Performance optimization of a MAC protocol with multiple contention slots in MIMO ad hoc networks

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Abstract

The Multiple-Input Multiple-Output (MIMO) technique can be used to improve the performance of ad hoc networks. Various medium access control (MAC) protocols with multiple contention slots have been proposed to exploit spatial multiplexing for increasing the transport throughput of MIMO ad hoc networks. However, the existence of multiple request-to-send/clear-to-send (RTS/CTS) contention slots represents a severe overhead that limits the improvement on transport throughput achieved by spatial multiplexing. In addition, when the number of contention slots is fixed, the efficiency of RTS/CTS contention is affected by the transmitting power of network nodes. In this paper a joint optimization scheme on both transmitting power and contention slots number for maximizing the transport throughput is presented. This includes the establishment of an analytical model of a simplified MAC protocol with multiple contention slots, the derivation of transport throughput as a function of both transmitting power and the number of contention slots, and the optimization process based on the transport throughput formula derived. The analytical results obtained, verified by simulation, show that much higher transport throughput can be achieved using the joint optimization scheme proposed, compared to the non-optimized cases and the results previously reported.

Key words: ad hoc networks, MIMO, performance optimization, MAC protocol with multiple contention slots, transport throughput

1 Introduction

Wireless ad hoc networks have attracted a great deal of attention in various applications for their flexibility to operate without any infrastructure. The Multiple-Input Multiple-Output (MIMO) technique has also been widely applied in wireless networks for mitigate fading effects and consequently enhance performances of the network [1-3]. Recent research on MIMO ad hoc networks has mainly focused on either mitigating fading of wireless links by exploiting spatial diversity [4-6] or improving the efficiency of networks by exploiting spatial multiplexing [7-12].

To employ the MIMO technique in ad hoc networks the medium access control (MAC) protocol needs to be properly designed. The conventional MAC protocols designed for Single-Input Single-Output (SISO) systems have been extended to exploit the spatial diversity in MIMO systems [3, 6] in ad hoc networks. In particular, some new MAC protocols have also been proposed to create spatial multiplexing of MIMO transmissions [8-12]. Spatial multiplexing in a MIMO ad hoc network forms multiple links in a neighborhood for simultaneous data transmissions to improve the transmission efficiency of the network [7]. In [8] a multiple contention slots MAC protocol named Mitigating Interference using Multiple Antennas MAC (MIMA-MAC) has been proposed. The transmitter uses a single antenna from the available multiple antennas for data transmission and the receiver uses all the multiple antennas equipped for signal reception and interference suppression. The medium access contention in multiple request-to-send/clear-to-send (RTS/CTS) contention slots is introduced for multiple transmitters in a neighborhood before simultaneous data transmission takes palce. An enhanced version of this MAC protocol with multiple contention slots called Mitigating Interference using Multiple Antennas with Antenna Selection MAC (MIMA/AS-MAC) is presented in [9]. Similar approaches are also reported, such as the Parallel RTS Processing MAC protocol for controlling the maximum number of coexisting data streams in a neighborhood [10], the Multiple Antennas Receiver-Initiated Busy-Tone MAC protocol [11], and a MAC protocol that takes into account of the strength of interference and the spatial correlation between interference and the desired signal in order to exploit the interference cancellation capacity of the MIMO system [12]. However, to the best of our knowledge, in the MAC protocols that employ multiple contention slots for multiple transmitters in a neighborhood, the effects of the contention slot number and transmitting power on transport throughput have not been investigated and consequently the work on joint optimization of these two factors for improving transport throughput has not been reported.

In the MAC protocols that employ multiple RTS/CTS contention slots, multiple transmitters in a neighborhood contend for medium access before transmitting their data simultaneously. The multiple RTS/CTS contention slots impose a severe overhead that limits the performance improvement by exploiting spatial multiplexing in ad hoc networks. Therefore, there is a need to optimize the number of contention slots in order to have the best trade-off between the spatial multiplexing gain and the overhead caused by multiple RTS/CTS contention slots. For a given number of contention slots, the efficiency of RTS/CTS contention in a MAC protocol will also be affected by the transmitting power that determines the number of neighboring nodes. Therefore, to maximize transport throughput the number of contention slots and transmitting power should be optimized jointly. In this paper, we establish an analytical model for a simplified MAC protocol with multiple contention slots in MIMO ad hoc network. Based on this model, transport throughput, as a function of the number of contention slots and transmitting power, is derived and maximized through the joint optimization of the two factors. Both numerical and simulation results are produced to show the benefits of the scheme proposed through comparisons with other MAC protocol and the simplified protocol without optimization.

The paper is organized as follows. In Section 2, a simplified MAC protocol with multiple RTS/CTS contention slots is introduced. In Section 3, an analytical model of the MAC protocol is established. Numerical and simulation results are presented with discussions in Section 4. In Section 5 the effect of channel error on the performance is analyzed. Finally, we conclude the paper in Section 6.

2 The MAC protocol with multiple RTS/CTS contention slots

We assume that each node in an ad hoc network is equipped with multiple antennas. To exploit spatial multiplexing, a transmitting node transmits independent data streams from one of the multiple antennas to one receiving node, while at the receiving node all the antennas are used to receive the data and suppress interference [8-10]. The number of receiver antennas determines the degree of freedom (DOF), which is equal to the maximum number of coexisting links in a neighborhood [9]. The channel is assumed quasi-static and thus unchanged during the transmission of a packet. When the number of independent data streams is less than or equal to DOF, the receiver can differentiate the data streams received simultaneously and suppress interference through some algorithms such as zero-forcing or maximum likelihood detection based on the estimated channel state information [9]. Therefore, multiple transmitter-receiver pairs can coexist in a neighborhood when spatial multiplexing is created in an ad hoc network. To allow multiple transmitters in a neighborhood to transmit data to their target receivers simultaneously, some MAC protocols with multiple contention slots have been proposed, i.e. MIMA-MAC [8] and its enhanced versions [9-12] which have more delicate functions such as antenna selection, parallel RTS processing and busy tone medium access. In [12] the spatial correlation between the signal and interference is taken into account to exploit the spatial dimension of freedom offered by MIMO in designing the MAC protocol. In this paper we will investigate the effects of the contention slot number and transmitting power on transport throughput, aiming to improve the transport throughput by jointly optimizing these two factors. In our investigation, in order to keep the model from being over-complicated, a simplified MAC protocol is introduced and studied, where only the essential functions for nodes to contend for medium access and transmit data packets simultaneously are included in the protocol. The methodology used here can be extended to embrace more complex functions such as carrier sense and back-off procedures in future work.

