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A Threshold-Selective Multiuser Downlink MAC scheme for 802.11n Wireless Networks

Elli Kartsakli [1], Nizar Zorba [2], Luis Alonso [1] and Christos Verikoukis [3]
[1] *Signal Theory & Communications Dept., Universitat Politècnica de Catalunya, Barcelona, Spain*
email: {ellik, luisg}@tsc.upc.edu
[2] *University of Jordan, Jordan*
email: n.zorba@ju.edu.jo
[3] *Centre Tecnològic de Telecomunicacions de Catalunya Barcelona, Spain*
email: {cveri}@cttc.es

***Abstract*—The recently approved 802.11n standard establishes the integration of MIMO technology in WLANs with the goal of achieving high data rates. However, it does not exploit the multiuser capabilities of the MIMO channel. In this paper we present a multiuser downlink transmission scheme that combines low-complexity beamforming at the Physical layer with an opportunistic channel-aware MAC scheduling policy. A mathematical model for the throughput calculation of the proposed scheme is presented and validated through link-layer simulation results.**

***Index Terms*—Local area networks, multiaccess communication, MIMO systems, multiuser channels.**

I. INTRODUCTION

Multiple-Input Multiple-Output (MIMO) technology and its single receiving antenna version, Multiple-Input Single-Output (MISO), promise a significant performance boost and are included in the IEEE 802.11n standard [1]. Multiple antenna transmission techniques can provide rapid and robust point-to-point, as well as simultaneous point-to-multipoint wireless connectivity. Even though the 802.11n standard has been designed with MIMO technology in mind, it only focuses on point-to-point transmissions and does not include any MAC mechanisms for multiuser scheduling.

Few contributions on practical multiuser MAC mechanisms for MISO/MIMO systems exist in the literature. One example is a scheme called Multi-User Distributed Coordination Function (MU-DCF) [2]. This protocol is based on a four-way handshake, initiated by a special multiuser RTS (Request-To-Send) frame that includes a polling address list. However there are several issues, mostly regarding the physical layer (PHY) implementation that are not considered.

In previous work, the authors have proposed four multiuser donwlink MAC schemes for infrastructure WLANs based on the 802.11n standard [3]. The best results have been obtained for an opportunistic channel-aware MAC scheme called Multiuser Threshold Selective algorithm (Mu-Thres), that can achieve a considerable throughput enhancement when its parameters are correctly tuned. However, all the presented results have been based solely on simulations. The main contribution of this paper is to present a detailed theoretical framework for the throughput calculation of the Mu-Thres scheme. An accurate match between theory and simulation is achieved and the presented formulation can be further used to optimally select the tunable parameters of the algorithm.

The paper is organized as follows. Section II describes the PHY layer beamforming transmission technique and Section III presents the principles of the Mu-Thres algorithm. The main contribution of this work, the theoretical throughput analysis, is given in Section IV and some results are presented in Section V. Finally Section VI is dedicated to conclusions.

II. PHY LAYER TRANSMISSION TECHNIQUE

In this section we will briefly present the PHY layer multiuser transmission technique in order to facilitate the understanding of the MAC layer scheme. A more detailed description can be found in [3].

We have considered an infrastructure downlink WLAN, with one Access Point (AP) with $n_t = 2$ antennas and N users, with $N > n_t$. Without loss of generality, a MISO scenario with single-antenna users has been assumed, even though our analysis can be also applied to MIMO systems. By exploiting the spatial signal processing capabilities of MIMO/MISO technology and employing an appropriate transmission technique, the AP can serve up to n_t users at the same frequency, time and code. Details on the channel model are given in Section V-A.

