed analysis framework indicates that the proposed system can provide a significant increase in throughput especially in busy network scenarios.

The modification required by the proposed system to 802.11 is moderate: an MUD capable access node along with a little modification done at the MAC level. The proposed analysis framework can be easily extended for calibrating any given network.

The rest of the paper is organized as follows. Section 2 provides an analysis on the sum capacity of multi-access channels and derives the network throughput of 802.11-MUD by utilizing regenerative properties. Section 3 presents numerical results to verify the effectiveness of the proposed system and considers the optimization of the system with respect to the transmission attempt (TA) probability. Finally, Section 4 makes concluding remarks.

2. Sum capacity and throughput analysis

In this section, we consider the throughput enhancement of 802.11-MUD systems. Connoting the maximum number m of simultaneously detectable users at the access node, we call it an 802.11-MUD-m system. It is assumed that more than m simultaneous transmissions cause a collision and result in the corruption of all transmitted information.

It is not difficult to envision that we could get some throughput enhancement at least through the following two mechanisms. The first is an increase in the sum rate due to simultaneous transmission. The second is less collisions due to MUD. The spectral efficiency during the MPR is increased with the number of simultaneous transmissions allowed within the same frequency spectrum, compared to the spectral efficiency of a single-user transmission. For the analysis of sum-rate increase, we utilize the information theoretic analysis framework, while for the analysis of network throughput of the 802.11-MUD-m system, the classical renewal theoretic framework [18] is adopted.

2.1. Information Theoretic Sum Capacity

It is well known in the information theory [19] that the sum capacity of a multiple-access channel under the assumption of a MUD-capable receiver is greater than the individual channel capacity of each user in the system, although it is less than or equal to the sum of all the individual channel capacities. An individual capacity here means the capacity of the channel when a single user occupies the channel all alone. It is not surprising that the throughput can be enhanced by supporting simultaneous detection at the receiver. Then, an immediate question is how much enhancement we can obtain. The aim of this subsection is thus to answer this question and find a suitable means to represent the capacity enhancement so as to facilitate the renewal theoretic analyses later. Specifically, the following questions are considered:

(1) In which cases the sum-capacity gets *equal* to the sum of individual capacities?
(2) In which cases the sum-capacity gets *smaller* than the sum of individual capacities?
(3) How to define a metric that can be used to represent both cases in the renewal theoretic analyses of network throughput?

First, let us consider the first two. For simplicity, suppose that the channels from wireless stations to the access point can be modeled as mutually independent additive white Gaussian noise (AWGN) channels, each with a fixed channel gain. With the assumption of Gaussian input constellations, the sum capacity of this system is given by [19]

$$\frac{C}{W} = \log\left(1 + \sum_{k=1}^{m} \mathrm{SNR}_k\right), \tag{1}$$

where C is the channel capacity, W is the available channel bandwidth and SNR_k is the signal-to-noise ratio of user k. The unit is [bits/s/Hz] or [bits/channel-use]. Now, note that under the condition that all the SNR_ks are the same and very small, the increase in the sum capacity can be as high as m-fold. In the case of high SNR, on the other hand, the capacity improvement is only additive and logarithmic to m, i.e., $\log(m)$. This follows from the facts that $\log(1+mx) \approx \log(mx) = \log(m) + \log(x)$ for $x \gg 1$, and $\log(1+mx) \approx mx$ for x close to 0. This is the consequence of making the ideal assumption that the input signal constellation is Gaussian distributed.

For a more realistic setting, fixed finite-size constellations, e.g. Q-ary phase-shift keying (PSK) and quadrature amplitude (QAM) modulations, are used. In this case, the sum capacity of the multiple-access channel can be shown to increase linearly with the number m of simultaneous transmissions (i.e., m-fold improvement) in the high SNR region. As an illustration, we plot in Fig. 1 the capacity region of a two-user access channel with Rayleigh fading when each user adopts a fixed 4-QAM constellation. At low SNR region, the capacity region is pentagonal, implying that the sum capacity is less than the sum of the two individual capacities. As SNR goes up, we notice that the pentagonal

