Dual Busy Tone Multiple Access (DBTMA) - Performance Results

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Abstract

The Dual Busy Tone Multiple Access (DBTMA) scheme was designed for distributed multi-hop networks. The protocol uses the RTS/CTS dialogue to reserve the shared channel. In multi-hop networks, some nodes in the range of the transmitter and/or the range of the receiver might not be able to hear a successful RTS/CTS message exchange. This may lead to access collisions and data destruction. Hence we use two narrow bandwidth busy tones, to notify neighbor nodes of the on-going use of the channel. In this paper, we analyze the capacity of the DBTMA protocol. The effects of various parameters on the network utilization in multi-hop networks are also discussed. We compare, through analytical results and simulation means, the performance of the DBTMA protocol with schemes that solely use the RTS/CTS dialogue to prevent collisions and we show that DBTMA provides superior performance to such schemes.

1 Introduction

Multiple Access Control (MAC) protocols are used to schedule access of multiple competing nodes in communication networks to a shared channel. In multi-hop networks, nodes that are out of the range of the transmitter, but not the receiver are called *hidden terminals* [1] [2]. Without proper notification, hidden terminals do not have information about the on-going transmissions. Their possible access to the channel during the time of the transmission will destroy the DATA packet being received at the receiver and degrade the network utilization. Similarly, those nodes in the range of the transmitter but not the receiver are called *exposed terminals* [2]. When Carrier Sense Multiple Access is used to prevent channel collisions, exposed terminals are prevented from accessing the channel, although such access would not cause collisions.

There have been numerous MAC protocols that attempted to solve the hidden- and the exposed-terminal problems. Examples of such protocols are: Busy Tone Multiple Access (BTMA) [1], Multiple Access Collision Avoidance (MACA) [2], and MACA for Wireless networks (MACAW) [3]. In BTMA, a busy tone is emitted by the base station to notify terminals about the on-going channel use. In MACA [2], Karn originally proposed the use of short control packets, the Request-To-Send (RTS) and Clear-To-Send (CTS) packets, for collision avoidance on the shared channel. A ready node transmits an RTS packet to request the channel. The "receiver" replies to the "transmitter" with a CTS packet. All other nodes that hear the RTS packet back-off for a time long enough for the "transmitter" to receive the CTS packet. All nodes that hear the CTS packet back-off for a time long enough for a DATA packet reception. In MACAW, additional control packets are introduced to improve the performance of the scheme and to reduce unfairness among the nodes in accessing the channel. FAMA requires full channel reservation by the transmitting node (i.e., to gain the "floor"), before any DATA packets are sent over the channel.

Since DATA packets are long, collision and corresponding destruction of DATA packets can be very costly in wireless resources. Our analysis and simulations show that the probability of CTS packet being destroyed could be as high as 60% for high traffic load in multi-hop networks. In [4], we proposed the Dual Busy Tone Multiple Access (DBTMA) protocol, a scheme that eliminates DATA packet collisions in a practical wireless communication environment. In DBTMA, in addition to the use of the RTS/CTS dialogue, there are two out-of-band busy tones, whose purpose is to notify neighbor nodes of the on-going transmission. Nodes sensing the busy tones defer from using the channel, in the "direction" as specified by the type of the busy tone. The scheme provide means for **continuous** channel monitoring and does not require successful reception of the RTS/CTS dialogue by the potentially interfering nodes to prevent collisions.

In this paper, we analyze the channel throughput of DBTMA in a single-hop network. Our analytical model as-

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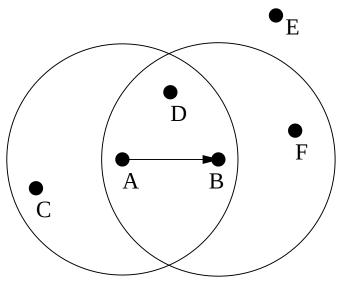

Figure 1: A Simple Multi-Hop Network

sumes finite number of identical nodes in the network. To simplify our analysis, we assume that the arrival of DATA packets is Poisson, that the packets are of fixed length, and that blocked packets are cleared from the system. Based on this model, we calculate the probability of an RTS packet being successfully received and then estimate the channel capacity. Furthermore, we confirm our analytical model by simulation. Additionally, we compare the DBTMA scheme with schemes that rely solely on the RTS/CTS dialogue to prevent channel collisions.

In the next section an example of DBTMA operation is presented. We analyze the DBTMA performance within a single transmission area in the third section and evaluate the performance through simulation in the fourth section. Section 5 summarizes our work.