The MAC protocol assumes that the nodes in the network are synchronized, which can be achieved by employing a scheme such as the global positioning system (GPS). The transmission time is divided into fixed-size frames. The frame structure of the simplified MAC protocol with multiple contention slots is shown in Fig. 1. A MAC frame contains four periods: contention period, training period, data period, and Acknowledgement (ACK) period. The contention period for medium access consists of multiple RTS/CTS contention slots. The training period for training sequence transmission to estimate channel states consists of multiple training slots. The data period is for simultaneous data packet transmission by the transmitters which have acquired a channel during the contention period. The ACK period for the receivers transmitting ACK packets to confirm that they have received the data packets without error consists of multiple ACK slots. The numbers of contention slots, training slots and ACK slots are set to be the same [9], and is denoted as m_c. The adjacent frames are separated by Distributed Inter-frame Space (DIFS), and any two adjacent periods or slots within a frame are separated by Short Inter-frame Space (SIFS). DIFS and SIFS are adopted from the IEEE 802.11 MAC standards. According to the frame structure, the duration of a frame t_f is given by

$$t_f = m_c(t_c + t_{tr} + t_{ACK}) + t_D + DIFS \tag{1}$$

where t_c is the duration of a contention slot, t_{tr} is the duration of a training slot, t_{ACK} is the duration of an ACK slot, and t_D is the duration of data period. Compared with other slots the duration of a training slot is very short [8-10]. Other durations are given respectively by

$$t_c = \frac{L_{RTS} + L_{CTS}}{r_b} + 2 \times SIFS \tag{2}$$

$$t_{ACK} = \frac{L_{ACK}}{r_b} + SIFS \tag{3}$$

$$t_D = \frac{L_D}{r_b} + SIFS \tag{4}$$

where r_b is the transmission bit rate; L_{RTS} is the size of a RTS packet, L_{CTS} is the size of a CTS packet, L_D is the size of a data packet, and L_{ACK} is the size of an ACK packet, all in bits.

To better explain the MAC protocol, we present an exemplary process of the protocol in Fig. 2. Four nodes with two antennas each are located within the transmission range of each other, as shown in Fig. 2 (a). Node 1 wants to send a data packet to node 2; likewise node 3 intends to send a data packet to node 4. The transmitter randomly selects a contention slot to transmit the RTS packet to its target receiver for medium access contention. If the receiver has no data to transmit and has not received any

RTS packet before, it replies with the CTS packet in the corresponding CTS sub-slot. The nodes that have successfully exchanged RTS/CTS acquire a transmission channel. In this example, the RTS/CTS exchange between node 1 and node 2 is conducted in contention slot 1 and the RTS/CTS exchange between node 3 and node 4 is conducted in contention slot 2, as shown in Fig. 2 (b). The transmitter and the receiver determine which training slot and ACK slot to use based on the contention slot in which they have successfully exchanged RTS and CTS. Therefore, in this example, node 1 and node 3 use training slot 1 and training slot 2, respectively, and node 2 and node 4 use ACK slot 1 and ACK slot 2, respectively. During the data period, the transmitters that acquire a channel during the contention period will transmit data packets simultaneously. Receivers are responsible for processing the received data and suppressing interference using the estimated channel state information.

3 System model of the MAC protocol

We consider a MIMO ad hoc network consisting of N nodes that are uniformly distributed in an $a \times a$ square area. Each node in the network is equipped with D antennas, i.e., the degree of freedom is D. We define the neighborhood of a node as a group of nodes that are within the transmission range of the node. The average node number in the neighborhood of an arbitrary node x including itself, M, is given by

$$M = \lfloor (N-1)P_n \rfloor + 1 \tag{5}$$

where $\lfloor z \rfloor$ denotes the largest integer that does not exceed real z and P_n is the probability that an arbitrary node is within the neighborhood of node x, and is given by

$$P_n = \int_0^R f(r)dr \tag{6}$$

where R is the maximum transmission distance of node x. As in [13], the probability density function characterizing the distance r between two nodes in the square area, $f(r)$, is given by

$$f(r) = \frac{4r}{a^4} \cdot f_0(r) \tag{7}$$

and

$$f_0(r) = \begin{cases} \frac{\pi}{2}a^2 - 2ar + \frac{1}{2}r^2, & 0 \le r \le a \\ a^2 \cdot \arcsin(\frac{a}{r}) + 2a\sqrt{r^2 - a^2} - a^2 - a^2 \cdot \arccos(\frac{a}{r}) - \frac{1}{2}r^2, & a \le r \le \sqrt{2}a \\ 0, & otherwise \end{cases} \tag{8}$$

We assume that the free space propagation model is applied with square-law path loss, hence R is given by

$$R = \frac{c}{4\pi f_c} \cdot \sqrt{\frac{P_t}{P_{rth}}} \tag{9}$$

where f_c is the carrier frequency, c is the speed of light, P_t is the transmitting power, and P_{rth} is the minimum required signal power received by the receiver or receiver sensitivity.

We assume that a node generates a new packet destined to its neighbor after a random idle period that is exponentially distributed with an average of $1/\lambda$ seconds, where λ is the average number of packets generated in a node per second. The probability that a node has data to transmit at the beginning of a MAC frame, p, is given by

$$p = 1 - e^{-\lambda \cdot t_f} \tag{10}$$

Suppose that an arbitrary node x has a newly generated packet destined to a randomly selected node y in its neighborhood. In the simplified MAC protocol the transmission from node x to node y is successful if and only if the following conditions are satisfied:

(i) during the contention period the RTS/CTS exchange between node x and node y is successful;

(ii) node y receives all the training sequences from neighboring transmitters successfully in order to estimate channel states;

(iii) the number of transmitters, k, that have acquired a channel within y's neighborhood is less than the degree of freedom (DOF), D, and thereby node y can receive data packets from node x correctly and suppress the interference produced by neighboring transmitters; and

(iv) node x can successfully receive the confirmed ACK packet from node y.

