01 Jan 2006

Improving Channel Throughput of WLANs and Ad Hoc Networks Using Explicit Denial of Requests

Maggie Xiaoyan Cheng
Missouri University of Science and Technology, chengm@mst.edu

Yadi Ma

Yi Wang

Recommended Citation

M. X. Cheng et al., "Improving Channel Throughput of WLANs and Ad Hoc Networks Using Explicit Denial of Requests," *Proceedings of the IEEE Global Telecommunications Conference, 2006*, Institute of Electrical and Electronics Engineers (IEEE), Jan 2006.
The definitive version is available at https://doi.org/10.1109/GLOCOM.2006.967

Improving Channel Throughput of WLANs and Ad Hoc Networks Using Explicit Denial of Requests

Maggie Cheng Yadi Ma Yi Wang
Department of Computer Science
University of Missouri
Rolla, MO 65401
{chengm,ym95d,ywhr9}@umr.edu

***Abstract*— A new Multiple Access Control scheme for wireless ad hoc networks and WLANs is proposed. This scheme uses explicit denial of channel requests and a busy tone to improve channel throughput. Performance analysis shows significant improvement when the network is under heavy traffic load.**

***Index Terms*— MAC, WLAN, ad hoc network, throughput**

I. INTRODUCTION

The current wireless local area network (WLAN) standard IEEE 802.11 suffers from the well known hidden terminal problem. When it is used in a multiple-hop ad hoc network, it suffers from both the hidden terminal problem and the exposed terminal problem.

To maximize channel throughput, an optimal MAC scheme should find the maximum set of collision-free transmissions that can carry on simultaneously, so that there is no collision on data packets and the exposed nodes are free to transmit. However because channel requests come and go, to find such a set of transmissions is a challenging task in a dynamic and decentralized environment.

Both the hidden terminal problem and the exposed terminal problem lead to a waste of channel capacity. The hidden terminal problem causes data collision; the exposed terminal problem makes exposed nodes refrain from channel access even though the transmissions can carry on simultaneously. To improve channel utilization, both need to be effectively addressed.

To solve the hidden terminal problem, a collision avoidance scheme must be used. Using a single shared channel, RTS-CTS scheme is designed for this purpose. However, RTS-CTS scheme aggressively reserves the channel, which maximizes the exposed terminal problem yet still cannot completely avoid the hidden terminal problem. These two problems are like a pair of adversaries that are hard to please by one single strategy. Two extreme schemes are ALOHA and FAMA-NCS [1]. ALOHA does not use any collision avoidance scheme, therefore it does not have the exposed terminal problem, but it suffers from the hidden terminal problem the most. FAMA-NCS completely avoids the hidden terminal problem, but it comes at the cost of excessive channel waste in order to successfully reserve the channel and it suffers severe exposed terminal problem. The ultimate goal to solve these two problems is to improve channel throughput. The optimal solution is the one that strikes the balance between the two and promises the highest channel throughput. Schemes that address only one problem at the cost of maximizing the other do not provide high channel utilization.

The use of a separate channel can greatly mitigate the hidden terminal problem without sacrificing the exposed terminals. It improves channel throughput by reducing the number of control packets sent to the data channel and hence reducing the chance of packet collision. Since data packets are protected by the busy tone, the absence of the busy tone can be interpreted as an “Okay to go”, thus exposed nodes can transmit. So intuitively, busy tone schemes are promising to improve channel throughput. Previous works that use busy tone signals include RI-BTMA [2]) and DBTMA ([3]) etc., which have shown performance gain of using busy tones toward the ones without busy tones. However, as illustrated later in section II, we found there is still room to improve channel throughput by further mitigating the hidden terminal problem and increasing the probability of data transmission, which motivates the design of a new scheme.