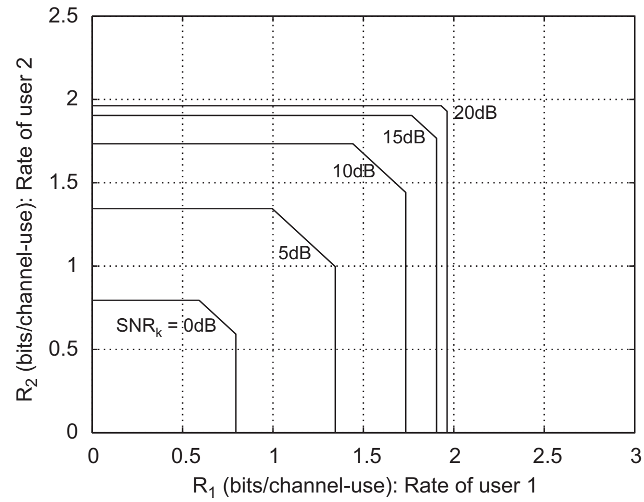

Fig. 1. The capacity region of a two-user access channel with Rayleigh fading (assuming $\mathrm{SNR}_1 = \mathrm{SNR}_2$). Each user adopts a fixed 4-QAM constellation.

capacity region becomes a square region, implying that the sum capacity is the same as the sum of the two individual capacities. In practice, there always is a limit on the constellation size. Thus, a nearly multifold increase in the sum capacity can be expected whenever SNRs exceed a certain threshold.

On the other hand, an adaptive modulation scheme can be used to increase or decrease the size of the constellation in response to the variation of instantaneous SNRs. In this case, the factor of improvement in the sum capacity becomes logarithmic again, just like the Gaussian-distributed constellation case.

Now, we are ready to address the third question. For this, we introduce an information–theoretic utility parameter α_k (called the normalized per-user transmission rate):

$$\alpha_k := \frac{\max_{p(x_1)\cdots p(x_k)} I(X_1, \ldots, X_k; Y)}{k \times \max_{p(x_1)} I(X_1; Y)}, \tag{2}$$

where $I(X_1, X_2, \ldots, X_k; Y)$ denotes the mutual information between the k inputs $X_1, X_2, \ldots, X_k$ and the output Y over the channel $p(y|x_1, x_2, \ldots, x_k)$ and the input distribution $p(x_1)p(x_2)\ldots p(x_k)$. This is a flexible and fundamental definition that can cover all cases under consideration. Note that the normalized rate is a number not greater than 1 and $\alpha_k = 1$ means that the sum capacity is equal to the sum of individual capacities. As a special case, we have $\alpha_1 = 1$ according to the above definition.

In what follows, we assume without loss of generality that any single-user transmission is done at the *unit* rate, i.e., 1 bit/s/Hz. Then, the normalized rate α_k can be interpreted as the actual per-user transmission rate in a successful k-users' simultaneous transmission.

Take the two-user access channel in Fig. 1 as an example; we have $\alpha_2 \approx 0.87$ for $\mathrm{SNR}_k = 0\,\mathrm{dB}$ and $\alpha_2 \approx 0.99$ for

$\text{SNR}_k = 20$ dB. In the first case, the sum rate is $1.74 = 0.87 \times 2$ bit/s/Hz. In the second case, it is $1.98 = 0.99 \times 2$ bits/s/Hz. They are the factors of throughput increase during the period of time when successful simultaneous transmissions are made.

2.2. Throughput analysis of 802.11-MUD-m

We next move on to the throughput analysis of the 802.11-MUD-*m* system. Assume there are M competing stations (users) operating in a *saturation condition* (a.k.a. heavy load condition) [20–22] in which each of the M station always has packets ready for transmission to the access node.

For notational convenience, we denote as $\overline{X}$ the average value of a random variable X and express time intervals in terms of the number of timeslots T_{slot}.

The 802.11-MUD system is modeled based on the assumption that before each transmission, a station experiences a backoff time, which is an independent sample from a geometric distribution:

$$\Pr\{\text{backoff time} = n\} = p(1-p)^n, \quad n = 0, 1, \ldots, \tag{3}$$

where the parameter p represents the TA probability of a station in one timeslot. Then, the average backoff time is given by $\mu_b = 1/p - 1$. In 802.11, a station uses a random variable for the backoff time, which is uniformly distributed in the interval from zero to the contention window size. The TA probability is a parameter dependent on the previous transmission successes and failures. However, as verified by simulations in [20], geometrically distributed backoff time provides a good approximation to the behavior of 802.11, at least from the throughput point of view. In view of this, we can treat 802.11 as a special case of 802.11-MUD with $m = 1$, i.e., 802.11-MUD-1, and the following analysis also applies to 802.11 system.