There is no more than one ACK packet transmitted in one slot as the index of ACK slot is determined by that of contention slot where the transmitter and the receiver have successfully exchanged RTS and CTS packets. Therefore, there is no collision in transmission of ACK packets. The probability of successful data packet transmission from node x to node y can be expressed as

$$\begin{aligned} P_s = {} & P\{RTS/CTS\ exchange\ between\ x\ and\ y\ is\ successful\}\cdot \\ & P\{y\ receives\ all\ the\ training\ squences\ from\ neighboring\ transmitters\ successfully\}\cdot \\ & \sum_{k=0}^{D-1} P\{k\ transmitters\ besides\ x\ within\ y's\ neigborhood\ acquire\ channel\} \end{aligned} \tag{11}$$

Since node x randomly selects a contention slot to exchange RTS/CTS packets with node y, the first probability term in Eq.(11) is given by

$$\begin{aligned} & P\{RTS/CTS\ exchange\ between\ x\ and\ y\ is\ successful\} \\ & = \sum_{i=1}^{m_c} [P\{x\ select\ the\ ith\ contention\ slot\}\cdot \\ & \quad P\{\ RTS/CTS\ exchange\ between\ x\ and\ y\ in\ the\ ith\ contention\ slot\ is\ successful\}] \\ & = \frac{1}{m_c}\cdot\sum_{i=1}^{m_c} P\{\ RTS/CTS\ exchange\ between\ x\ and\ y\ in\ the\ ith\ contention\ slot\ is\ successful\} \end{aligned} \tag{12}$$

The probability term of the last line in Eq. (12) can be derived as follows.

The probability that there are M_1 nodes besides node x in the neighborhood of node y that have data to transmit at the beginning of a frame is given by

$$\begin{aligned} &P\{M_1 \text{ nodes besides } x \text{ within } y\text{'s neighborhood have data to transmit}\} \\ &= \binom{M-2}{M_1} p^{M_1}(1-p)^{M-2-M_1},\ M_1 = 0,1,2,\cdots M-2. \end{aligned} \tag{13}$$

The probability that there are M_2 nodes among M_1 nodes that have data destined to node y is given by

$$\begin{aligned} &P\{M_2 \text{ nodes have data destined to } y \mid M_1\} \\ &= \binom{M_1}{M_2} \left(\frac{1}{M-1}\right)^{M_2} \left(1-\frac{1}{M-1}\right)^{M_1-M_2},\ M_2 = 0,1,2,\cdots M_1. \end{aligned} \tag{14}$$

Let A_1 denote the event that M_1 nodes do not transmit RTS packets in the i th slot, and A_2 denote the event that node y has not successfully received RTS packets from M_2 nodes before the i th slot. The probability that both A_1 and A_2 occur can be expressed as

$$\begin{aligned} &P(A_1 \cap A_2) \\ &= P(A_1)\cdot P(A_2 \mid A_1) \\ &= P(A_1)\cdot[1-P(\overline{A_2} \mid A_1)] \end{aligned} \tag{15}$$

where

$$P(A_1) = \frac{(m_c-1)^{M_1}}{m_c^{M_1}}, \text{ and} \tag{16}$$

$$P(\overline{A_2} \mid A_1) = \begin{cases} \dfrac{\binom{M_2}{1}\binom{i-1}{1}(m_c-2)^{M_1-1}}{(m_c-1)^{M_1}}, & i>1, M_1 \ge M_2 > 0, \mathit{and}\ m_c > 2 \\ 0 \quad , & \mathit{otherwise.} \end{cases} \tag{17}$$

Suppose that M_1 nodes besides node x in the neighborhood of node y have data to transmit at the beginning of a MAC time frame, among which M_2 nodes have data destined to node y. The RTS/CTS exchange between node x and node y in the i th contention slot is successful only if i) node y has no data packet to transmit; ii) M_1 nodes do not transmit RTS packets in the i th slot; and iii) node y has not successfully received RTS packets from M_2 nodes before the i th slot. The corresponding probability can then be formulated as

$$\begin{aligned} &P\{RTS\,/\,CTS\ exchange\ between\ x\ and\ y\ in\ the\ ith\ contention\ slot\ is\ successful \mid M_1, M_2\} \\ &= P\{y\ has\ no\ data\ to\ transmit\}\cdot P(A_1 \cap A_2) \\ &= (1-p)\cdot P(A_1 \cap A_2) \end{aligned} \tag{18}$$

Combining Eqs. (13)-(18), the probability term in Eq. (13) can be obtained accordingly as

$$\begin{aligned} &P\{RTS\,/\,CTS\ exchange\ between\ x\ and\ y\ in\ the\ ith\ contention\ slot\ is\ successful\} \\ &= \sum_{M_1=0}^{M-2}\sum_{M_2=0}^{M_1}[P\{M_1\ nodes\ besides\ x\ within\ y's\ neighborhood\ have\ data\ to\ transmit\}\cdot \\ &\quad P\{M_2\ nodes\ have\ data\ destined\ to\ y \mid M_1\}\cdot \\ &\quad P\{RTS\,/\,CTS\ exchange\ between\ x\ and\ y\ in\ the\ ith\ contention\ slot\ is\ successful \mid M_1, M_2\}] \end{aligned} \tag{19}$$

Now let us consider the second probability term in Eq. (11). Node y receives all the training sequences from neighboring transmitters successfully if and only if the training sequences from neighboring transmitters of node y are transmitted in separate training slots. According to the simplified MAC protocol presented in Section 2, it is the transmitter and the receiver that determine which training slot to use based on the contention slot in which they have successfully exchanged RTS and CTS packets. The neighboring transmitters of node y except node x (e.g., node T_1 and node T_2 in Fig. 3) may contend for medium access successfully in the same contention slot (e.g., the j th slot) due to their target receivers (e.g., node R_1 and node R_2 in Fig. 3) being located far from each other. In this case, the training sequences from node T_1 and node T_2 can not be received successfully by node y. Thus the event that the neighboring transmitters of node y transmit their training sequences in separate training slots is equivalent to that there are less than two nodes among the nodes in the network which successfully contend for medium access in an arbitrary contention slot is within the neighborhood of node y. The second probability term in Eq. (11) is given by

$$P\{y\ can\ receive\ all\ the\ training\ \ squences\} = \sum_{j=0}^{1} \binom{M_s}{j} \cdot P_n^{\,j} \cdot (1-P_n)^{M_s-j} \tag{20}$$

where M_s is the average number of nodes in the network except node y that successfully contend for medium access in an arbitrary contention slot, and it is given by

$$M_s = \left[\frac{p \cdot P_{cs} \cdot (N-1)}{m_c} \right] \tag{21}$$

where $\left[z \right]$ denotes the integer that is closest to real z, P_{cs} denotes the probability that an arbitrary node in the network contends for medium access successfully, which is probability that node x and one of its neighboring node y exchange RTS/CTS successfully and is expressed by Eq.(12).

