Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks

Jing Deng and Zygmunt J. Haas
School of Electrical Engineering
323 Frank Rhodes Hall
Cornell University
Ithaca, NY 14853, U. S. A.
Tel: +1-607-255-3454, Fax: +1-607-255-9072
E-mail: `haas@ee.cornell.edu`, URL: `http://www.ee.cornell.edu/~haas/wnl.html`

Abstract

In packet radio networks, hidden terminal problem and exposed terminal problem can severely reduce the utilization of a Medium Access Control (MAC) protocols. To avoid these problems, RTS/CTS-based schemes were proposed. However, as shown in this paper, utilization of these schemes is still degraded, especially in the cases in which the propagation and the transmission delays are long. We propose here a new MAC protocol, termed the *Dual Busy Tone Multiple Access (DBTMA)*, and we evaluate its performance. In DBTMA, two busy tones are used to separate the use of the forward and the reverse communication directions. Our simulations show that the network utilization of DBTMA is about twice as that of RTS/CTS-based schemes. We also discuss the effect of nodal mobility on the network utilization in packet radio networks, concluding that it is negligible under normal operational conditions.

1 Introduction

Medium Access Control (MAC) schemes are used to coordinate access to the single channel in packet radio networks. Due to the non-transitivity property of the radio communication, the well-known hidden terminal problem and the exposed terminal problem may occur. These problems severely affect the channel utilization in MAC protocols.

Carrier Sense Multiple Access (CSMA) senses the channel for carrier before it transmits to reduce the probability of collisions [1]. Unfortunately, the condition that every user can hear all other users, which is a prerequisite for CSMA, is not satisfied in most packet radio networks. Busy Tone Multiple Access (BTMA) was introduced to alleviate the hidden terminal problem in systems with single base station [2], but it doesn't solve the problem in systems without single base station. The recently proposed protocols, MACA and MACAW, are control-message (RTS and CTS, which means Request-To-Send and Clear-To-Send respectively) protocols. They were introduced to solve the hidden terminal problem and the exposed terminal problem [3] [4]. The RTS and CTS packets are scheduled to acquire the channel. By receiving these control packets, other nodes will defer their transmission for proper period of time. However, our calculations show that the probability of packet collision is very high; about 60%. Nodal mobility is another problem should be considered.

To address the loss of channel utilization in the RTS/CTS-based networks, we propose a new MAC protocol, termed Dual Busy Tone Multiple Access (DBTMA), for packet radio networks. It is based on two previous elements, the busy tone and the RTS/CTS dialogue mechanism.

2 Effect of Mobility

In this section, we calculate the probability of data packet collisions due to nodal mobility. We have the following denotations:

- S: size of the coverage area
- N: number of nodes in the coverage area
- R: transmit radius of a mobile (we assume no power control) *
- T_D: data packet transmission delay (including propagation delay)
- d: nodal density (N/S)

First, we calculate the number of nodes which will migrate into node A's transmission area from outside in time $T = T_D$. The maximum distance away from the coverage area of node A, into which the node can migrate and interfere with node A's reception, is $L = VT$. We consider the thin *dl* ring in Fig. 1. The direction of the velocity of those nodes which will move into node A's transmission area in time T must satisfy:

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*Power control is impractical in packet radio networks.

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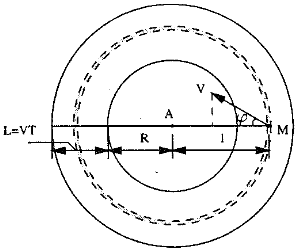


Figure 1: The Mobility Problem

$$\varphi \leq \varphi_{max}(l) = min\left\{cos^{-1}\left(\frac{l-R}{VT}\right),\ sin^{-1}\left(\frac{R}{l}\right)\right\}$$

The number of nodes in the dl ring which will migrate into node A's transmission area in time T is:

$$N(dl) \quad = \quad \frac{\varphi_{max}(l)}{\pi} \cdot 2\pi \cdot l \cdot d \cdot dl$$