We observe the system at the beginning of each idle period as shown in Figs. 2 and 3. Note that the optional RTS/CTS (R/C) handshake is not considered for the moment. Our analysis, however, will be extended later to the system with R/C handshake implemented. Suppose the packet length L follows an independent geometric distribution with parameter q, i.e.,

$$\Pr\{L = n\} = q(1-q)^{n-1} \quad \text{or} \quad \Pr\{L \leqslant n\} = 1 - (1-q)^n \tag{4}$$

for any positive integer n. The average length is thus $\overline{L} = 1/q$. From the assumptions of geometrically distributed backoff time and independent packet lengths, the process that defines the state of the channel, idle or busy, is *regenerative* [18] at each renewal epoch, i.e., at the beginning of each idle period.

In what follows, we make use of the regenerative properties to analyze the performance of 802.11-MUD. As illustrated in Figs. 2 and 3, we consider a renewal period to be composed of an idle backoff period and a busy transmission period. During the busy period, either a successful transmission or a collision may occur. Note that this is different from [20], where a renewal period refers to the interval between two successive successful transmissions. As is shown below, the definition of renewal period in this paper enables us to analyze the multi-user and single-user transmissions in a simple unified manner.

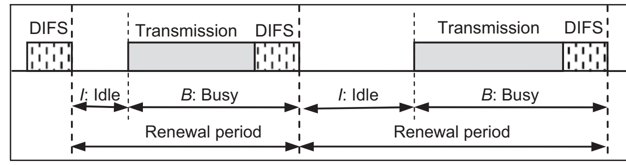

Fig. 2. An illustration of the channel status.

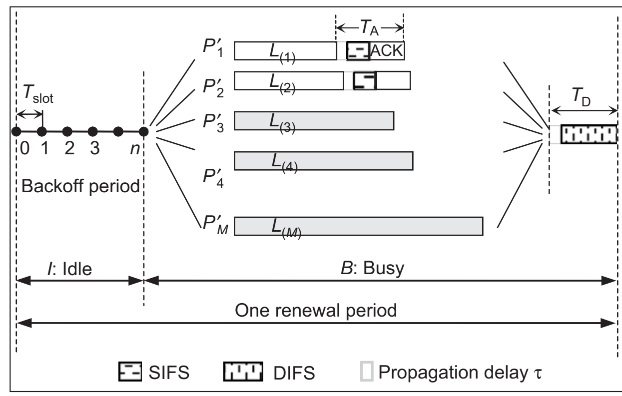

Fig. 3. An illustration of the renewal period of 802.11-MUD-2 without RTS/CTS. Each renewal period is composed of an idle period (backoff time) and a busy period (packet transmission period plus protocol overhead). In 802.11-MUD-2, k-stations' simultaneous transmissions are considered as a success if $k \leqslant 2$ or a collision if $k > 2$ (the gray bars). P'_k denotes the probability of k-stations' simultaneous transmissions after the backoff period and $L_{(k)}$ denotes the maximum length of the k involved packets, i.e., the overall duration of k stations' simultaneous transmissions.

The renewal period is composed of an idle period I in which the shared wireless medium remains idle due to the backoff mechanism, and a busy period B accounting for the packet transmission period and protocol overheads, such as DIFS, SIFS, ACK, etc. By invoking the regenerative properties [18, Chapter 6.4], we can define the network throughput S as the successful information transmission per renewal period, i.e.,

$$S = \frac{\overline{U}}{\overline{I} + \overline{B}}, \tag{5}$$

where $\overline{I} + \overline{B}$ is the average length of the renewal period and $\overline{U}$ represents the average length of the equivalent successful transmission time which will be defined later in (13).