In this paper, we propose a new busy tone-based multiple access scheme. The scheme assumes that a separate narrow-banded channel is available to send busy tone signals. When a node has data to transmit, it sends a RTS packet; to acknowledge the RTS, the receiver turns on the busy tone; the sender will send the data packet upon receiving the busy tone; the receiver keeps sending the busy tone until the data packet is completely received. In addition, the sender aggressively pursues the channel: when RTS is sent but no busy tone is heard, it tries a second time with a shorter request packet PRE; receiver can use an explicit denial of request NTS (Not-To-Send) packet to deny the channel request whenever necessary. The use of NTS helps further reduce the hidden terminal problem that busy tone alone fails to solve; the use of the PRE packet increases the chance of data transmission. Since this is the first time that an explicit “Not-To-Send” is used to deny channel access request and it belongs to the busy tone family, we name it BTMA-NTS scheme.

The work is supported in part by National Science Foundation under grant CCF-0514940.

The scheme provides high channel throughput. In the infrastructure mode of WLANs, DATA packets will not collide with any other packets, so the hidden terminal problem is completely solved; in a multiple-hop ad hoc environment, the chance for DATA collision from hidden terminals is significantly reduced. The exposed terminal problem is minimized so the exposed node will inhibit itself from channel access for at most the transmission time of a RTS packet, which is the same as the DBTMA scheme.

Section II provides details of the operation of BTMA-NTS, and suggests variations of BTMA-NTS that can be used in different scenarios. Section III presents analytical throughput results compared with the DBTMA scheme. Section IV surveys the most related work as well as the legacy MAC schemes that use RTS-CTS and CSMA.

II. A NEW MAC SCHEME: BTMA-NTS

A. Operation of The BTMA-NTS Scheme

In the BTMA-NTS scheme, an out-of-band receiver busy tone BT_r is used. The main channel is used for control messages and DATA packets. The following control messages are defined:

1) RTS: Request To Send, which is to initiate channel request by the transmitter.
2) NTS: Not To Send, which is to deny the channel request.
3) PRE: PREamble, which is the second channel request sent to the receiver.

The operation of the scheme is described as follows, with node A as the sender and node B as the receiver.

Assume node A has a data packet ready to send. If BT_r is not on and the channel is idle, it sends a RTS packet right away. If BT_r is not on but the channel is busy, it keeps sensing the channel to determine the packet type. If the incoming packet is a RTS or PRE, it will wait until the channel is clear to increase the success rate of control packets. If it is a DATA packet, in which case node A is an exposed node, it will go ahead and send a RTS. If BT_r is on, it defers access with a random delay. After A sends a RTS packet, two scenarios are possible:

Scenario 1: If the RTS is successfully received by the receiver B, B will turn on the busy tone to indicate it is ready to receive data and to warn others not to interfere; A waits for a mandatory WAIT1 time after it finishes transmitting RTS. If A hears the busy tone during the waiting time, it starts sending the DATA packet after the timer times out; B turns off the busy tone when DATA transmission is finished.

Scenario 2: If the RTS is collided with others at B, A will not hear the busy tone. In this case, A will try a second time by sending a PRE message after WAIT1 amount of time has elapsed since it finishes transmitting RTS. If B hears the PRE, it will turn on the busy tone to allow A to transmit. A waits for a mandatory WAIT2 time after it finishes transmitting PRE; if A hears busy tone during the waiting time, it starts sending the DATA packet after the timer times out; B turns off the busy tone when DATA transmission is done.