The total number of nodes which will migrate into node A's transmission area in time T is, thus:

$$\begin{aligned} N_c &= \int_{l=R}^{R+VT} \frac{\varphi_{max}(l)}{\pi} \cdot 2\pi \cdot l \cdot d \cdot dl \\ &= 2d \int_{l=R}^{R+VT} l \cdot \varphi_{max}(l) dl \qquad (1) \end{aligned}$$

Under normal operational conditions:

$$\varphi_{max}(l) = cos^{-1}\left(\frac{l-R}{VT}\right)$$

So:

$$\begin{aligned} N_c &= 2d \int_{l=R}^{R+VT} l \cdot cos^{-1}\left(\frac{l-R}{VT}\right) dl \\ &= d \cdot \left[\frac{\pi}{4} \cdot (V \cdot T)^2 + 2 \cdot V \cdot T \cdot R\right] \qquad (2) \end{aligned}$$

To calculate the percentage of time a node is in the transmission state, we consider a circular area [†] of πR^2. Ignoring the collisions, only one node can transmit. So, the percentage of time a node is transmitting is approximately $k_t = 1/(d\pi R^2)$. By averaging this over all the potentially colliding nodes, we have the average $N_m = N_c \cdot k_t$ number of nodes which may interfere with the reception of the node in question (due to nodal mobility).

$N_m \approx 0.01$ for the value of parameters in our simulations, which is confirmed by numerical evaluation. Consequently, we show that the effect of nodal mobility in packet radio networks is negligible under normal operational conditions.

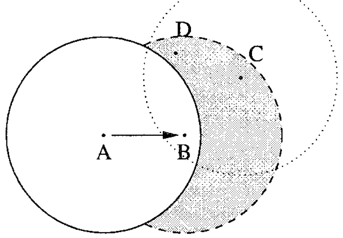


Figure 2: The Scenario of the CTS Packet Destruction

3 Probability of Packet Collisions

In this section, we approximate the probability of packet collisions in the RTS/CTS-based packet radio networks.

We have additional denotations as following:

- T_C: control packet transmission delay (including propagation delay)
- T_w: optimal maximum back-off time
- β: percentage of ready nodes

Maximum back-off time (T_w) is a critical parameter. A ready node selects randomly a time between 0 and T_w as the time in which it tries to acquire the channel by sending out an RTS packet. Improper T_w may lead to low network utilization or unstable performance. If it is too small, more collisions will occur. If it is too large, the channel will be wasted being idle. Assume that there are N_a ready nodes in a specific area and all nodes are uniformly distributed on the area. Every node has the same maximum back-off time (T_w). So, in every T_w/N_a second there will be, on the average, one RTS transmission generated from these N_a nodes. The optimal T_w should be the value such that it enables the nodes in the transmission area to generate, on the average, one new RTS transmission in a period of $2T_C$, which is the transmission time for an RTS/CTS dialogue. So $2T_C$ is approximately equal to T_w/N_a, while N_a is $d \cdot \pi \cdot R^2$. So, we have:

$$T_w \quad \approx \quad 2 \cdot \pi \cdot R^2 \cdot d \cdot T_C \qquad (3)$$

This is the formula we use to calculate the optimal maximum back-off time T_w.

First, we calculate the probability of a CTS packet being destroyed. In Fig. 2, node A tries to send a data packet to node B. For those nodes in the shaded area, the vulnerable period of receiving node B's CTS packet will be $2T_C$. The average number of nodes in the shaded area which will start new RTS transmissions in the vulnerable period is:

[†] The circle approximates the coverage area of node A.

$$N_C = \beta \cdot S_{shaded} \cdot d \cdot \frac{2T_C}{T_w} \qquad (4)$$

where S_{shaded} is the size of the shaded area.

S_{shaded} is the area covered by node B but not node A, $\overline{S_{\overline{A}\cap B}} \approx 0.6\pi R^2$. So, $\overline{N_C} \approx 0.6\beta$.

When the system is under heavy traffic load, which means that every node is almost always ready, β will be approximately 1. $\overline{N_C}$ is then about 0.6.

Second, we calculate the probability of the data packet being destroyed, given that the reception of a CTS packet is destroyed in some nodes in the shaded area by other nodes (or even by itself).