Define P_k as the probability that k wireless stations start their transmissions at the same timeslot, and P'_k as the corresponding conditional probability given $k \geqslant 1$ (i.e., given that the idle period is terminated). We have

$$P_k = \binom{M}{k} p^k (1-p)^{M-k} \quad \text{and} \quad P'_k = \frac{P_k}{1-P_0}. \tag{6}$$

Thus, the average length of the idle period is given by

$$\overline{I} = \sum_{n=0}^{\infty} n P_0^n (1-P_0) = \frac{P_0}{1-P_0}. \tag{7}$$

We next move on to the calculation of the average length of the busy period. Denotes, L_i the packet length of station i which follows the geometric distribution of (4). Then, the maximum length $L_{(k)} = \max\{L_1, L_2, \ldots, L_k\}$, i.e., the overall duration of k stations' simultaneous transmissions, follows the distribution

$$\begin{aligned} \Pr\{L_{(k)} = n\} &= \Pr\{\forall L_i \leqslant n\} - \Pr\{\forall L_i \leqslant n-1\} \\ &= [1-(1-q)^n]^k - [1-(1-q)^{n-1}]^k, \end{aligned} \tag{8}$$

where the second line is due to the fact that the packet lengths L_i's are independent for different stations and each follows the distribution in (4). Thus, the expectation of the maximum length is given by

$$\begin{aligned} \overline{L}_{(k)} &= \sum_{n=1}^{\infty} n\{[1-(1-q)^n]^k - [1-(1-q)^{n-1}]^k\} \\ &= \sum_{i=1}^{k} \binom{k}{i} \sum_{n=1}^{\infty} n[(-(1-q)^n)^i - (-(1-q)^{n-1})^i] \\ &= \sum_{i=1}^{k} \binom{k}{i} \frac{(-1)^{i+1}}{1-(1-q)^i}, \end{aligned} \tag{9}$$

where the last line is obtained by simple algebraic manipulation.

As illustrated in Fig. 3, the average length of the busy period in 802.11-MUD-m is given by

$$\overline{B} = \sum_{k=1}^{M} P'_k \overline{L}_{(k)} + \sum_{k=1}^{m} P'_k T_A + T_D, \tag{10}$$

where T_A and T_D are the respective intervals of ACK + SIFS + τ and DIFS + τ expressed in terms of the number of timeslots, and τ denotes the propagation delay. The first term in (10) represents the overall transmission period averaged over all possibilities of k $(k = 1, 2, \ldots, M)$ stations' simultaneous transmissions, regardless of success or collision. The second term accounts for the ACK period which only follows a successful transmission ($k = 1, 2, \ldots, m$ for a 802.11-MUD-m system). Substituting (6) and (9) into (10), we have

$$\begin{aligned} \overline{B} = \frac{1}{1-P_0} &\left\{ \sum_{k=1}^{M} P_k \sum_{i=1}^{k} \binom{k}{i} \frac{(-1)^{i+1}}{1-(1-q)^i} + \sum_{k=1}^{m} P_k T_A \right\} \\ &+ T_D. \end{aligned} \tag{11}$$

It is convenient to quantify the successful information transmission time U in a way similar to those used in the literature, i.e., let U connote the time required to complete a successful single-user transmission. For 802.11-MUD-m, the simultaneous transmissions of at most m stations can be successfully received by the MUD-capable access point. Thus, U is defined as the *equivalent* transmission time, i.e., the time for a single user to transmit the same amount of information with unit rate ($\alpha_1 = 1$). For example, a successful two-station transmission with $L_1 = 5$ and $L_2 = 10$ (timeslots), each at a fixed rate $\alpha_2 = 0.75$ contributes to an equivalent transmission time $U = \alpha_2 \times (5+10) = 11.25$ (timeslots). Note that by this definition, the resulting network throughput in (5) could end up being greater than one.

The per-user transmission rate α_k is quantified according to definition (2). In practice, it can be calculated based on the signal-to-noise ratio (SNR) and MUD capability at the receiver. It might be as high as 1 if sufficiently high SNR is achieved. In this paper, however, we assume α_k's are predetermined values for simplicity.[1] For example, some simulation results in the following section are obtained by assuming moderate MUD capability with $\alpha_2 = 0.75$ and $\alpha_3 = 0.5$.