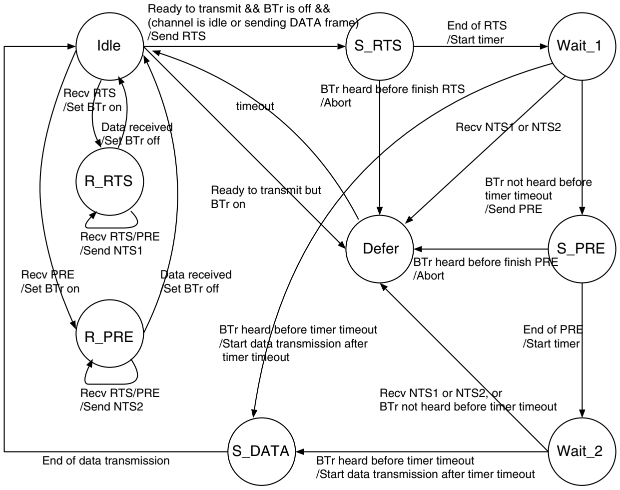


Fig. 1. The Finite State Machine of the MAC scheme

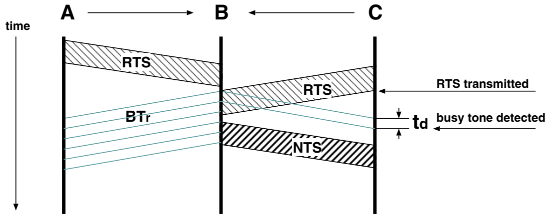


Fig. 2. B uses NTS to deny the request from a hidden terminal C

Due to the propagation delay, it is possible that a hidden node C has finished transmitting a RTS or PRE message before it hears the busy tone from B (Fig. 2). In both scenarios, if B receives RTS or PRE messages during the time it is waiting for data to come and the busy tone is on, it will send an NTS message. B uses NTS1 to suppress a request when it is waiting for DATA after a RTS (in `R_RTS` state in Fig. 1), and uses NTS2 to suppress a request when it is waiting for DATA after a PRE (in `R_PRE` state in Fig. 1). If sender A has received an NTS message that is intended for A, or A has heard busy tone before or during the transmission of RTS or PRE, it will abort transmission and try again later after a random delay. WAIT1 and WAIT2 are defined as follows.

- WAIT1=$2\tau + t_d + TRANSP_{NTS1}$
- WAIT2=$2\tau + t_d + TRANSP_{NTS2}$

Where τ is the maximum propagation time within the data transmission distance, t_d is the busy tone detection delay, and $TRANSP$ is the time to transmit a packet. The complete operation of the scheme is summarized in the Finite State Machine in Figure 1.

B. Unique Features of BTMA-NTS

An NTS1 message contains the same information as a RTS message except that the packet type is different; an NTS2 message only contains the receiver address B and two time stamps to indicate when B receives the PRE for which the busy tone is turned on and when B starts to send NTS2. The two time stamps are useful for senders to determine whether this NTS2 is intended for them. Figure 2 shows that B successfully receives the RTS from A and turns on the busy tone. C sends a RTS subsequently. However when $2\tau + t_d > TRANSP_{RTS}$, it is possible that node C has finished transmitting RTS when it detects the busy tone, in which case C will misunderstand the busy tone as a permit to transmit, but actually it is a permit for A and C should not transmit. The use of NTS eliminates the chance of data collision at B unless the NTS message is not received by C. However, the chance for NTS being collided at C is 0 in the WLAN infrastructure mode and is $<< 1$ in the multiple-hop ad hoc mode. The DBTMA scheme also uses a busy tone to protect DATA transmission, but it fails to solve the hidden terminal problem in this case.

The use of PRE as a second request increases the chance of data transmission, because PRE is much shorter than RTS. Therefore PRE has a much higher chance to succeed than RTS does. BTMA-NTS differs from DBTMA in the following ways:

1) Only one busy tone is used. The transmitter busy tone BT_t in DBTMA is replaced by carrier sense, and BTMA-NTS still performs equally well in terms of solving the exposed terminal problem.
2) When RTS fails, a best effort PRE is sent to try a second time. The use of PRE increases the chance for DATA transmission, which increases channel utilization.
3) Explicit denial of requests is used to avoid data collision. The use of NTS messages eliminates DATA collision in the WLAN infrastructure mode and reduces the probability of DATA collision in the multiple-hop ad hoc mode. The performance gain over DBTMA is manifested when $2\tau + t_d > TRANSP_{RTS}$.

C. Variants of BTMA-NTS scheme

Based on the basic operation rules of BTMA-NTS, the following variants could be used for different situations.