A low-complexity multiuser transmission technique called Multibeam Opportunistic Beamforming (MOB), proposed in [4], is used at the PHY layer. Since 802.11n supports beamforming, MOB can be easily implemented on 802.11n-based equipment by setting the steering matrices accordingly. The main procedure of the MOB technique is that the AP generates n_t random orthogonal beams. The Signal-to-Noise-Interference-Ratio (SNIR) related to each beam is measured by the users and fed back to the AP, as it will be explained in detail in Section III. The AP extracts the multiuser gain from the system by selecting the user with the highest instantaneous SNIR for each beam (i.e. opportunistic user selection). The SNIR takes into account any interference caused by simultaneous transmissions on other beams. Given that no more than one beam is assigned per user, at most n_t users are scheduled for downlink transmission when the respective SNIRs are known. The ultimate goal of this scheme is to find a set of orthogonal users to achieve performance enhancement through multiuser transmission while keeping the interference low. Note that MOB only requires partial Channel State Information (CSI) at the transmitter side in terms of the user SNIR.

III. Multiuser Threshold Selective (Mu-Thres) Algorithm

The goal of the Mu-Thres algorithm is to exploit multiuser diversity and assign opportunistically a set of users with good link quality to the downlink orthogonal beams, thus maximizing the system rate. In order to reduce the control overhead required for the acquisition of the CSI from the users, the algorithm imposes a SNIR threshold so that only users with a relatively good link quality are allowed to participate in the feedback process. The Mu-Thres scheme is easy to implement within the 802.11n standard and is backward compatible with the legacy single user transmission, in the sense that MOB and legacy users can coexist in the system.

The frame exchange sequence of the Mu-Thres scheme is initiated with the broadcast transmission of an RTS frame by the AP. The PHY layer preamble of the RTS contains all the necessary training fields to enable the evaluation of the SNIR value for each of the n_t transmitting beams by all the receiving users. For this purpose, a number of HT-LTFs (High Throughput Long Training Fields) has been added, as defined in 802.11n standard. Depending on whether the maximum SNIR value measured by the user is above or below the SNIR threshold, the user is either allowed to participate in the next phase of the algorithm, or forced to remain silent until the beginning of the new frame sequence, respectively.

A contention phase is then initiated, that consists of m slots of predefined length, with m being a system parameter subject to optimization. The users who satisfy the threshold condition randomly select a slot with probability $1/m$ and transmit a CTS (Clear-To-Send) packet. The CTS contains the maximum SNIR value measured by the user and an integer identifier for the respective beam. Nevertheless, if more than one users transmit simultaneously in the same slot, a collision takes place and the involved CTS frames are considered lost. A slot can also remain empty if no user selects it for transmission.

The next stage of the algorithm depends on the outcome of the contention phase. If no CTS has been correctly received (because of either collisions or lack of user participation due to the SNIR threshold) no data is transmitted and a new contention phase is initiated. Notice that, assuming synchronization among the users, a collision in the mth slot only affects the involved CTS packets and does not have any effect on packets transmitted in a different slot of the same contention phase. Thus, if at least one user survives the contention phase, transmission of donwlink data packets can take place. Using the information from the received CTS frames, the AP assigns the best set of users on the beams (at most one user per beam) and transmits a maximum of n_t data packets simultaneously. Rate adaptation is also performed and the transmission rate on each beam is determined by the measured SNIR value. Finally, the users acknowledge the data reception by sequentially sending an ACK frame. The order in which ACKs are sent follows the mapping of the users onto the beams. The transmission process is illustrated in Fig. 1.

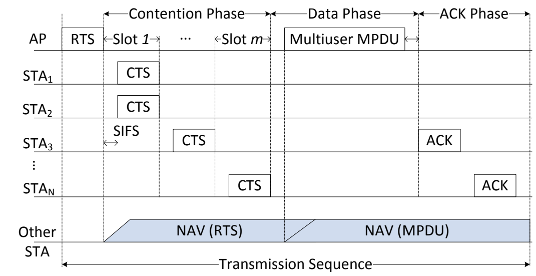

Fig. 1. Transmission sequence for the Mu-Probabilistic Scheme

Note that, unlike the contention phase where collisions among CTS frames can occur, the transmission of data is collision-free. The data packets employ the channel over the same time, frequency and code but are transmitted over different beams. This can be supported by the 802.11n standard, by exploiting the multiplexing capabilities of MIMO/MISO systems. This is actually an important shift from current systems where the simultaneous transmission of multiple packets in the same medium leads to collision and packet loss.