The third probability term in Eq. (11) is given by

$$\begin{aligned} &P\{k\ transmitters\ within\ y's\ neigborhood\ acquire\ channel\} \\ &= \binom{M-2}{k} (p \cdot P_{cs})^k (1 - p \cdot P_{cs})^{M-2-k},\ k = 0,1,2,\cdots M-2. \end{aligned} \tag{22}$$

Combining Eqs. (1)-(22), the probability of successful data packet transmission from node x to node y, P_s, can be calculated accordingly.

Given the size of a data packet, L_D, the time duration of the MAC frame, t_f, the number of nodes in the network, N, and the probability that a node has data to transmit at the beginning of a MAC frame, p, we define the network carried load, G, in bits per second as

$$G = N \cdot p \cdot \frac{L_D}{t_f} \tag{23}$$

We also define the product of throughput (in bits per second) and average distance between transmitters and receivers in the network as the transport throughput. This bit-distance product that can be transported by the network has been used as an indicator of a network's capability of transporting data from one end to the other [13, 14]. The transport throughput S_t is given by

$$S_t = P_s \cdot G \cdot E[l] \tag{24}$$

where l is the random variable of distance between transmitters and receivers. The probability density function of l is given by [13]

$$f(l) = \begin{cases} \dfrac{2l}{R^2}, & 0 \le l \le R \\ 0, & otherwise. \end{cases} \tag{25}$$

The average distance between transmitters and receivers is given by

$$\begin{aligned} E[l] &= \int_0^R l \cdot \frac{2l}{R^2} dl = \frac{2}{3} R \\ &= \frac{c}{6\pi \cdot f_c} \cdot \sqrt{\frac{P_t}{P_{rth}}} \end{aligned} \tag{26}$$

Combining Eqs. (23), (24), (26) and (1), transport throughput S_t can be obtained as

$$\begin{aligned} S_t &= P_s \cdot G \cdot E[l] \\ &= P_s \cdot \frac{N \cdot p \cdot L_D}{m_c (t_c + t_{tr} + t_{ACK}) + t_D + DIFS} \cdot \frac{c}{6\pi \cdot f_c} \cdot \sqrt{\frac{P_t}{P_{rth}}}. \end{aligned} \tag{27}$$

The parameters used for representing t_c, t_{ACK} and t_D can be found in Eqs. (2)-(4).

4 Results and discussions

In this section both the analytical model established in the last section and the simulation method are used to evaluate the performance of the simplified MAC protocol with multiple contention slots in MIMO ad hoc networks. Our primary goal of this work is to investigate the effects of transmitting power P_t and the number of contention slots m_c on the transport throughput of the network. For this purpose, we set physical and link layer parameters in relation to Eq. (27) based on the IEEE 802.11 specification, as used in [8-10]. All the system parameters used are summarized in Table 1.

Table 1: The summary of parameters

Parameters	Values	Parameters	Values

N	200	L_{CTS}	(24+14)×8 bits
a	1000 m	L_D	(24+2024)×8 bits
f_c	2.4 GHz	L_{ACK}	(24+14)×8 bits
P_{rth}	-63.5 dBm	t_{tr}	10 μs
r_b	1 Mbps	DIFS	50 μs
λ	5	SIFS	10 μs
L_{RTS}	(24+20)×8 bits		

Figs. 4-8 show the results of transport throughput in connection with transmitting power and the number of contention slots when the number of the antennas of a node (or DOF) is 4.

In Fig. 4, the transport throughput is plotted against the number of contention slots under selected transmitting power. The difference in transport throughput between numerical and simulation results is within 5%, which confirms the effectiveness of the analytical model derived. It can be seen that transport throughput increases rather sharply with the number of contention slots when few contention slots are used in the MAC frame, since in this situation there are adequate resources available (a sufficient number of nodes which have data to transmit in a neighborhood and hence adequate DOF) for supporting simultaneous data transmissions in a neighborhood. As more contention slots are used, the overhead of multiple RTS/CTS contention slots as a result of the increased number of contention slots becomes severer and the number of simultaneous data transmissions is limited by DOF. Consequently, transport throughput decreases as the number of contention slots increases. Therefore, an optimal number of contention slots can be determined to maximize the transport throughput of the network, which is also related to the transmitting power, as shown in Fig. 5.

In Fig. 6, the transport throughput is plotted against transmitting power under different numbers of contention slots. Again, both numerical and simulation results closely agree with each other. Similar properties to those in Fig. 4 can be seen here, i.e., with low transmitting power used transport throughput increases as the transmitting power increases. When transmitting power is low there are few transmitting nodes in a neighborhood. As the transmitting power increases the number of neighboring nodes increase, and more nodes in a neighborhood will contend for medium access successfully to support simultaneous data transmissions; therefore the transport throughput is growing. When the transmitting power is high, there are many nodes in a neighborhood contending for medium access. As the transmitting power increases the efficiency of medium access contention is reduced, resulting in fewer nodes in a neighborhood that are able to contend for medium access successfully. Consequently, the transport throughput will decrease. Again, an optimal transmitting power can be determined to maximize the transport throughput of the network, which is varied with the number of contention slots available, as shown in Fig. 7.

In Fig. 8, the transport throughput is depicted as a function of both transmitting power and the number of contention slots. The curve marked with circles illustrates the maximum transport throughput corresponding to the optimal number of contention slots over transmitting power. The curve marked with squares illustrates the maximum transport throughput corresponding to the optimal transmitting power over the number of contention slots. The global maximum transport throughput, which is a result of joint optimization on both transmitting power and the number of contention slots, is indicated by the dark solid circle and clearly has a higher value than any of those produced by non-joint optimization or non-optimization schemes. For example, the global maximum transport throughput can reach 1149.51 Mbps*m when the optimal transmitting power is 200 mW and the optimal number of contention slots is 8.

We have also obtained the optimal results for DOF to be 2 and 3, respectively. The numerical and simulation results for the cases of DOF = 2, 3 and 4 are summarized in Table 2. Obviously, both the optimal transmitting power and optimal number of contention slots and, consequently, the global maximum transport throughput increase with DOF. This is because as DOF increases, more potential transmitters in a neighborhood can transmit data packet simultaneously.