1) Without Carrier Sense: The exposed terminal problem can be completely solved if we get rid of the carrier sense before sending RTS. This could be justified especially in a multiple-hop ad hoc network, because the carrier sense at the sender side cannot hear the hidden terminals any way. Without carrier sense, the success rate of RTS and PRE packets will be decreased. But the absence of carrier sense also reduces the channel waste due to unnecessary waiting time. When traffic load is low in a multihop ad hoc network, it could be feasible to remove the carrier sense.

2) With Two Busy Tones: If there are two out-of-band channels available, it is more efficient to get rid of the carrier sense and use both channels for receiver busy tones than to use one for transmitter busy tone and the other for receiver busy tone. We can use BT_{r1} to indicate that the receiver carrier is busy thus to warn others not to send, and use BT_{r2} to acknowledge RTS (or PRE) and provide continuous protection during DATA reception.

3) With Long Range Busy Tone: Most radio transmitters (almost all radio transmitters) have a larger interference range than effective transmission range. The interference range in an open environment is usually 1.78 times the effective transmission range. This means there are hidden terminals that fail to receive the busy tone from the receiver but still be able to interfere with DATA reception at the receiver. To address this type of hidden terminal problem, the busy tone transmission power could be increased to make the busy tone transmission range equal to the interference range of the main channel.

III. THROUGHPUT ANALYSIS

The maximum throughput of a multiple-hop ad hoc network is largely dependent on the routing scheme, and the distribution of source and destination pairs. Therefore we only provide the throughput analysis for a single-hop network where every node is in the transmission range of every other node.

In the throughput analysis, we make the following assumptions:

- The propagation delay to reach the farthest node is τ.
- The aggregated traffic of the network has a Poisson distribution with a mean rate λ, i.e., there are λ channel requests in each second. The mean rate for RTS is λ_1; the mean rate for PRE is λ_2. $\lambda_1 + \lambda_2 = \lambda$.
- The transmission times of PRE, RTS, and DATA frames are T_P, T_R, and T_D. The busy tone detection time is t_d.

Channel throughput[1] is the fraction of time that the channel is used to transmit DATA. Idle time, collision time and control message transmission time are all considered as wasted time. Using the similar definitions as in [3] and [4], we consider the time from one busy period to the next as a cycle. Within each cycle, let D be the average time the channel is used for transmitting DATA frames, let I be the average idle time due to the inter space between requests, and let B be the average channel busy time. The throughput can be computed as

$$S = \frac{D}{B + I}$$

A. Without Carrier Sense

We first look at the throughput when carrier sense is not used before sending RTS. A DATA frame can be transmitted when RTS is successful, or RTS is collided but PRE is successful. The probability that RTS is successfully received is

$$P_{s_1} = e^{-\lambda T_R}$$

In this case, the channel busy time is

$$T_{s_1} = T_R + WAIT1 + T_D + 2\tau$$

---

[1] normalized by the channel data rate R

The probability that RTS is collided but PRE is successful is

$$P_{s_2} = (1 - e^{-\lambda T_R}) \cdot e^{-2\lambda_1 T_P}$$

Where $\lambda_1 = \lambda/(2 - e^{-\lambda T_R})$. In this case, the channel busy time is

$$T_{s_2} = T_R + WAIT1 + T_P + WAIT2 + T_D + 2\tau$$

The average busy time in a failure case is

$$T_f = \tau + WAIT1 + T_P + \frac{3}{2}T_R$$

Therefore the total busy time is

$$B = P_{s_1}T_{s_1} + P_{s_2}T_{s_2} + (1 - P_{s_1} - P_{s_2})T_f$$

The idle time between requests is $I = \frac{1}{\lambda}$, and the average data transmission time is

$$D = P_{s_1}T_D + P_{s_2}T_D$$

This gives a throughput of

$$S = \frac{P_{s_1}T_D + P_{s_2}T_D}{P_{s_1}T_{s_1} + P_{s_2}T_{s_2} + (1 - P_{s_1} - P_{s_2})T_f + \frac{1}{\lambda}}$$