2 DBTMA

In our DBTMA scheme, we use RTS/CTS dialogue to establish communication between two neighbor nodes. We also use two narrow-band busy tones to notify neighbor nodes of the on-going communication. The two busy tones are: the transmit busy tone (BT_t) and the receive busy tone (BT_r). Since the busy tones occupy narrow bandwidth, the overhead that they consume is very small and we neglect their bandwidth consumption in our performance evaluation.

The detail of our DBTMA protocol can be found in [4]. In what follows, we present an example of the DBTMA scheme's operation. Node A (Fig. 1) has a DATA packet for its neighbor (node B). Before its transmission, it senses the BT_r signal and, if no BT_r signal is sensed, it transmits an RTS packet to node B. When node B receives the RTS packet, it decides whether or not it can receive by sensing the BT_t signal. If no BT_t signal is sensed, it will proceed with reception. It sets up its BT_r signal and replies to node A with a CTS packet. After node A receives the CTS packet, it sets up its BT_t signal and transmits its DATA packet to node B. Both busy tones will be reset after the transmission is completed.

Our dual busy tone mechanism provides a way for neighbor nodes to monitor the channel continuously. All the nodes in the range of node B, e.g., node D and node F, will sense the BT_r signal and back-off. This is the case, even if the RTS/CTS dialogue between node A and node B was not heard correctly because of other interfering transmissions (e.g., the transmission of node E). Thus, the hidden terminal problem is taken care of. The exposed terminal problem is addressed by the absence of the receive busy tone (and the presence of the transmit busy tone), e.g., node C will sense the BT_t signal and decide that it can transmit but not receive.

3 Analytical Calculation

In this section, we analyze the channel throughput of a single transmission area with a number of nodes using the DBTMA protocol. We have the following assumptions:

- The DATA packet transmission time, the control packet (RTS, CTS) transmission time and the propagation time are: δ, γ and τ, respectively;
- There are N identical nodes in the single transmission area. Each of them generates Poisson arrival DATA packets. The total traffic load is λ arrivals each unit time (δ). Hence, the arrival rate of DATA packets on each node is $\lambda_1 = \lambda/N$;
- New arrivals during the time that a node has a packet in process or it is blocked will be discarded.

Following the method presented in [1] to calculate the channel throughput, we define a busy period with any transmission on the channel as the period between two consecutive idle periods. A busy period might be a period with successful DATA transmission, or a period with packet collisions. We treat the transmission cycle on the channel as a renewal process. The channel throughput can be calculated as:

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

where $\overline{U}$, $\overline{B}$ and $\overline{I}$ are the average utilization time for DATA packet transmission, the average busy time, and the average idle time of the channel in each cycle.

After one node sends an RTS packet to its intended receiver, it waits for a time long enough for the CTS packet to come back. So, every request will block the node from accepting new arrivals for $t = 2\gamma + \tau$ seconds. The probability of a node being idle is:

$$P_i = \frac{1/\lambda_1}{t + 1/\lambda_1} = \frac{1}{1 + \lambda_1 t}$$

Since all nodes are in the same transmission area, once an RTS packet is successful and the BT_r signal is setup, the DATA packet transmission will not be subject to collisions. The probability of an RTS packet being successful is the probability that it is the only RTS transmission at the time, given that there is at least one transmission on the channel:

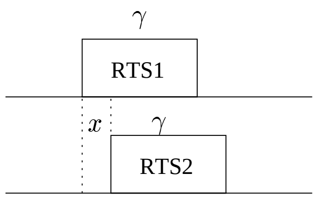

Figure 2: Two RTS's Collision

$$\begin{aligned} P_s &= P_s(RTS) \\ &= \frac{Prob\{Only\ One\ Transmission\}}{Prob\{At\ Least\ One\ Transmission\}} \\ &= \frac{\binom{N}{1}(1-P_i)(P_i)^{N-1}}{1-(P_i)^N} \\ &= \frac{N\lambda_1 t}{(1+\lambda_1 t)^N - 1} \qquad (1) \end{aligned}$$

A busy period is defined as times in which there is some transmission on the channel, either successful or unsuccessful. The busy period can be calculated as:

$$\overline{B} = P_s T_s + (1-P_s)T_f \quad ,$$

where T_s is the expected time of successful transmission period and T_f is the expected time of unsuccessful period.