The equivalent successful transmission time U in 802.11-MUD-m is given by

$$U = \begin{cases} \alpha_k \sum_{i=1}^{k} L_i, & k \leqslant m, \\ 0, & k > m. \end{cases} \tag{12}$$

The average value of U is thus obtained as

$$\overline{U} = \sum_{k=1}^{m} P'_k \alpha_k k \overline{L} = \frac{1}{q} \sum_{k=1}^{m} k\alpha_k \frac{P_k}{1-P_0}. \tag{13}$$

Substituting (7), (11), and (13) into (5), we can express the throughput S_m of 802.11-MUD-m as follows:

$$S_m = \frac{\frac{1}{q}\sum_{k=1}^{m} k\alpha_k P_k}{P_0 + \sum_{k=1}^{M} P_k \sum_{i=1}^{k} \binom{k}{i} \frac{(-1)^{i+1}}{1-(1-q)^i} + T_A \sum_{k=1}^{m} P_k + T_D(1-P_0)}. \tag{14}$$

When the parameter q is small, i.e., the average packet length is much longer than the length of protocol overheads including ACK, SIFS, and DIFS, we can ignore the third and fourth terms in the denominator of (14). In addition, since 802.11 can be regarded as a special case of 802.11-MUD-m with $m = 1$, the throughput improvement of 802.11-MUD-m over 802.11 is approximately given by

$$\frac{S_m}{S_1} \approx \sum_{k=1}^{m} \frac{k\alpha_k P_k}{P_1} = \frac{1}{M} \sum_{k=1}^{m} k\alpha_k \binom{M}{k} \left(\frac{p}{1-p}\right)^{k-1}. \tag{15}$$

Similar to 802.11, 802.11-MUD-m can be implemented with R/C handshake mechanism if the average packet length

[1] In addition, we assume for simplicity that each station has a fixed transmission rate during its transmission period; i.e., each station remains its transmission rate after other stations finish their transmission.

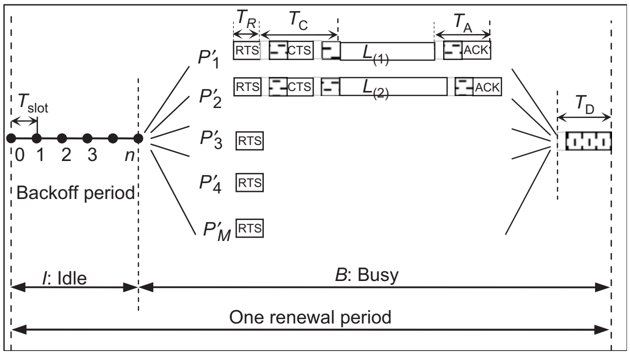

Fig. 4. An illustration of the renewal period of 802.11-MUD-2 with RTS/CTS (the RTS timeout period is ignored for simplicity). The transmission is successful if no more than $k = 2$ stations start their transmission of RTS simultaneously. Otherwise, the access point detects a collision and does not respond with CTS. In this case, there is no packet transmission during the busy period.

is large. In this case, a renewal period of the transmission process is illustrated in Fig. 4. In a way similar to (14), the network throughput can be obtained as

$$S_{m,\mathrm{R/C}} = \frac{\frac{1}{q}\sum_{k=1}^{m}, k\alpha_k P_k}{(\cdots)}, \tag{16}$$

where the denominator $(\cdots)$ is given by

$$(\cdots) = P_0 + \sum_{k=1}^{m} P_k \sum_{i=1}^{k} \binom{k}{i} \frac{(-1)^{i+1}}{1-(1-q)^i} + (T_\mathrm{A} + T_\mathrm{C}) \sum_{k=1}^{m} P_k + (T_\mathrm{D} + T_\mathrm{R})(1 - P_0)$$

and T_R and T_C are the intervals of RTS and CTS + 2(SIFS + τ), respectively. Ignoring the third and fourth terms in the denominator of (16) and by simple manipulation, we can express the throughput improvement of 802.11-MUD-m over 802.11 (with R/C handshake) as follows:

$$\frac{S_{m,\mathrm{R/C}}}{S_{1,\mathrm{R/C}}} \approx \frac{\left(\frac{P_0}{P_1} + \frac{1}{q}\right)\left(\sum_{k=1}^{m} k\alpha_k P_k\right)}{P_0 + \sum_{k=1}^{m} P_k \sum_{i=1}^{k} \binom{k}{i} \frac{(-1)^{i+1}}{1-(1-q)^i}}. \tag{17}$$

3. Numerical results and discussions

In this section, we present numerical results which show the throughput improvement of 802.11-MUD attributed to the MUD capability of the access point. Also, we optimize the 802.11-MUD system for throughput enhancement by varying the TA probability.