B. With Carrier Sense

In BTMA-NTS, carrier sense is implemented before sending RTS. In a fully connected network, carrier sense can avoid unnecessary collision and improve the success rate of RTS. Accordingly, RTS will be successful when there is no other RTS arriving within the first $min\{\tau, T_R\}$ time and there is no PRE arriving within the first T_R time. Let $t_{min1} = min\{\tau, T_R\}$. The probability for RTS to succeed is

$$P_{s_1} = e^{-\lambda_1 t_{min1}} \cdot e^{-\lambda_2 T_R}$$

Let $t_{min2} = min\{\tau, T_P\}$. The probability that PRE is successful is

$$P_{s_2} = (1 - P_{s_1})e^{-2\lambda_1 t_{min2}}$$

The average busy time in a failure case is

$$T_f = \tau + WAIT1 + \frac{1}{2}T_P + \frac{3}{2}T_R$$

In the following, we compare the channel throughputs of BTMA-NTS (with carrier sense by default), BTMA-NTS-NOCS (without carrier sense), and DBTMA([3]), with different channel data rates, radio transmission ranges and busy tone detection delays. The lengths of DATA frames and RTS frames are δ and γ respectively. Figure 3 shows that as τ, t_d and data rate R increase, the throughput of DBTMA scheme drops more and faster than those of the other two schemes, mainly because in DBTMA there still exists collision on DATA frames when $2\tau + t_d > T_R$, while BTMA-NTS and BTMA-NTS-NOCS schemes successfully eliminate collision in this case. Each row shows how the throughputs change with t_d, and each column shows how the throughputs change with R and τ. It is also observed that in a fully connected network, BTMA-NTS always outperforms BTMA-NTS-NOCS, and the performance gain of BTMA-NTS over BTMA-NTS-NOCS is more significant in a network with shorter transmission range, as shown in Figure 3.(a) and (b). In all six plots, BTMA-NTS is the ultimate winner as traffic load λ increases.

IV. RELATED WORK

A. Using a single shared channel

MAC schemes that use a single shared channel to send control packets and data packets include MACA family, FAMA family and IEEE 802.11. The original 802.11 does not include the use of short control packets RTS and CTS before data transmission. RTS-CTS scheme was first used in the CSMA/CA scheme in the Apple Local talk networks. Karn ([5]) adopted the RTS-CTS prologue but removed the carrier sense part of CSMA/CA and proposed MACA for packet radio networks, with a goal to solve the hidden terminal problem. All nodes that hear the RTS will defer channel access until the receiver replies with a CTS packet; all nodes that hear the CTS will defer channel access until the data transmission is over. This RTS-CTS handshaking effectively reduced the chance of packet collision from hidden terminals when RTS and CTS packets both are successfully received. However, when the RTS and CTS control packets are sent from the single shared channel, the collision of these control packets is possible, which makes MACA fail to completely solve the hidden terminal problem. MACAW ([6]) enhanced MACA by using a different back-off algorithm and an additional control packet DS after RTS-CTS handshaking to announce a DATA frame is following.

Current 802.11 (CSMA/CA) ([7], [8]) adopted the RTS-CTS prologue to reserve the channel before data transmission, however, the hidden terminal problem remains the same as in MACA. In the infrastructure mode, the only problem is the hidden terminal problem. When 802.11 is used in multiple-hop ad hoc networks, another problem comes out, which is known as the exposed terminal problem and reduces channel utilization. The exposed terminal problem in 802.11 is due to the mandatory carrier sense at the physical layer. The use of RTS-CTS prologue does not solve the exposed terminal problem at all; in fact it even maximizes the problem because all the exposed terminals defer channel access for a continuous NAV (network allocation vector) time until the data transmission is over and ACK is received. Xu et al. pointed out this problem in [9].