Table 2: Optimization results when DOF is 2, 3 and 4

DOF	Optimal transmitting power (mW)		Optimal contention slots number		Global maximum transport throughput (Mbps*m)	
	Numerical	Simulation	Numerical	Simulation	Numerical	Simulation
2	81	86	5	5	845.88	891.92
3	153	155	6	7	1028.24	1026.83
4	200	197	8	8	1149.51	1170.74

In order to demonstrate the improvements of transport throughput achieved by using joint optimization on transmitting power and the number of contention slots, we simulate the simplified MAC protocol with joint optimization, the simplified MAC protocol without optimization, and MIMA-MAC proposed in [8-9]. In MIMA-MAC the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism is adopted to reduce collisions between contending transmitters. Before the transmission of an RTS packet, there is a back-off period consisting of a small number of mini-slots, during which the transmitters randomly select a mini-slot for transmitting the RTS packet. In the simplified MAC protocol (with or without joint optimization), however, the CSMA/CA mechanism does not apply. For the simplified MAC protocol without joint optimization and MIMA-MAC, the transmitting power is set to be 24.5 dBm and the number of contention slots is chosen as the same as DOF that is set to be 2 [9-10]. In Fig. 9, the transport throughput is plotted against the average number of packets generated per second λ at a node for different MAC schemes. It can be seen that the simplified MAC protocol with joint optimization achieves higher network capacity, in terms of the transport throughput, by 38% than MIMA-MAC, and 85% than the simplified MAC protocol without joint optimization, when λ is over 10 packets/s.

To show how the transmission bit rate affects the optimization results, the transport throughput is plotted against contention slots number under the transmission bit rates r_b =1, 5.5, 11 Mbps, respectively, in Fig. 10 using the numerical method. The transmitting power is set to be 400 mW and DOF is 4. It can be seen that the maximum transport throughput are achieved at the different optimal number of contention slots when the bit rate changes. The higher the bit rate the smaller the number of contention slots is required to maximize the transport throughput. The transmission rate for the preamble and Physical Layer Convergence Protocol (PLCP) header at the physical layer remains 1 Mbps when transmission bit rate increases from 1 Mbps to 11 Mbps, thus the RTS/CTS contention cost in the MAC protocol with multiple contention slots will increase. The RTS/CTS contention cost can be reduced through the optimization process that results in fewer contention slots to be used for medium access contention when higher transmission bit rate is adopted.

5 Performance analysis of the MAC protocol with channel error

In the studies above channel error is not considered in our model. To investigate how channel error affects the performance of the MAC protocol with multiple contention slots in MIMO ad hoc networks the error probability is introduced into the model. There are five types of packets to transmit in the simplified MAC protocol, namely RTS, CTS, training sequence, data, and ACK packets. The RTS, CTS and ACK packets are transmitted in the SISO manner. The MIMO spatial multiplexing technique is employed to transmit data packets. The training sequence is used to estimate the channel state and normally considered to be error free [9-12]. A Rayleigh-fading channel with square-law path loss is assumed. We also assume that no error correction code (ECC) blocks are included in the system.

For SISO transmission the signal is further attenuated on top of the square-law path loss by a fading scalar, which is a zero-mean circularly symmetric complex Gaussian (ZMCSCG) random variable with unit variance. The received signal-to-noise ratio (SNR) γ_{SISO} is a random variable and its probability density function is given by [15]

$$f(\gamma_{SISO}) = \frac{1}{\bar{\gamma}_{SISO}} e^{-\frac{\gamma_{SISO}}{\bar{\gamma}_{SISO}}} \tag{28}$$

where $\bar{\gamma}_{SISO}$ is the average received SNR and given by

$$\bar{\gamma}_{SISO} = \frac{G \cdot P_t}{P_N} \tag{29}$$

where P_N is the background noise power level at the receiver. Under the free space propagation model, G is given by

$$G = \left(\frac{c}{4\pi f_c}\right)^2 \cdot \frac{1}{l^2} \tag{30}$$

where l is the distance between the transmitter and the receiver.

Since the RTS, CTS and ACK packets are relatively short, the transmission of these packets is assumed successful when the received SNR at the receiver γ_{SISO} is above a given threshold γ_0 if there is no contention. In this case, the probability of successful transmission of RTS, CTS and ACK packets between arbitrary two nodes is given by

$$\begin{aligned} p_s^{SISO} &= P(\gamma_{SISO} > \gamma_0) \\ &= \int_{\gamma_0}^{\infty} f(\gamma_{SISO}) d\gamma_{SISO} \end{aligned} \tag{31}$$

The average probability of successful RTS, CTS and ACK packets transmission between a node and its neighboring node is given by

$$P_s^{SISO} = \int_0^R p_s^{SISO} f(l) dl \tag{32}$$

where $f(l)$ is the probability density function of the distance between arbitrary two nodes, which is given by Eq. (25).

For MIMO transmission with spatial multiplexing, the signal is further attenuated on top of the square-law path loss by a scalar fading matrix, in which each entry is an independent and identically distributed ZMCSCG random variable with unit variance. Suppose that a node receives $k+1$ ($k < D$) data streams simultaneously from its neighboring nodes and the i th data stream is destined to itself. As shown in [16], when we use a zero-forcing (ZF) receiver for interference cancellation, the SNR probability density function of the i th data stream can be calculated as

$$f(\gamma_{MIMO}) = \frac{1}{\bar{\gamma}_{MIMO}\Gamma(D-k)} e^{-\frac{1}{\bar{\gamma}_{MIMO}}\gamma_{MIMO}} \left(\frac{1}{\bar{\gamma}_{MIMO}}\gamma_{MIMO}\right)^{D-(k+1)} \tag{33}$$

where $\Gamma(\cdot)$ denotes the Gamma function. $\bar{\gamma}_{MIMO}$ is the average SNR of the data stream destined to the receiver, which is given by

$$\bar{\gamma}_{MIMO} = \frac{G \cdot P_t}{P_N} \tag{34}$$

The receiver can receive the destined data stream successfully if the SNR γ_{MIMO} of the data stream exceeds the given threshold γ_0. Thus if the number of data stream is no more than DOF the probability of successful data packets transmission between arbitrary two nodes is given by

$$\begin{aligned} p_s^{MIMO} &= P(\gamma_{MIMO} > \gamma_0) \\ &= \int_{\gamma_0}^{\infty} f(\gamma_{MIMO}) d\gamma_{MIMO} \end{aligned} \tag{35}$$

The average probability of successful data packet transmission between a node and its neighboring node is given by

$$P_s^{MIMO} = \int_0^R p_s^{MIMO} f(l) dl \tag{36}$$

If channel error is considered Eq. (11) will be changed to Eq. (11'), as shown below, for calculating the probability that a successful transmission from an arbitrary node x to one of its neighboring nodes in the simplified MAC protocol. In this expression four conditions must be satisfied, which are described in Section 3.