The parameters used for the numerical evaluation are listed in Table 1 . Similar to [20], our analysis model (with the assumption of geometrically distributed backoff time) can be used to well approximate the performance of the 802.11 as long as the average backoff time is set appropriately (i.e., set to be the same average value as obtained by the simulation of the standard 802.11). According to the developed properties and simulation results in [20, Lemma 2 and Table IV], we calculate the average backoff time μ_b and the corresponding TA probability $p = 1/(1 + \mu_b)$ as 0.0384, 0.0189, and 0.0137 for $M = 10$, 50, and 100, respectively. For clarity, these probabilities are denoted as p_{802} to distinguish from the optimal TA probabilities p^* to be discussed later.

Table 1. System parameters

Parameters	Values	No. of timeslot (s)
Slot time	50 µs	1
SIFS	28 µs	0.56
DIFS	128 µs	2.56
Bit rate	2 Mbps	–
ACK	14 bytes	1.12
RTS	20 bytes	1.60
CTS	14 bytes	1.12
Propagation delay	1 µs	0.02

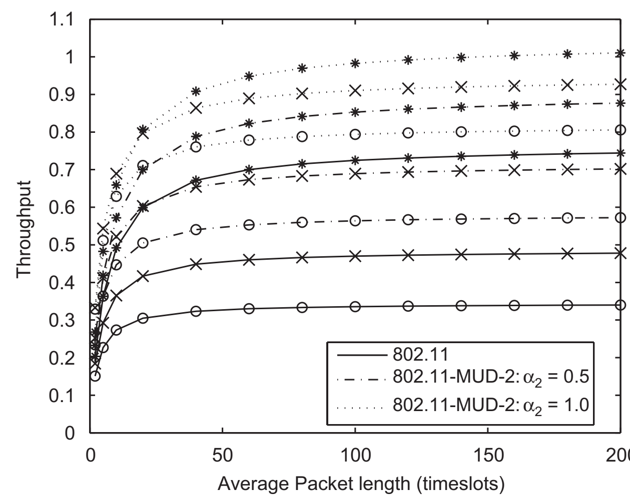

Fig. 5. Throughput vs. average packet length: a comparison between 802.11-MUD-2 and 802.11 ($p = p_{802}$) in different network scenarios with $M = 10$ ($*$), 50 ($\times$), or 100 ($\circ$).

3.1. Throughput comparison

Illustrated in Fig. 5 is the throughput comparison of 802.11-MUD-2 (with $\alpha_2 = 0.5$ or 1.0) and 802.11 when $p = p_{802}$. We consider three different network scenarios where the number M of competing stations in the neighborhood of the access point is equal to 10, 50, or 100, respectively. It is clear that by being capable of supporting up to two simultaneous transmissions, 802.11-MUD-2 achieves an obvious performance improvement even with $\alpha_2 = 0.5$

indicating less efficient MUD. A larger α_2 leads to further improvement so that the throughput may even be greater than 1 (as explained in Section 2.2). In all cases, we observe the low throughput in the region of short average packet lengths, say $\overline{L} \leqslant 50$. This is because the protocol overhead (i.e., DIFS, SIFS, and ACK) becomes relatively significant. The throughput curves become flat in the region of $\overline{L} \geqslant 50$. Also, it is clear that the throughput of 802.11 suffers much as the number of competing stations increases. This obviously is due to the increasing number of collisions. The performance degradation is alleviated by 802.11-MUD-2 to some extent. As will be shown in the next subsection, the throughput of 802.11-MUD can be further improved by optimizing the TA probability.

3.2. Optimal TA probability

The TA probability p can be optimally chosen for a given network load to regulate the average number of active stations. In Fig. 6, having fixed the average packet length $\overline{L}$ either at 50 or at 100, we vary the average number, $\sum_{k=0}^{M} kP_k = Mp$, of simultaneous transmissions in the case of $M = 10$, 50, and 100. The throughput is shown to be a unimodal function of Mp; thus there is a unique optimal tradeoff point to balance the increases of both the sum rate and the collision probability when simultaneous transmissions are allowed. The optimal point is indicated with the asterisk sign in Fig. 6. As is shown, the abscissa Mp^* of the optimal point is quite stable for each 802.11-MUD-m system: its value is less sensitive to the changes of both the network load M and the average packet length $\overline{L}$. For example, the throughput is degraded by at most 5% as long as the actual TA probability p is such that $Mp \in [0.5Mp^*, 2Mp^*]$. These observations are supported by an approximate analysis of the network throughput in the appendix.