Fullmer and Garcia-Luna-Aceves developed FAMA family protocols, which unified the MAC protocols that use both carrier sense and RTS-CTS prologue ([4], [10], [1], [11]). RTS-CTS prologue is used to acquire the channel, called *floor* in FAMA protocols. FAMA protocols require the acquisition of the channel before a sender can transmit data packets, and it is supposed that only one station can acquire the channel in a receiver's range. However, hidden nodes need to understand the CTS packet to stay off the channel. In all FAMA protocols except FAMA-NCS, collision of CTS packet makes it impossible to eliminate the hidden terminal problem;

FAMA-NCS [1] on the other hand, makes a transmitter stay off the channel whenever it hears any transmission, and enforces the use of large CTS packets to make sure a hidden node always receives at least a portion of a CTS packet. Thus any collision heard by a sender will be treated as CTS packet collision and will prevent the node from sending. FAMA-NCS avoided the hidden terminal problem at the high cost of low channel utilization. FAMA protocols do not address the exposed terminal problem.

We can now conclude that MAC schemes that do not use a separate control channel cannot completely avoid the hidden terminal problem as long as the control packets need to be correctly received to take effect, because no smart control packet can avoid the collision of itself; and those that do not need the control packets to be correctly received to take effect will unnecessarily make nodes refrain from channel access and decrease channel throughput; those that use carrier sense the same way as in 802.11 cannot completely avoid the exposed terminal problem because the presence of carrier prevents an exposed terminal from transmitting.

B. *Using multiple channels*

Having realized that using a single shared channel cannot effectively solve the hidden terminal problem, multiple channel approaches are proposed that use one or two out-of-band busy tones. In the RI-BTMA scheme proposed in [2], a transmitter would send a preamble before the transmission of DATA, which serves the purpose of channel request; a single busy tone at the receiver side is used that serves two purposes: to give the transmitter the permission to send and to prevent other hidden nodes from sending. It is a pioneer work in using busy tones to avoid collision. The limitation of this work is that it uses a slotted scheme that relies on clock synchronization, and it ignores the propagation delay in the operation.

Haas et al. extended the RI-BTMA scheme to use two busy tones and work in a non-slotted manner. In DBTMA ([3]), a separate transmitter busy tone BT_t and a separate receiver busy tone BT_r are used. A node that transmits a RTS packet will simultaneously transmit a BT_t signal for the same duration. The receiver node upon successful reception of RTS will send a BT_r signal until the data reception is finished. A node that wishes to send a RTS packet needs to wait until both busy tones are cleared from the channel. CSMA is not used in DBTMA, but sending nodes are required to keep sensing the busy tones during transmission. The transmitter busy tone is used to protect the RTS packet from collision; the receiver busy tone can give the sender permission to transmit and also protect DATA from collision. To replace CSMA on data channel with the use of a transmitter busy tone BT_t effectively minimizes the exposed terminal problem in DBTMA, so that an exposed node only stays off the channel for a RTS packet time. For solving the exposed terminal problem, DBTMA is superior to MACA, and it is only second to ALOHA. However for the hidden terminal problem, DBTMA still can not completely avoid it. When the condition $2\tau + t_d > TRANSP_{RTS}$ becomes true, the receiver busy tone for one transmitter could possibly be misunderstood by hidden nodes as a permit to send and therefore cause collision on DATA packets. The proposed scheme BTMA-NTS in this paper, like RI-BTMA and DBTMA schemes, also uses a separate channel for out-of-band signaling, but the use of NTS packets effectively address the hidden terminal problem in DBTMA.

V. CONCLUDING REMARKS

In this paper, we propose a new wireless MAC scheme BTMA-NTS. BTMA-NTS uses a receiver busy tone to acknowledge a sender's request and to prevent DATA from further collision. The rationale of using RTS-busy tone to replace RTS-CTS dialogue is to reduce the number of control messages sent onto the main channel and to avoid collision on control packets. In most transmissions, the use of the mandatory CTS could be overkill. The new scheme effectively addresses both the hidden terminal problem and the exposed terminal problem. In WLAN infrastructure mode, it completely eliminates the hidden terminal problem. In ad hoc mode, it significantly mitigates the problem. In BTMA-NTS, the exposed node will refrain from channel access only during the transmission of control packets. The performance gain of BTMA-NTS over other schemes shows the use of explicit denial of requests and best-effort PRE messages improves channel throughput.