A successful transmission period consists of an RTS packet transmission time followed by τ, a CTS packet transmission time followed by τ, and a DATA packet transmission time followed by τ. Thus the length of a successful cycle is:

$$T_s = 2\gamma + 3\tau + \delta$$

An unsuccessful transmission period consists of multiple number of RTS packets colliding. Since the probability of more than two RTS packets collision is significantly smaller than collisions of exactly two RTS packets, we neglect the former in our calculations. The transmission of RTS packet is similar to transmission using the pure ALOHA protocol. Because of the Poisson arrival assumption, (i.e., memoryless and exponentially-distributed inter-arrival times), the starting time of the colliding RTS packet is uniformly distributed throughout the duration of the first RTS packet (Fig. 2). So the average collision duration is:

$$T_f = \int_0^\gamma \frac{1}{\gamma}(x+\gamma)dx = 1.5\gamma \quad .$$

The average utilization period can be expressed as:

$$\overline{U} = P_s \cdot \delta \quad .$$

An idle period is the time between two consecutive busy periods:

$$\overline{I} = \frac{1}{\lambda} \quad .$$

So, the channel throughput can be calculated as:

$$\begin{aligned} S &= \frac{\overline{U}}{\overline{B} + \overline{I}} \\ &= \frac{P_s \cdot \delta}{P_s \cdot (2\gamma + 3\tau + \delta) + (1-P_s)\cdot 1.5\gamma + 1/\lambda} \quad , \end{aligned}$$

where P_s is given by Eq. (1).

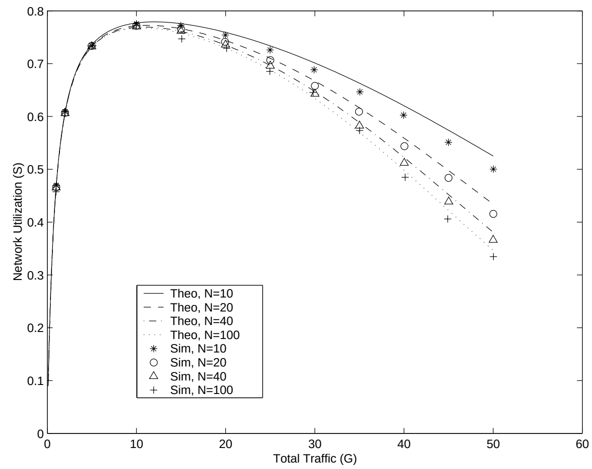

Figure 3: DBTMA, single area, $L_c = 48bits$, $R_d = 20Kbps$

4 Performance Evaluation

To confirm our analytical calculation of the channel throughput, we have simulated wireless networks with different sets of parameters. We used an event driven simulation, which we built in C language. Our simulation runs are based on the following parameters (with a single parameter being varied in any simulation test):

- Coverage Area (S): $100 \times 100\ m^2$;
- Transmission range (R): 1,000 m;
- Channel rate (R_d): 20,480 Kbps or 2.048 Mbps;
- DATA packet length (L_d): 1,024 bits;
- Control packet (RTS, CTS) length (L_c): 48, 96, or 192 bits;
- Number of nodes (N): 10, 20, 40 or 100.

In Fig. 3, 4 and 5, we show simulation results and analytical results of the channel throughput for different nodal density (N), control packet length (L_c), and DATA channel rate (R_d), respectively. In these figures, our analytical results are shown as curves, while the simulation results are represented as discrete points.

In Fig. 3, we compare the channel throughput for networks with different nodal density (N). We set L_c to 48 bits and R_d to 20,480 Kbps. Channel throughput increases as the traffic load grows, until it reaches a maximum value, about 0.78 for all N we tested. Then the channel throughput decreases. This is the same pattern as encountered in the pure ALOHA system. It is not surprising, since the transmission of RTS packets is, indeed, a form of pure ALOHA, although DATA packet transmission follows only successful RTS transmission. As expected, the channel throughput of networks with larger N is lower. The gaps in network coverage, which reduce the degree of transmission concurrency, for networks with different N affect