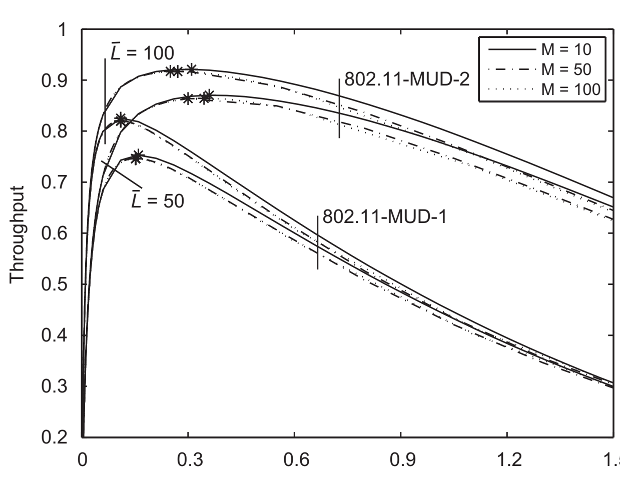

Fig. 6. Throughput vs. Mp for different 802.11-MUDs and average packet lengths $\overline{L}$ ($\alpha_2 = 0.75$). The optimum point of each curve is noted by an asterisk sign and its abscissa is denoted as Mp^*.

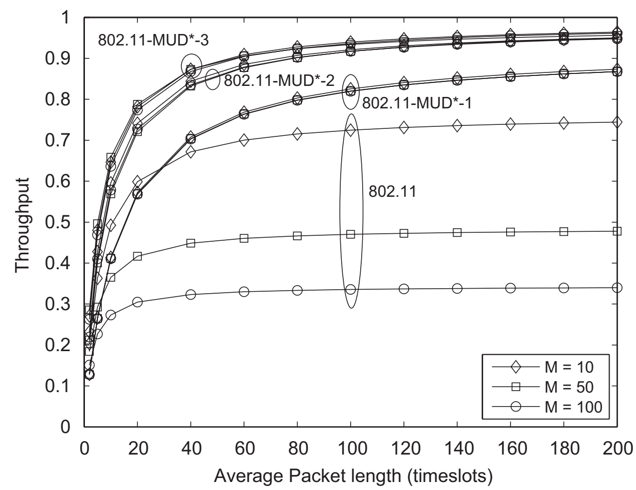

Fig. 7. Throughput vs. average packet length: an illustration of further throughput improvement of 802.11-MUD*-m with optimal p^* over that of the 802.11 with $p = p_{802}$ ($\alpha_2 = 0.75$, $\alpha_3 = 0.5$).

For clarity, we refer to an 802.11-MUD system as 802.11-MUD* when the optimal TA probability p^* is adopted. From the above observations, we expect that the 802.11-MUD* system can be implemented in practice in a robust fashion. The TA probability can be easily tuned up to be near the optimal value after a reasonable estimation of the network parameters such as the number of active stations (an accurate estimate of M may not be available due to practical issues such as the hidden-terminal problem). In practice, the optimal Mp^*'s can be pre-calculated for a set of frequently used packet lengths. Wireless stations can use this set to easily select the optimal TA probability based on the estimated network load M and average packet length $\overline{L}$. For example, for the average packet length of 1250 bytes (100 timeslots), the optimal average numbers of simultaneous transmissions are $Mp^* = 0.110$, 0.277, and 0.476 for 802.11-MUD*-1, 802.11-MUD*-2, and 802.11-MUD*-3, respectively.

Finally, we illustrate in Fig. 7 the throughput of 802.11-MUD* system achieved with the optimal TA probabilities. It is clearly observed that the throughput no longer suffers from the high network load and is increased by twice or thrice compared to the 802.11 system.