IV. Theoretical Model for Throughput Evaluation

We will now provide an analytical model for the throughput calculation of the Mu-Thes scheme, as a function of the number of users N, the contention slots m and the SNIR threshold γ. A saturated system is considered, where there are always packets to be sent to all the associated users. The proposed model has been developed for $n_t = 2$ transmitter antennas at the AP, since this seems to be the most practical setup in existing systems and also permits a more intuitive interpretation of the analytical model. The analysis could be extended to a larger number of antennas but this would significantly increase the computational complexity.

Consider an Adaptive Modulation and Coding (AMC) scheme that offers R available rates $\{r_1, \ldots, r_R\}$, in ascending order. Each transmission rate can be used when the measured SNIR of the particular link lies within a predefined SNIR range (e.g., Table 1). Obviously, the SNIR of a link is time-varying and depends on the instantaneous channel conditions, but the probability of a user being in each SNIR range can be statistically estimated, as the channel distribution is known (as explained more thoroughly in [3]). Following the calculations in [5] for the MOB system, the approximate Cumulative Distribution Function (CDF) of the SNIR value y that is available at the transmitter with a noise variance of σ^2 is

$$F(y) = \left[1 - \frac{e^{-(y n_t \sigma^2)}}{(1+y)^{n_t - 1}}\right]^{n_t} = \left[1 - \frac{e^{-(2y\sigma^2)}}{(1+y)}\right]^2 \quad (1)$$

as each user feeds back the maximum SNIR with respect to the n_t beams. The probability $P_r(r_w)$ of a user having a particular rate r_w, with $w \in [1, R]$, is equal to the probability of having a SNIR below a threshold γ_{w+1} and above a threshold γ_w and can be calculated with the use of the CDF as

$$P_r(r_w) = F(\gamma_{w+1}) - F(\gamma_w). \quad (2)$$

As mentioned before, the Mu-Thres scheme defines a SNIR threshold γ so that only users with SNIR $\geq \gamma$ can participate in the contention phase. Equivalently, it can be said that a corresponding rate threshold r_γ is imposed and users with $r_w \geq r_\gamma$ (with $w \geq \gamma$) can contend for access. The average throughput $S(m, N, r_\gamma)$ for m slots, N users and a threshold of r_γ is defined as

$$S(m, N, r_\gamma) = \frac{\bar{x}(m, N, r_\gamma)}{\bar{t}(m, N, r_\gamma)} \tag{3}$$

where $\bar{x}$ is the average number of transmitted bits per frame

$$\bar{x}(m, N, r_\gamma) = \sum_{i=1}^{2} i \cdot l \cdot \left(\sum_{w=\gamma}^{R} P_f(i, m, N, r_\gamma, r_w) \right) \tag{4}$$

and $\bar{t}$ is the average frame duration

$$\begin{aligned} \bar{t}(m, N, r_\gamma) &= t(0, m) \cdot P_f(0, m, N, r_\gamma) \\ &+ \sum_{i=0}^{2} \sum_{w=\gamma}^{R} t(i, m, r_w) \cdot P_f(i, m, N, r_\gamma, r_w). \end{aligned} \tag{5}$$

The terms included in the above equations will be explained next. The index i expresses the three possible frame types: $i = 0$ indicates an empty frame in which no data transmission has taken place; $i = 1$ corresponds to single transmission of a data packet of length l bits; finally $i = 2$ indicates a double transmission frame where two users have simultaneously transmitted data packets, corresponding to $2 \cdot l$ transmitted bits.