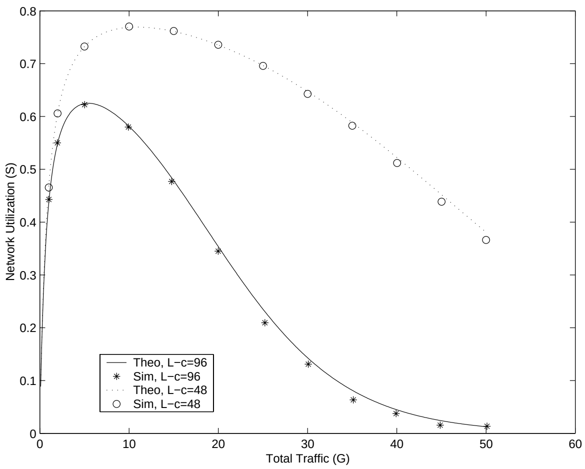

Figure 4: DBTMA, single area, $N = 200$, $R_d = 20Kbps$

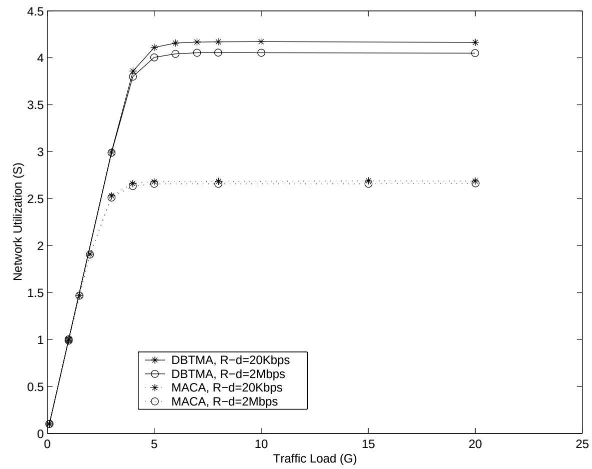

Figure 6: DBTMA vs. MACA, $L_c = 48bits$, $N = 200$

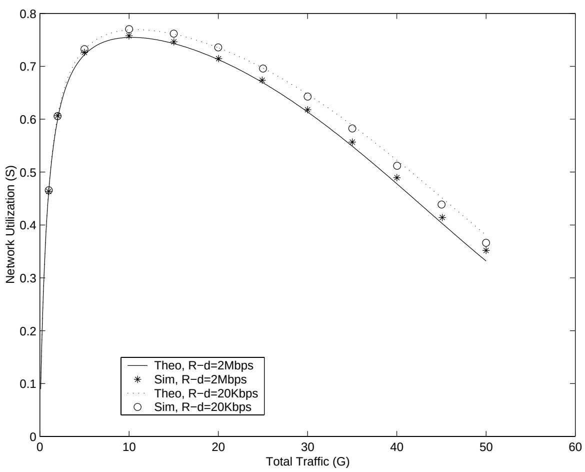

Figure 5: DBTMA, single area, $L_c = 48bits$, $N = 200$

the network throughput significantly more in higher traffic load than in lower traffic load.

In Fig. 4, we show the effect of L_c, as we set N to 40, and R_d to 20,480 Kbps. Channel throughput decreases when L_c increases. The reason is that the length of a control packet (the RTS packet) is the vulnerable time for the request. Longer vulnerable time results in lower probability of successful request and, hence, lower channel throughput. These results suggest to use smaller values of L_c. Thus, for short DATA packets, the DATA packet itself, instead of an RTS packet, should be sent.

The effect of DATA channel rate (R_d) is also studied. In Fig. 5, we draw the analytical and simulative results based on different R_d. We set N and L_c to 40 and 48 bits, respectively. The throughput of a network with larger R_d is slightly lower than that of smaller R_d. In fact, normalized propagation delay (τ) is proportional to R_d. As τ increases, the effect of propagation delay is more significant, with lower channel throughput.

All the previous three graphs were obtained based on the assumption that blocked DATA packets are cleared from the system. While this assumption simplifies the analysis, it is not a practical one. In a real network, a blocked packet waits for a random period of time and then tries again to use the channel, until it is successful in transmission or until the retransmission time reaches a maximum value. Hence, we have also simulated the DBTMA protocol with a backoff algorithm. In order to compare the performance of our protocol, we have also simulated a basic RTS/CTS protocol (e.g. MACA) under the same networks conditions: network coverage area of $5 \times 5\ km^2$ and R of $1\ km$. Nodes are distributed over the coverage area randomly and uniformly, and any two nodes that are less than R apart are neighbors. We display our simulation results in Fig. 6, 7, and 8.

In Fig. 6, the performance of DBTMA and MACA with different R_d is shown. We set L_c and N to 48 bits and 200, respectively. We find a 60-70% increase in network utilization for DBTMA over MACA. For MACA, the probability of CTS packet being destroyed is quite high in multi-hop networks under high traffic load. Hence, it has low network utilization. DBTMA, with the use of busy tones, protects the DATA packet transmission even in the situations where the RTS/CTS dialogue is not heard correctly by some nodes. The small gap of the network utilization between different R_d is due to the different normalized propagation delay (τ), as seen in Fig. 5. The effect of τ is more significant in DBTMA than in MACA. The reason is that the propagation time of the busy tone is the only source of vulnerability after successful RTS/CTS dialogue in DBTMA. In MACA, however, failure to hear the CTS packets is the main source for DATA packet collisions.