$$\begin{aligned} P_s = {} & P\{RTS/CTS \text{ exchange between } x \text{ and } y \text{ is successful}\} \cdot \\ & P\{y \text{ receives all the training squences from neighboring transmitters successfully}\} \cdot \\ & [\sum_{k=0}^{D-1} P_s^{MIMO} \cdot P\{k \text{ transmitters besides } x \text{ within } y\text{'s neigborhood acquire channel}\}] \cdot \\ & P_s^{SISO} \end{aligned} \tag{11'}$$

where P_s^{SISO} represents the impact of channel error on ACK packet transmission, and P_s^{MIMO} represents the impact of channel error on data packet transmission. In addition, the impact of channel error on the exchange between RTS and CTS packets along with the effect of contention must be included in the calculation of the probability of successful RTS/CTS exchange, thus Eq. (12) is changed to

$$\begin{aligned}&P\{RTS\ /\ CTS\ exchange\ between\ x\ and\ \ y\ is\ successful\}\\&=(P_s^{SISO})^2\cdot\sum_{i=1}^{m_c}[P\{x\ select\ the\ ith\ contention\ slot\}\cdot\\&\quad P\{\ RTS\ /\ CTS\ exchange\ between\ x\ and\ \ y\ in\ the\ ith\ contention\ slot\ is\ successful\}]\end{aligned}\qquad(12')$$

In Fig. 11, the effect of channel error on transport throughput is demonstrated through a comparison between the scenario with channel error considered, where Eqs. (11’) and (12’) are used, and the scenario without considering channel error, where Eqs. (11) and (12) are used. It can be see that the existence of channel error will cause reduction in transport throughput at any number of contention slots; however, the optimal number of contention slots for obtaining the maximum throughput remains unchanged. For the results in Fig. 11, the SNR threshold is set to be 10 dB and the background noise power is -90dBm.

6 Conclusions

In this paper, we have investigated the impacts of transmitting power and the number of contention slots on the transport throughput of MIMO ad hoc networks where the MAC protocol with multiple contention slots is employed. Based on the investigation, we have presented a scheme to maximize the transport throughput of the network by jointly optimizing the number of contention slots and transmitting power of network nodes. We have shown with both analytical and simulation results that significant improvements in transport throughput can be achieved through the joint optimization, in comparison with non-optimization approaches. For example, when DOF is 2 the simplified MAC protocol with joint optimization outperforms both MIMA-MAC and the simplified MAC protocol without joint optimization in transport throughput by 38% and 85%, respectively, when λ is over 10 packets/s. We have also examined the effects of DOF, the transmission bit rate and channel error on the optimized results. In particular, it is shown that increasing the bit rate will lead to the reduced optimal number of contention slots, while the introduction of channel error does not affect the optimal number of contention slots although the maximum achievable throughput is reduced. Our results can be used as a guideline in selecting proper transmitting power and the number of contention slots for the design of future MAC protocol in MIMO ad hoc networks.

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Figures

Fig. 1 The frame structure of the simplified MAC protocol with multiple contention slots

Fig. 2 Exemplary process of the MAC protocol

Fig. 3 An example of neighboring nodes of y contending for medium access

Fig. 4 Transport throughput over the number of contention slots under selected transmitting power levels, $DOF = 4$

Fig. 5 Optimal number of contention slots over transmitting power, $DOF = 4$

Fig. 6 Transport throughput over transmitting power under different number of contention slots, $DOF = 4$

Fig. 7 Optimal transmitting power over the number of contention slots, $DOF = 4$

Fig. 8 Transport throughput as a function of transmitting power and the number of contention slots, $DOF = 4$

Fig. 9 Transport throughput over the average number of packets generated per second λ at a node for different MAC schemes

Fig. 10 Transport throughput over the number of contention slots under different transmission bit rates, $DOF = 4$

Fig. 11 Transport throughput over the number of contention slots with and without channel error, $P_t = 120$ mW, $DOF = 4$

Fig. 1

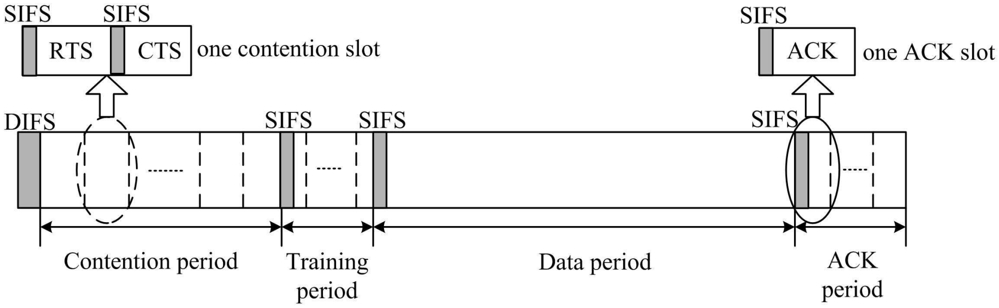
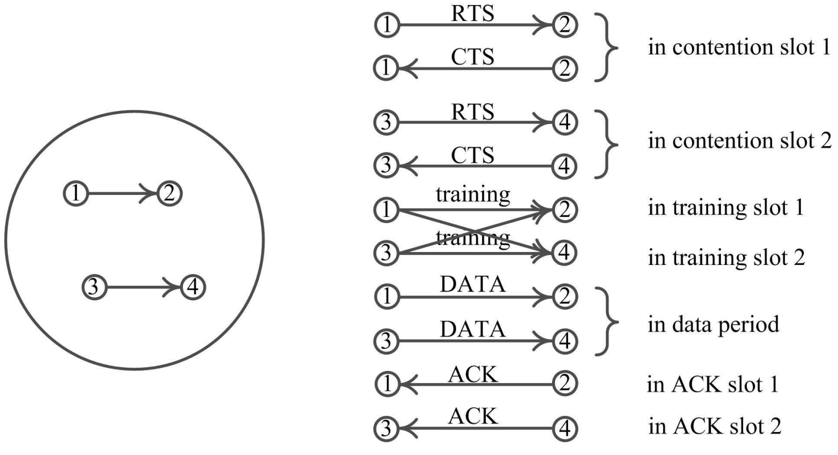
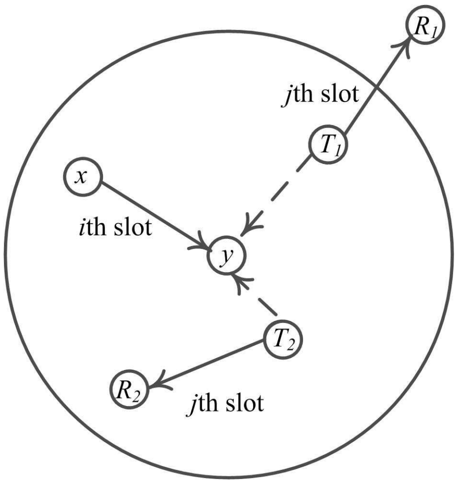