The average transmitted bits $\bar{x}$ are calculated by multiplying the transmitted bits per frame type by the probability of having that particular frame type, for all data rates above or equal to the threshold. This probability of having a frame of type i transmitted with a rate of r_w, for a given number of slots m, users N and threshold r_γ is denoted by $P_f(i, m, N, r_\gamma, r_w)$.

In the denominator of (3), the term $t(i, m, r_w)$ expresses the transmission time of a frame sequence of type i when rate r_w is used. Note that in the case of an empty frame ($i = 0$), the frame duration and the probability P_f are independent of the transmission rate and the index r_w is dropped for convenience. The calculation of these terms along with a more detailed explanation will be given in the remaining part of this section.

It is easier to comprehend the throughput formulation by considering the actual implementation steps of the Mu-threshold algorithm. First, only a fraction n of the total N users, those with an available rate of $r_w \geq r_\gamma$ (with $w \geq \gamma$), are allowed to participate in the contention phase. As the channel statistics are known, the probability that exactly n out of N users have a rate above the threshold r_γ, can be calculated with the use of the SNIR CDF in (1), as

$$P_{select}(n, r_\gamma) = \binom{N}{n} \big(1 - F(r_\gamma)\big)^n \big(F(r_\gamma)\big)^{N-n}. \tag{6}$$

Those n users that pass the threshold selection phase will contend for channel access by transmitting a CTS in one of the m slots. If a slot is selected by exactly one user, the contained CTS is successfully received and the respective user is said to have survived the contention phase. The probability $P_{survive}(s, m, n)$ of having exactly s out of n users surviving the contention phase of m slots is equivalent to the probability of having exactly s successful slots (i.e. selected by a single user) whereas the remaining $m - s$ slots are empty or have suffered a collision. This is a combinatorial problem known as “assignment of n object in m cells” and its complete analysis is given in [6]. The final expression for $P_{survive}(s, m, n)$ is

$$\begin{aligned} &P_{survive}(s, m, n) = \\ &= \frac{(-1)^s m! n!}{m^n s!} \sum_{j=s}^{min(m,n)} \frac{(-1)^j (m-j)^{n-j}}{(j-s)!(m-j)!(n-j)!}. \end{aligned} \tag{7}$$

Once P_{select} and $P_{survive}$ have been calculated, we can proceed to the calculation of P_f for the three different frame types. The number of surviving users s determines what frame sequence will be transmitted. If no user has a rate above the threshold ($n = 0$), or no user survives the contention phase ($n > 0$ but $s = 0$), an empty frame will follow. Thus, the probability of having an empty frame can be calculated as

$$\begin{aligned} P_f(i = 0, m, N, r_\gamma) &= P_{select}(0, r_\gamma) \\ &+ \sum_{n=1}^{N} P_{select}(n, r_\gamma) \cdot P_{survive}(0, m, n). \end{aligned} \tag{8}$$

A single transmission frame occurs when there is at least one surviving user ($s \geq 1$) and all the surviving users select the same beam. Hence, the probability of having a single transmission frame with rate r_w is

$$\begin{aligned} &P_f(i = 1, m, N, r_\gamma, r_w) = \\ &= \sum_{n=1}^{N} \left(P_{select}(n, r_\gamma) \cdot \sum_{s=1}^{n} \left[(P_{survive}(s, m, n) \right.\right. \\ &\quad \left.\left. \cdot \; Pr\Big\{ s \text{ users on same beam} \Big\} \cdot P_{r1}(r_w, s) \right] \right) \end{aligned} \tag{9}$$

where $P_{r1}(r_w, s)$ is the probability that rate r_w is used for transmission.

It is considered that each user may be assigned to either of the two available beams with an equal probability of 0.5. The probability $Pb(b, s)$ of having b out of s users assigned on the first beam (and hence $s - b$ users on the second) is

$$P_b(b, s) = \binom{s}{b} \cdot \left(\frac{1}{2}\right)^b \cdot \left(\frac{1}{2}\right)^{s-b} = \binom{s}{b} \cdot 2^{-s}. \tag{10}$$

It can be easily derived that the probability that all s users select the same beam is equal to 2^{1-s}.