Assume node C starts a new RTS transmission in the vulnerable period ($2T_C$). Its transmission destroys the reception of the CTS packet in some nodes, which are in the transmission area of node B and node C ($S_{B\cap C}$). These nodes may start transmission when node B is receiving the data packet from node A (because they haven't received the CTS packet), destroying the data packet on node B.

The average number of nodes which will start new transmissions in time T_D is:

$$\overline{N_D} \approx \overline{S_{B\cap C}} \cdot d \cdot \beta \cdot \frac{T_D}{T_w} \approx \frac{\beta \cdot T_D}{5 \cdot T_C}$$

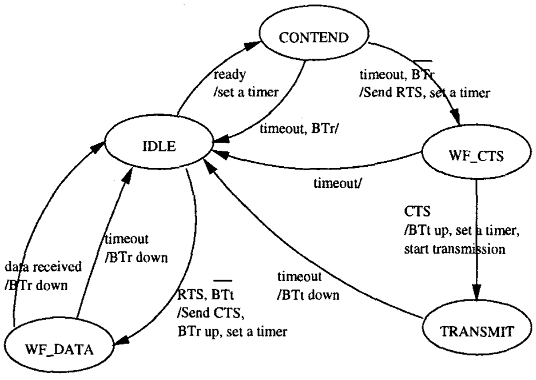
In RTS/CTS-based schemes, control packets are much shorter than data packets. So the number of new RTS transmissions in time T_D is greater than 1 under heavy traffic load. Consequently, the probability of the data packet being destroyed given that a CTS packet has been destroyed is almost 1.

So, in the RTS/CTS-based packet radio networks under heavy traffic load, the probability of a CTS packet being destroyed and hence the data packet being destroyed is about 0.6, which means that the performance degrades by the same amount.

4 DBTMA

To solve the above problem of MAC protocols based on pure RTS/CTS dialogue, we propose the DBTMA scheme. In our DBTMA scheme, the single common channel is split into two sub-channels: a data channel and a control channel. Data packets are transmitted on the data channel. Control packets (RTS/CTS) are transmitted on the control channel. Two busy tones are assigned on the control channel: BT_t (the transmit busy tone), which shows that a node is transmitting on the data channel, and BT_r (the receive busy tone), which shows that a node is receiving on the data channel. The two busy tones are sine waves at two different frequencies with enough spectral separation.

In DBTMA, there are five states: IDLE, CONTEND, WF_CTS, TRANSMIT, and WF_DATA. Fig. 3 depicts the Finite State Machine (FSM) of our protocol.



Before "/" is the condition of the transition

After "/" is the action of the transition

Figure 3: The Finite State Machine of DBTMA

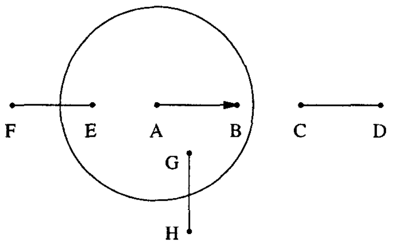


Figure 4: The Communication Scenario

The operation of the DBTMA protocol will be explained by the way of an example. The communication scenario is shown in Fig. 4. Node A is going to transmit to node B. Node C is within the transmission range of node B, but not within that of node A. Node E is within the transmission range of node A, but not within that of node B. Node G is within both of the transmission range of node A and B. Node D, F and H, which are all out of the range of node A and B, are within the range of node C, E and G, respectively. So, node C is a hidden terminal relative to the transmission from node A to node B, and node E is an exposed terminal. Note that all nodes might move.

Node A senses the control channel for the BT_r signal before it acquires the channel. If there is no BT_r signal (which means that no one in node A's transmission area is receiving on the data channel), node A sends an RTS packet on the control channel. When node B receives the RTS packet, it senses the BT_t busy tone signal. If there is no BT_t signal (which means that no one in node B's transmission area is transmitting on the data channel), node B replies with a CTS packet and turns on the BT_r signal (which tells other nodes that it is receiving). After receiving the CTS packet from node B, node A turns on the BT_t signal (which tells other nodes that it is transmitting) and starts the data packet transmission on the data channel. After completing its transmission, node A turns off the BT_t

signal. Upon receiving the data packet successfully, node B turns off the BT_r signal, ending the communication [6].