REFERENCES

[1] Chane L. Fullmer and J. J. Garcia-Luna-Aceves, "Solutions to hidden terminal problems in wireless networks", in *ACM SIGCOMM '97*, October 1997, vol. 27, pp. 39–49.

[2] C. Wu and V. O. K. Li, "Receiver-initiated busy-tone multiple access in packet radio networks", *ACM SIGCOMM Computer Communication Review*, vol. 17, pp. 336–342, 1987.

[3] Zygmunt J. Haas and Jing Deng, "Dual busy tone multiple access (dbtma) - a multiple access control scheme for ad hoc networks", *IEEE TRANSACTIONS ON COMMUNICATIONS*, vol. 50, no. 6, pp. 975–985, June 2002.

[4] Chane L. Fullmer and J. J. Garcia-Luna-Aceves, "Floor acquisition multiple access (fama) for packet-radio networks", in *ACM SIGCOMM '95*, October 1995, vol. 25, pp. 262–273.

[5] P. Karn, "Maca a new channel access method for packet radio", in *Proceedings of the 9th ARRL/CRRL Amateur Radio Computer Networking Conference*, September 1990, pp. 134–140.

[6] Vaduvur Bharghavan, Alan Demers, Scott Shenker, and Lixia Zhang, "Macaw: A media access protocol for wireless lan's", in *ACM SIGCOMM '94*, October 1994, vol. 24, pp. 212–225.

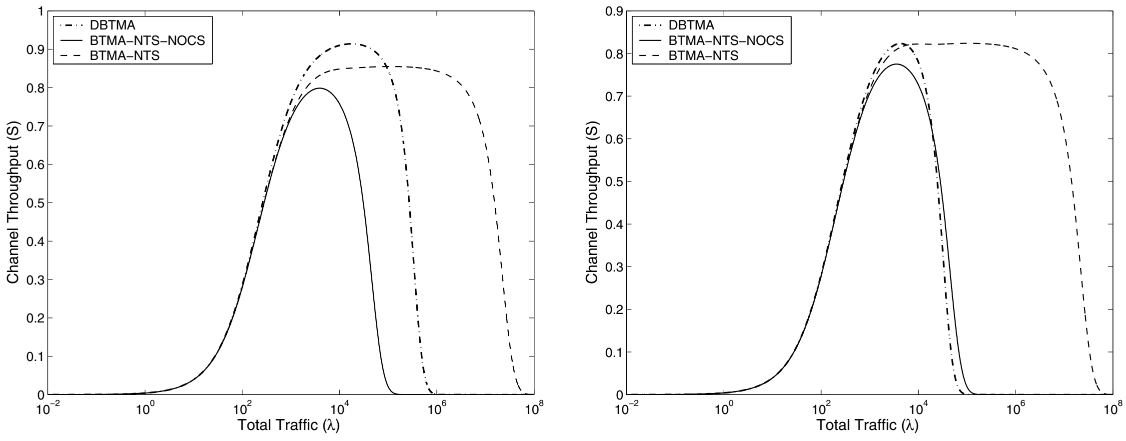
[7] "Wireless lan medium access control (mac) and physical layer (phy) specifications".

[8] B.P. Crow, I. Widjaja, J.G. Kim, and P.T. Sakai, "Ieee 802.11 wireless local area networks", *Communications Magazine, IEEE*, vol. 35, pp. 116–126, Sep 1997.