Since the scheme is opportunistic, the surviving user with the highest rate will be selected for transmission. So $P_{r1}(r_w, s)$ is the probability that r_w is the maximum available rate among s surviving users and can be calculated as

$$\begin{aligned} &P_{r1}(r_w, s) = \\ &= Pr\Big\{ (\geq 1 \text{ user with } r_w) \cap (\text{no user with } r > r_w) \Big\} \\ &= Pr\{ (\geq 1 \text{ user with } r_w) | (\text{no user with } r > r_w) \} \\ &\qquad \cdot Pr\{ ((\text{no user with } r > r_w) \} \\ &= (1 - Pr\{\text{all users with } r < r_w\}) \\ &\qquad \cdot Pr\{\text{all users with } r \leq r_w\} \Rightarrow \end{aligned}$$

$$P_{r1}(r_w, s) = \left(1 - \left[\frac{\sum_{v=\gamma}^{w-1} P_r(r_v)}{\sum_{v=\gamma}^{w} P_r(r_v)}\right]^s\right) \cdot \left[\frac{\sum_{v=\gamma}^{w} P_r(r_v)}{\sum_{v=\gamma}^{R} P_r(r_v)}\right]^s \quad (11)$$

So far, the calculation of the probability P_f for the cases of i =0 and i =1 has been presented. We will now proceed to the third case of having a double transmission frame (i =2). This case occurs when there are at least two surviving user ($s \geq 2$) and at least one user is assigned per beam (i.e not all users on the same beam).

The transmission rate on each beam will be equal to the highest rate available among the users assigned on that beam. An interesting observation is that, although different rates may be used on each of the two beams, the total frame sequence duration is determined by the lower rate (i.e. the longest transmission of the two). We define $P_{r2}(r_w, s)$ as the probability that the frame duration is determined by rate r_w, given that both beams are used for transmission. Then

$$P_f(i = 2, m, N, r_\gamma, r_w) = \sum_{n=2}^{N} P_{select}(n, r_\gamma) \cdot \sum_{s=2}^{n} P_{survive}(s, m, n) \cdot P_{r2}(r_w, s) \quad (12)$$

with the probability $P_{r2}(r_w, s)$ given by

$$P_{r2}(r_w, s) = \sum_{b=1}^{s-1} P_{r2\_cond}(r_w, b, s) \cdot P_b(b, s). \quad (13)$$

In this equation $P_b(b, s)$ is the probability of having b users on the first beam, calculated by (10). Then, $P_{r2\_cond}(r_w, b, s)$ is the conditional probability that the frame duration is determined by rate r_w, when b out of s users are assigned to the first of the two beams (and $s - b$ to the second). This probability can be calculated as

$$\begin{aligned} P_{r2\_cond}(r_w, b, s) = \\ &= Pr\{\text{beam 1: rate } r_w \text{ used}|b \text{ users}\} \\ &\quad \cdot Pr\{\text{beam 2: } r > r_w|s - b \text{ users}\} \\ &+ Pr\{\text{beam 2: rate } r_w \text{ used}|s - b \text{ users}\} \\ &\quad \cdot Pr\{\text{beam 1: } r > r_w|b \text{ users}\} \\ &+ Pr\{\text{beam 1: rate } r_w \text{ used}|s \text{ users}\} \\ &\quad \cdot Pr\{\text{beam 2: rate } r_w \text{ used}|s - b \text{ users}\} \Rightarrow \end{aligned}$$

$$\begin{aligned} P_{r2\_cond}(r_w, b, s) = \\ &= P_{r1}(r_w, b) \cdot \sum_{v=w+1}^{R} P_{r1}(r_w, s - b) \\ &+ P_{r1}(r_w, s - b) \cdot \sum_{v=w+1}^{R} P_{r1}(r_w, s) \\ &+ P_{r1}(r_w, b) \cdot P_{r1}(r_w, s - b) \end{aligned} \quad (14)$$

with $P_{r1}(r_w, s)$ calculated by (11). Equations (8), (9) and (12) can be used in (4) and (5) to calculate the system throughput.