5 Performance Evaluation

We simulated and compared the performance of DBTMA and RTS/CTS-based schemes. Our simulations are based on a packet radio network with the following set of parameters:

- Coverage area (S): 6×6 [km^2]
- Nodal transmission radius (R): 0.5, 2 [km]
- Number of nodes (N): 400
- The length of control packets (L_C): 48 [*bits*]
- The length of data packets (L_D): 1024 [*bits*]
- Link data rate (R_d): 2.048, 20.48, 2048 [*kbps*]

The results of our simulations are shown on Fig. 5 and 6. The "Traffic Load" is the aggregated traffic load in the whole coverage area. The "Network Utilization" is the total number of packets being transmitted and received successfully per packet transmission time. Note that the network utilization can be greater than 1, since a number of transmissions can occur concurrently, i.e., inherent channel reuse in packet radio networks. The "Percentage of Packet Collisions" is the percentage of collided data packets among data packets transmitted.

Fig. 5(a) and 5(b) show the network utilization of DBTMA and RTS/CTS-based schemes operating under two possible transmit radii (0.5, 2 [km]) respectively and three link data rates (2.048, 20.480, 2048 [*kbps*]). The results show that the network utilization of DBTMA is about twice as much as that of RTS/CTS schemes. The reason is that when RTS/CTS-based schemes reserve a channel, they reserve both of the forward and reverse directions for transmission, while DBTMA reserve the forward channel only, leaving the reverse channel for other transmissions. The network utilization in different transmit radii differ greatly because the possible concurrent transmissions in the 6×6 [km^2] area are much larger when transmit radius is smaller.

A further observation is that the link data rate has some effects on the performance of both of these protocols. Higher data rate is responsible for some drops in the network utilization. Our explanation is that the effect of propagation delay on the network utilization is comparably longer and hence more significant at higher data rate. One may find that the degradation in percentage of network utilization due to different data rates is a bit larger in DBTMA than in RTS/CTS schemes. One of the reason is the effect of propagation delay. The propagation delay leads an important role in the performance of network utilization in DBTMA. In RTS/CTS schemes, however, the most important factor is the transmission delay of control packets and data packets, which are larger than propagation delay under normal operational environment. We can also see that the degradation in percentage of network utilization is much higher in bigger transmit radius. This is due to the fact that the propagation delay increases with the increase of transmit radius.

Fig. 5(c) and 5(d) show the percentage of packet collisions of DBTMA and RTS/CTS schemes. The percentage of packet collisions in RTS/CTS schemes, which is about 30% under heavy traffic load, is much higher than DBTMA's 0.5%. This attributes to the higher network utilization of the DBTMA protocol.

We have also run simulations to show the effect of mobility in packet radio networks. The mobility model based on the following parameters [5]:

- Speed (V): 100 [*km/hour*]
- Direction deviation (γ): 0.1 [*radian/sec*]
- Position update interval (T_M): 0.0001 [*sec*]

Fig. 6 confirms that the change in the network utilization is negligible in packet radio networks with nodal mobility.

6 Concluding Remarks

The main objective of MAC protocols is to synchronize access of multiple nodes to shared communication medium, while maintaining high network utilization. Different communication environments require different approaches to achieve this goal. In packet radio networks, some nodes can listen to some other nodes, while others can not. This condition leads to the two problems in packet radio networks: the hidden terminal problem and the exposed terminal problem.

To cure these problems, some researchers in this field have proposed to totally abandon the carrier-sensing schemes and to rely on a reservation dialogue (the RTS/CTS dialogue) among the communication nodes. Examples of such schemes are the MACA and the MACAW protocols. These schemes, indeed, provide significant improvement to the Carrier Sensing schemes. However, as demonstrated in this paper, the RTS/CTS-based protocols can still be quite vulnerable to multiple collisions, especially when the propagation and the transmission delays are long.