In Fig. 7, we show the performance comparison for different nodal density (N). We fix R_d and L_c as 20,480 Kbps and 48 bits, respectively. In MACA, a slight decrease in the network utilization results from an increase in N, as the number of contending nodes is larger as N increases. In contrast, we find a significant increase of the network utilization for DBTMA as N increases. This is the effect of nodal density on the number of concurrent transmission in the network. As N increases, it is more probably to set

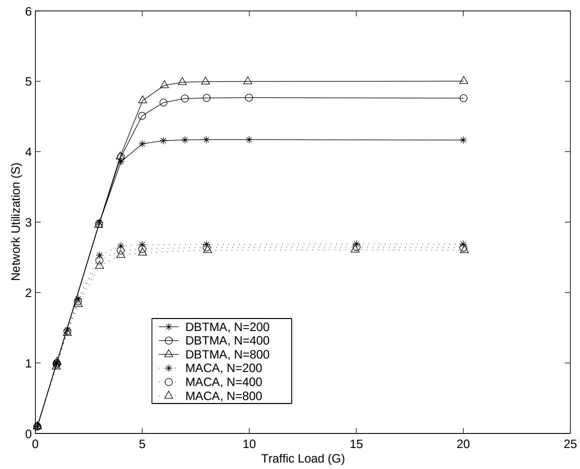

Figure 7: DBTMA vs. MACA, $L_c = 48bits$, $R_d = 20Kbps$

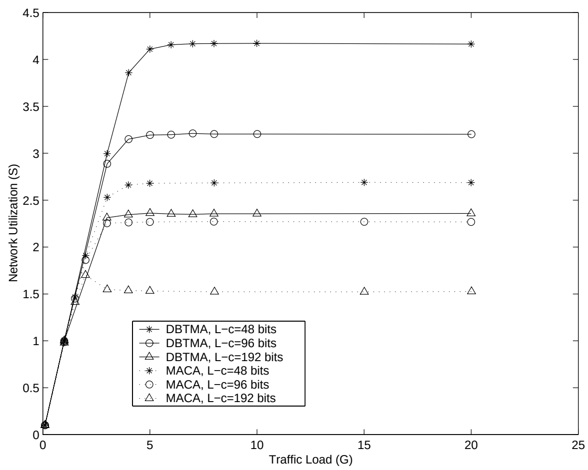

Figure 8: DBTMA vs. MACA, $N = 200$, $R_d = 20Kbps$

up communications in those spatial gaps among the network nodes and, thus, increase the transmission concurrency. This also explains why the increase of the network utilization is smaller when we vary N from 400 to 800, compared with the case when N is changed from 200 to 400, since in the former case most of gaps have been already filled in. As N increases, the network utilization reaches a maximum value, indicative of maximum possible concurrent transmission.

We compare DBTMA and MACA for different L_c in Fig. 8. As L_c increases, the network utilization decreases. This is the same trend that we have seen in Fig. 4. We also see that the performance of DBTMA degrades at approximately the same rate as MACA. Still, DBTMA maintains a higher network utilization than MACA.

5 Concluding Remarks

Due to the randomness of accesses to a shared channel, packet collisions are difficult to totally eliminate. Multihop networks pose even bigger challenge in this respect in the design of a MAC protocol, due to the existence of hidden terminals and exposed terminals. In order to protect DATA packet transmission, continuous notification of channel state needs to be present.

As the carrier sensing scheme give protection to the transmitter instead of the receiver of the DATA packet, some researchers have proposed to use a reservation dialogue (the RTS/CTS dialogue) between the communication nodes. However, the RTS/CTS-based protocols can still be quite vulnerable to collisions. In our DBTMA scheme, in addition to the use of the RTS/CTS dialogue, each node uses two out-of-band busy tone signals. These tones serve as notification for all nodes in the transmission range and in the reception range of the node in question, so that the possibility of collision is significantly reduced, while the network utilization is increased. Our dual busy tone mechanism assures that hidden terminals are prevented from using the channel and exposed terminals do not defer from accessing the channel. Our analytical and simulation results show the performance of the DBTMA protocol to be superior to that of other MAC protocols based on the pure RTS/CTS dialogue only.

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