The last parameter that must be defined is the frame duration $t(i, m, r_w)$ for a frame of type i that uses rate r_w, given by

$$t(i, m, r_w) = t_{data}(i, r_w) + t_{ovh}(i, m) \quad (15)$$

where $t_{data}(i, r_w)$ is the transmission time of the data packet for a frame of type i and $t_{ovh}(i, m)$ is the control overhead, that can be derived from the standard specifications.

The data transmission time can be easily calculated for a known packet size l and a given transmission rate r_w and is equal to zero in the case of an empty frame ($i = 0$). The overhead time t_{ovh} is also known for each frame type. The required overhead for all three frame types is the time required for the transmission of an RTS frame and the duration of the contention window of m slots, with each slot consisting of a CTS frame and a SIFS. In case of non-empty frames, the time required for the transmission of the ACK frames (one or two, depending on whether a single or double transmission has taken place, respectively) must be added.

V. Performance Evaluation

A. Simulation Setup

The proposed theoretical model has been used to calculate the throughput of the Mu-Thres scheme. In order to demonstrate the validity of the model, simulation results have been obtained with the help of a link link-layer simulation tool implemented in C++. An infrastructure downlink network of $N = 10$ users has been considered, with an infinite amount of data traffic for each user in the buffers of the AP (i.e., saturated downlink traffic). Packets have a fixed length of 2312 bytes.

It has been assumed that the AMC scheme ensures error-free data transmission, given that the rate for each transmission is selected according to the link quality. The particular SNIR values used for the AMC are given in Table I [7]. All control frames are transmitted at the lowest transmission rate (i.e., at 6 Mbps) to ensure reception without errors.

The 802.11n frame format has been adopted at the MAC layer and a summary of the simulation parameters is given in Table II. The Duration/ID field of the RTS frame contains the duration of the contention phase and since the transmission time of a CTS is constant, the number of allocated CTS slots m can be calculated without further overhead. The CTS frame contains one additional byte to include the SNIR value and the beam identifier (assuming an optimal SNIR quantization).

The AP has two transmitting antennas with a total gain of $10dBi$. The underlying MISO channel simulation has been based on the 802.11n channel models [8]. The channel entries

TABLE I
SNIR Thresholds

Rate (Mbps)	SNIR γ (dB)
0	$\leq$-8
6	-8 to 12.5
9	12.5 to 14
12	14 to 16.5
18	16.5 to 19
24	19 to 22.5
36	22.5 to 26
48	26 to 28
54	>28

TABLE II
Simulation Parameters

Parameter	Value
MAC Header	40 bytes
PHY Header	24 μs
SIFS	16 μs
aSlotTime	9 μs
RTS	20 bytes
CTS	15 bytes
DATA	2312 bytes
ACK	14 bytes
Bandwidth	20 MHz

follow $\sim \mathcal{CN}(0,1)$ and the noise variance is set to 0.01. The average SNIR is 15dB, corresponding to a mean rate of 12 Mbps. Since the channel realizations are random, the available rate for each user will oscillate around the mean value at every time instance.