SIFS
SIFS
RTS
CTS
one contention slot
SIFS
ACK
one ACK slot
DIFS
SIFS
SIFS
SIFS
....
.....
.....
Contention period
Training period
Data period
ACK period

Fig. 2


1
2
3
4
RTS
CTS
in contention slot 1
RTS
CTS
in contention slot 2
training
training
in training slot 1
in training slot 2
DATA
DATA
in data period
ACK
in ACK slot 1
ACK
in ACK slot 2

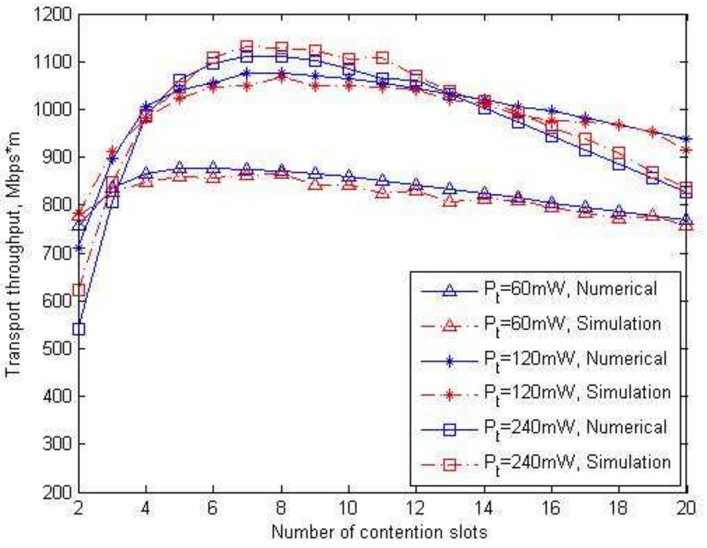
(a) (b)

Fig. 3



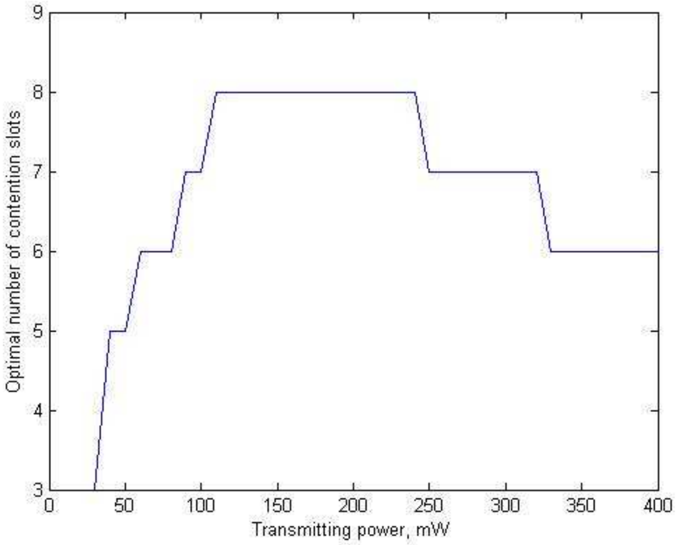
R_1
jth slot
T_1
x
ith slot
y
T_2
R_2
jth slot

Fig. 4



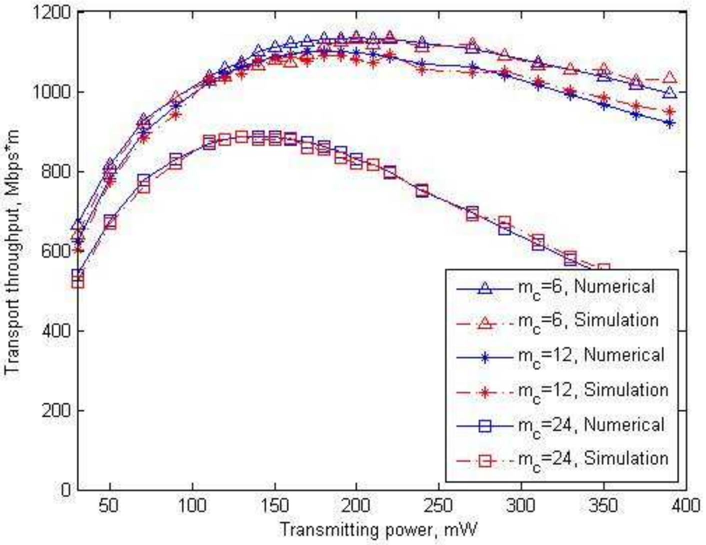
Transport throughput, Mbps*m
Number of contention slots
200
300
400
500
600
700
800
900
1000
1100
1200
2
4
6
8
10
12
14
16
18
20
P_t=60mW, Numerical
P_t=60mW, Simulation
P_t=120mW, Numerical
P_t=120mW, Simulation
P_t=240mW, Numerical
P_t=240mW, Simulation

Fig. 5



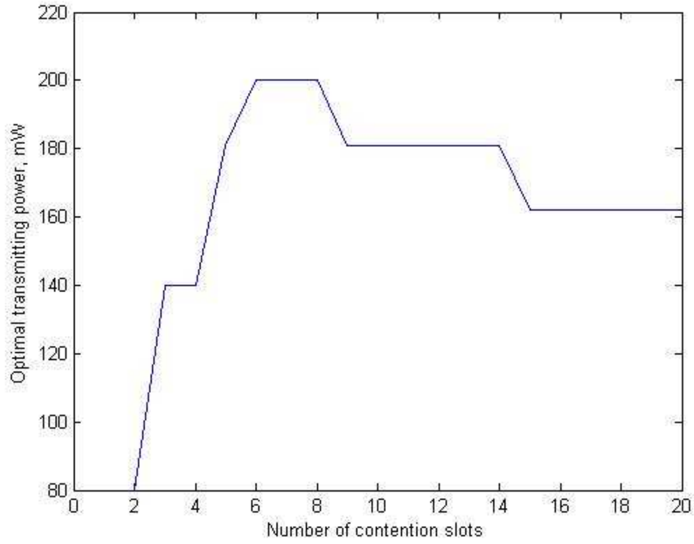
Optimal number of contention slots
Transmitting power, mW
3
4
5
6
7
8
9
0
50
100
150
200
250
300
350
400