3.3. The effect of RTS/CTS

To overcome the hidden terminal problem, the 802.11 MAC protocol can be implemented with an optional R/C channel reservation mechanism. This scheme can be easily adopted in 802.11-MUD* as well but its efficiency needs further investigation. As shown in Fig. 8, the use of R/C scheme contributes to about 10% throughput improvement for the 802.11-MUD*-1 system (i.e., 802.11 with optimal TA probability). However, its benefit becomes trivial in the 802.11-MUD*-m system if $m \geqslant 2$. Indeed, if the average packet length is small, the throughput is even slightly

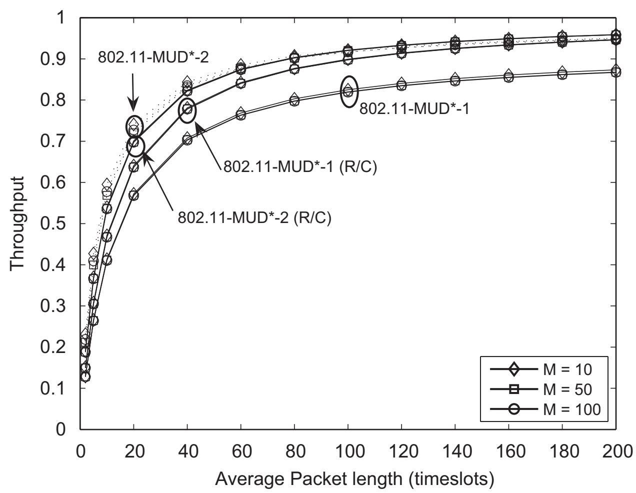

Fig. 8. Throughput vs. average packet length: a comparison of 802.11-MUD*-m with/without RTC/CTS handshake ($\alpha_2 = 0.75$, $p = p^*$).

degenerated due to the R/C overhead. Thus, the R/C scheme, when used in addition to the optimal transmission probability strategy, yields little additional benefit in enhancing throughput.

4. Conclusions

The use of the MUD capable access point in a multiple-access network requires a careful reconfiguration of the multiple-access protocol for maximizing the network throughput. Within the framework of a CSMA-based method, we have proposed a simple modification to the standard 802.11, called the 802.11-MUD*. The modification is to encourage a certain level of simultaneous transmissions and to maximize the benefit of the MUD-capable access node by optimizing the TA probability. The analysis is done in an information and renewal theoretic framework and the performance improvement of the 802.11-MUD* system over the 802.11 system has been quantified. The numerical results show twice or thrice throughput improvement of 802.11-MUD*, especially in a network with high traffic load. Our current work applies to a one-hop scenario. It will be of interest in future research to analyze the performance of 802.11-MUD* in multihop wireless networks.

Appendix

We present an approximate analysis on the network throughput (14) when (i) the average packet length is much longer (i.e., q is very small) than the lengths of protocol overheads, such as ACK, SIFS and DIFS and (ii) the network has a moderate to high traffic load (i.e., the optimal TA probability p^* is small).

From (i), the third and fourth terms in the dominator of (14) can be ignored. Also, a small q validates the approximation of $1-(1-q)^i \approx 1-(1-qi) = qi$. Thus, (14) can be rewritten as

$$S_m \approx \frac{\sum_{k=1}^{m} k\alpha_k P_k}{qP_0 + \sum_{k=1}^{M} P_k \sum_{i=1}^{k} \binom{k}{i} \dfrac{(-1)^{i+1}}{i}}. \tag{A.1}$$

We next consider the assumption of small p^* in (ii). For a probability p close to the small p^*, P_k quickly approaches zero as k increases (see Eq. (6)). Thus, the outer sum of the second term in the denominator of (A.1) can be truncated at the first few K terms ($K \ll M$) with sufficient accuracy. For $k \leqslant K$, we have $\binom{M}{k} \approx M^k/k!$ and $P_k/P_0 \approx (Mp)^k/(1-p)^k/k! \approx (Mp)^k/k!$ according to (6). Therefore, (A.1) can be rewritten as

$$S_m \approx \frac{\sum_{k=1}^{m} k\alpha_k \dfrac{(Mp)^k}{k!}}{q + \sum_{k=1}^{K} \dfrac{(Mp)^k}{k!} \sum_{i=1}^{k} \binom{k}{i} \dfrac{(-1)^{i+1}}{i}}. \tag{A.2}$$

The parameter q in the denominator of (A.2) can be further ignored since it is assumed to be small. In this way, the approximated network throughput formula becomes solely determined by the product Mp and is irrelative to the network load M and the average packet length ($\overline{L} = 1/q$). This explains the insensitivity of Mp^* to these network parameters as shown in Fig. 6.

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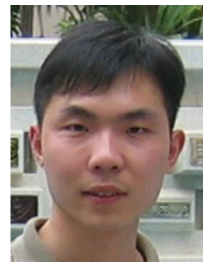

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