B. Model Validation

The throughput performance of the Mu-Thres scheme for different threshold values and a varying number of contention slots has been plotted in Figs. 2 and 3. The solid lines represent the simulation obtained throughput whereas the markers indicate the theoretical values calculated by using the model presented in Section IV. The close match between simulation and theory demonstrates the validity of the proposed model. In order to demonstrate the efficiency of the proposed algorithm, a SISO (Single-Input-Single-Output) 802.11g scenario has also been simulated, in which the AP randomly selects one user at a time and transmits a data packet using the rate that corresponds to the SNR (Signal-To-Noise-Ratio) of the respective link. The throughput obtained by the SISO algorithm in the simulated scenario is approximately 8.6 Mbps. The obtained throughput of the Mu-Thres algorithm varies depending on the selection of the SNIR threshold value and the number of contention slots. When the best parameter configuration is selected, the system throughput reaches 16.2 Mbps, which is an improvement of 87.7%. This significant gain is due to two reasons. First, the additional overhead required for the implementation of the multiuser schemes is compensated by the simultaneous transmission of two data packets. In addition, exploiting multiuser diversity by opportunistically transmitting to the best set of users ensures high rate transmissions, whereas in the SISO scenario the randomly scheduled user may suffer from a bad link quality, resulting to a slow transmission.

It can also be observed that the best configuration for the slot number m depends on the selected threshold. A low threshold results to a high number of contending users and therefore m must have a relatively high value, as shown in Fig. 2. On the other hand, for high thresholds (Fig. 3), the number of participating users is limited and the contention phase can be much shorter. For this particular scenario, throughput is maximized for a threshold of 24 Mbps (i.e., only users with a rate $\geq$ 24 Mbps can participate) and for $m = 2$ slots. Note, also, that performance drops when the threshold is set too high. since the number of users that satisfy the threshold condition drops, resulting to a high occurrence of empty frames (i.e., transmission sequences that consist of the RTS/CTS phase but do not have any DATA and ACK transmission).

VI. Conclusions

We have discussed an opportunistic multiple antenna MAC scheme, called Mu-Thres, for multiuser downlink transmission in infrastructure 802.11 based WLANs. A mathematical model for the accurate estimation of the system throughput as a function of the the number of slots and the SNIR threshold has been developed. This model has been validated through simulations and can be used as a basis for the optimal configuration of the system parameters to maximize performance.

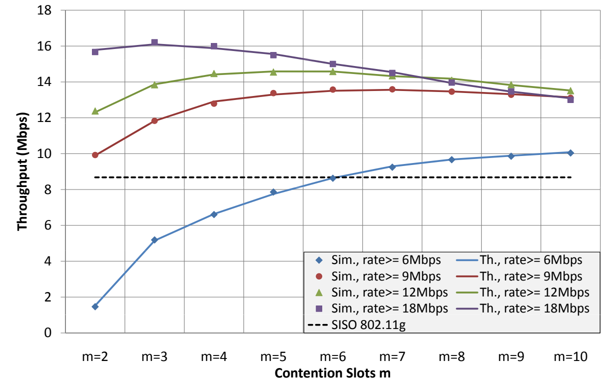

Fig. 2. Throughput for the Mu-Thres algorithm (low threshold values)

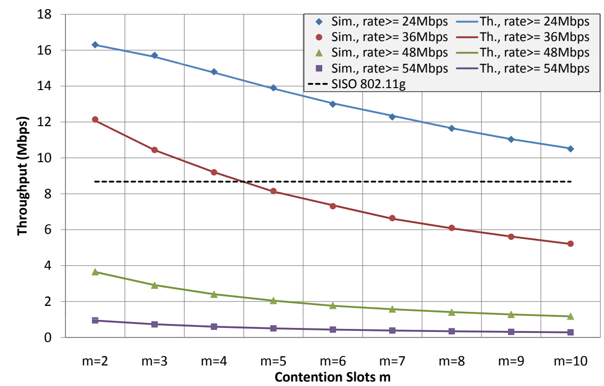

Fig. 3. Throughput for the Mu-Thres algorithm (high threshold values)

Still, there are many open issues in the context of multiuser downlink MAC schemes. Incorporating multi-destination or single-destination frame aggregation mechanisms is a promising way to reduce control overhead and increase throughput, especially when multiple rates are used for transmission. Research efforts can also be directed toward the development of an adaptive algorithm that dynamically adjust the MAC layer configuration to the traffic and channel conditions.

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