Fig. 6



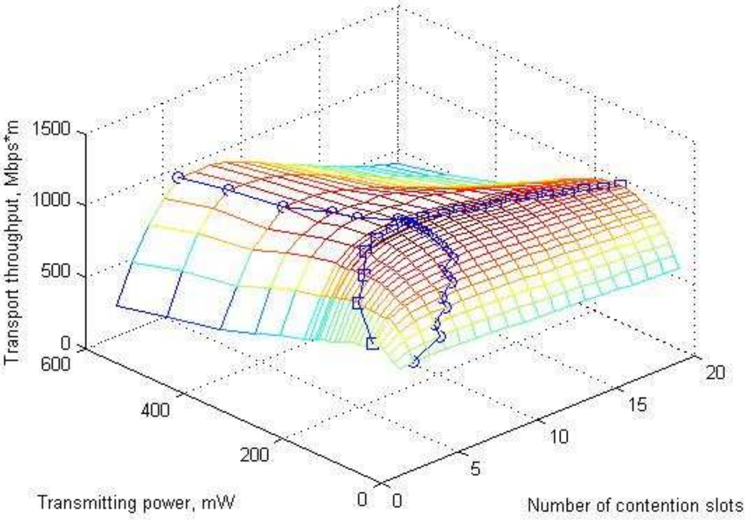
Transport throughput, Mbps*m
Transmitting power, mW
0
200
400
600
800
1000
1200
50
100
150
200
250
300
350
400
m_c=6, Numerical
m_c=6, Simulation
m_c=12, Numerical
m_c=12, Simulation
m_c=24, Numerical
m_c=24, Simulation

Fig. 7



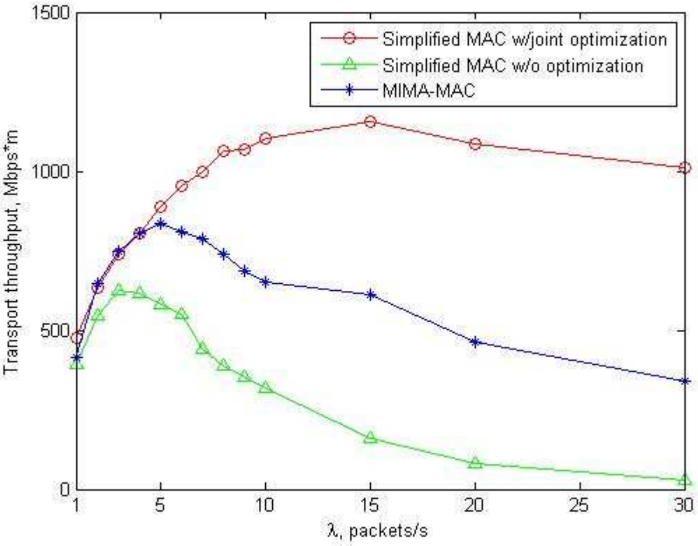
Optimal transmitting power, mW
220
200
180
160
140
120
100
80
0
2
4
6
8
10
12
14
16
18
20
Number of contention slots

Fig. 8



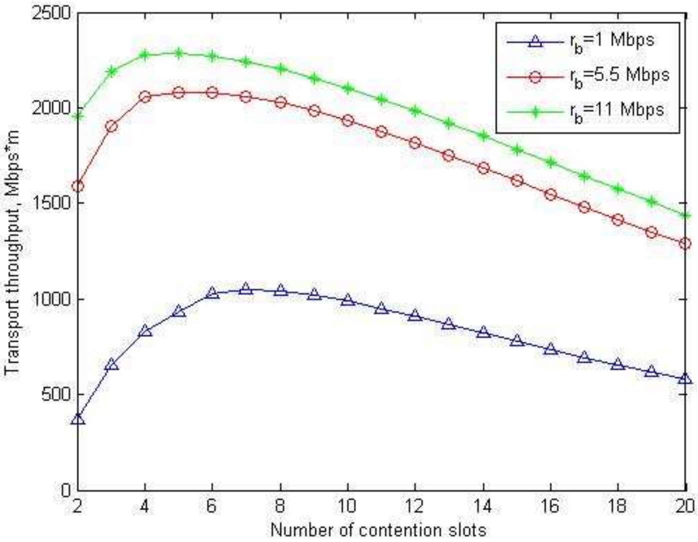
Transport throughput, Mbps*m
1500
1000
500
0
600
400
200
0
Transmitting power, mW
0
5
10
15
20
Number of contention slots

Fig. 9



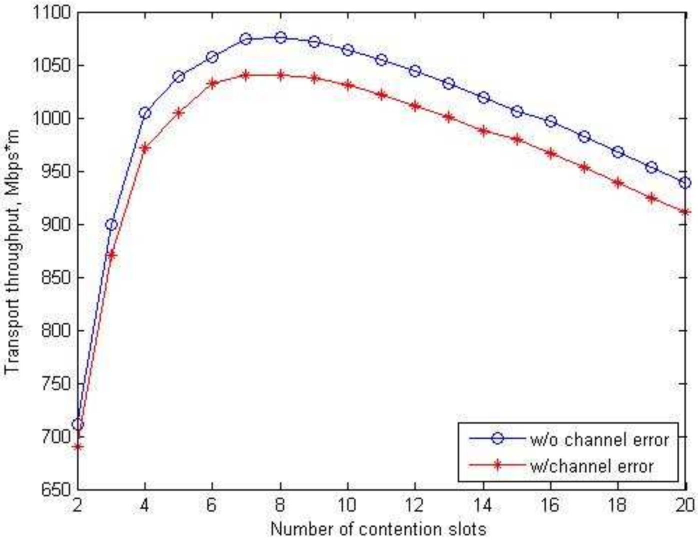
Simplified MAC w/joint optimization
Simplified MAC w/o optimization
MIMA-MAC
Transport throughput, Mbps*m
λ, packets/s
1500
1000
500
0
1
5
10
15
20
25
30

Fig. 10



r_b=1 Mbps
r_b=5.5 Mbps
r_b=11 Mbps
Transport throughput, Mbps*m
Number of contention slots
2500
2000
1500
1000
500
0
2
4
6
8
10
12
14
16
18
20

Fig. 11


Transport throughput, Mbps*m
Number of contention slots
1100
1050
1000
950
900
850
800
750
700
650
2
4
6
8
10
12
14
16
18
20
w/o channel error
w/channel error