We have proposed here a new multiple access scheme – the Dual Busy Tone Multiple Access (DBTMA) scheme – which is based on both, the RTS/CTS dialogue and the Carrier Sensing feature. In particular, the Carrier Sensing is performed by introduction of two busy tones, which indicate the status of the shared channel in a particular geographical area. The use of two tones, rather than a single one, allows to decouple the two communication directions, thus doubling the network capacity. Use of the continuous busy tone,

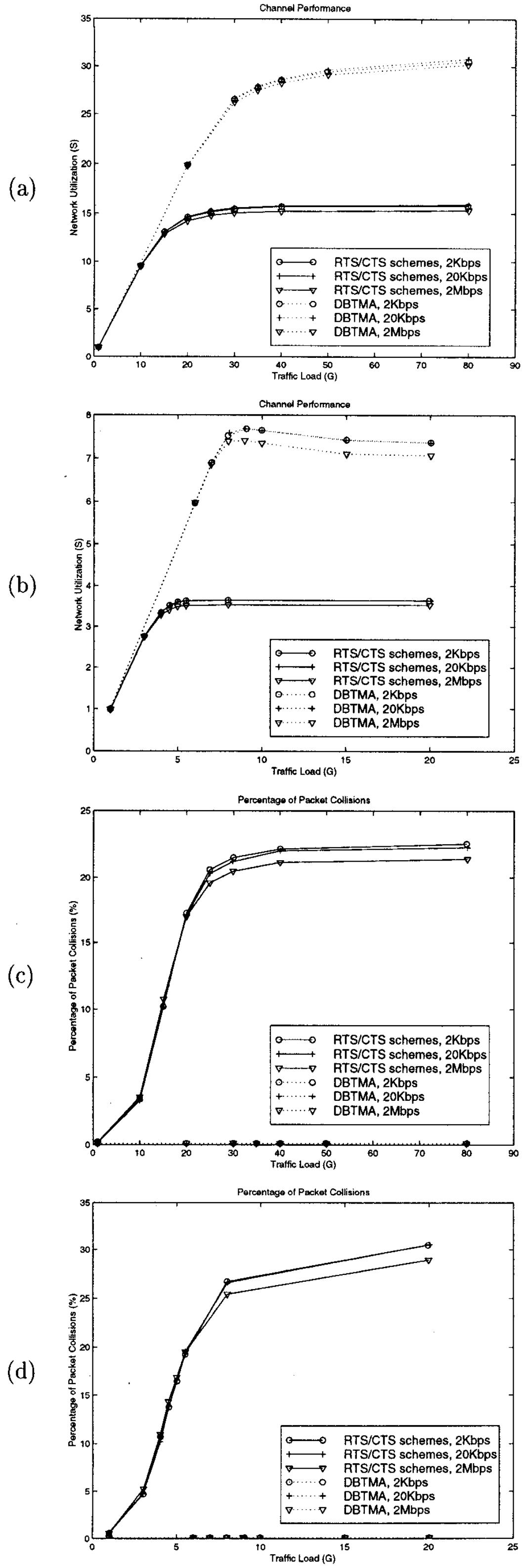


Figure 5: The Simulation Results: (a) R=0.5 (b) R=2 (c) R=0.5 (d) R=2

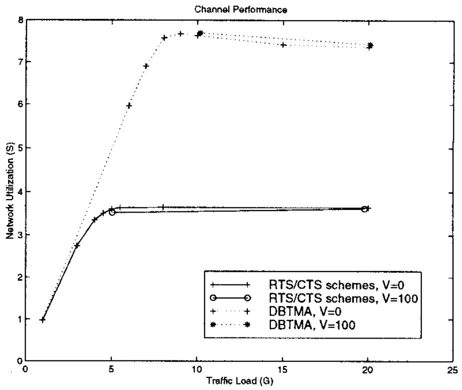


Figure 6: The Effect of Mobility

rather than the RTS/CTS messages only, allows to avoid problems associated with loss of these messages due to transmission errors and collisions. This significantly reduces the chances of destruction of the actual data packets due to transmission collisions, which further improves the scheme's utilization.

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