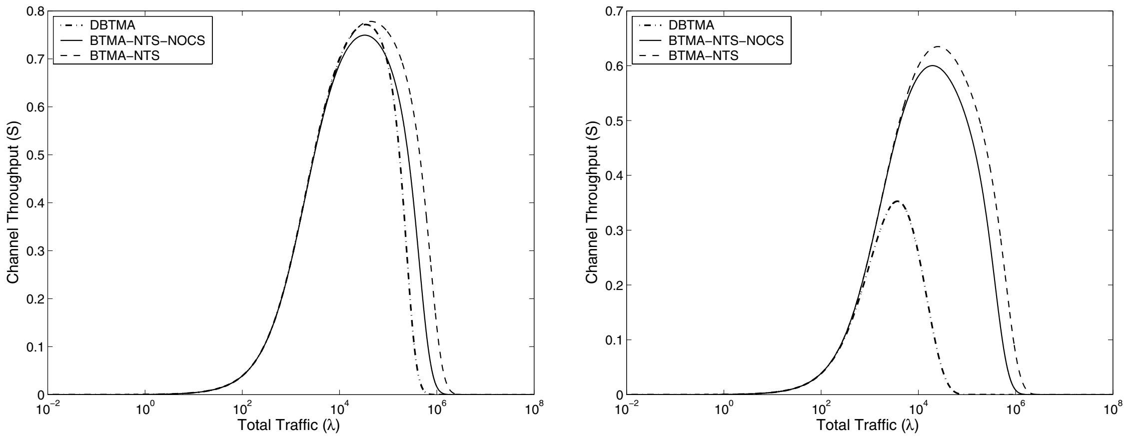
[9] S. Xu and T. Saadawi, "Does the ieee 802.11 mac protocol work well in multihop wireless ad hoc networks?", *Communications Magazine, IEEE*, vol. 39, pp. 130–137, June 2001.

[10] Chane L. Fullmer and J. J. Garcia-Luna-Aceves, "Fama-pj: a channel access protocol for wireless lans", in *ACM MobiCom '95*, December 1995, pp. 76–85.

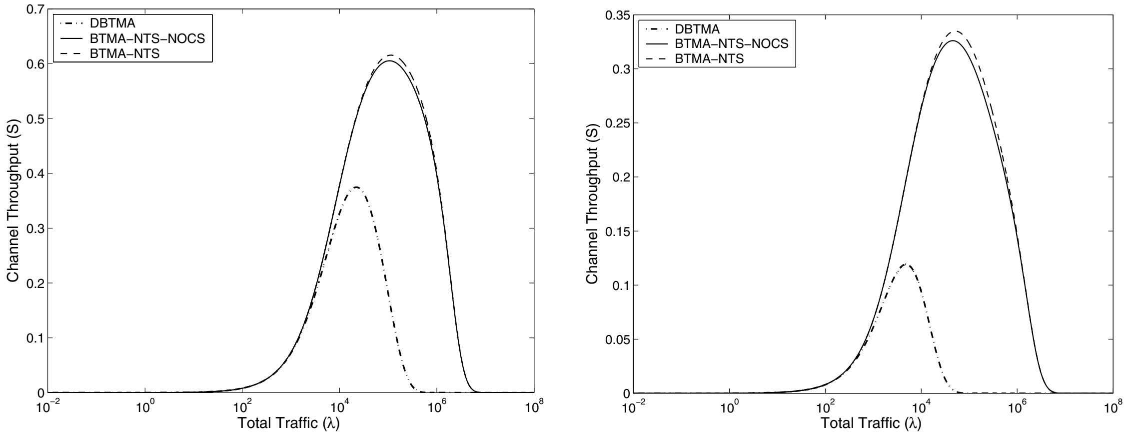
[11] J. J. Garcia-Luna-Aceves and Chane L. Fullmer, "Floor acquisition multiple access (fama) in single-channel wireless networks", *Mobile Networks and Applications*, vol. 4, no. 3, pp. 157–174, October 1999.



(a) $t_d = 10\mu s$ (b) $t_d = 100\mu s$



(c) $t_d = 10\mu s$ (d) $t_d = 100\mu s$



(e) $t_d = 10\mu s$ (f) $t_d = 100\mu s$

Fig. 3. Channel throughput comparison. δ=4096 bits, γ=256 bits; in (a) and (b), channel data rate R=1Mbps, radio range L=35m; in (c) and (d) channel data rate R=10Mbps, radio range L=1000m; in (e) and (f) channel data rate R=50Mbps, radio range L=1000m.