A SOLUTION TO HIDDEN TERMINAL PROBLEM OVER A SINGLE CHANNEL IN WIRELESS AD HOC NETWORKS

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ABSTRACT

In multihop wireless networks, hidden terminal problem is common and leads to collision which makes it difficult to provide the required quality for multimedia services or support priority-based services. Existing approaches to this problem either sacrifice throughput noticeably or require additional transceivers and channels. In this paper, we propose a new scheme in which a sender inserts a few dummy bits in the data frame and its intended receiver transmits short busy advertisements over the same channel to clear the floor for receiving. It only requires a single transceiver and a single channel. The performance analysis shows that the new scheme has a much higher efficiency than the existing approaches using a single channel and a single transceiver.

INTRODUCTION

Wireless multihop ad hoc networks, including mobile ad hoc networks, sensor networks, and wireless mesh networks, have attracted a lot of attention these years because they can support many applications in daily life as well as in military communications. In many scenarios, these networks are required to support a certain bandwidth with delay requirement or provide a high priority for some important services. However, packet loss due to the hidden terminal problem may lead to an unacceptable quality of these services. Therefore, solving the hidden terminal problem is a must to support these services.

In the hidden terminal problem, packet collision happens at the intended receiver if there is a transmission from a hidden terminal. Here, a hidden terminal is a node that cannot sense the ongoing transmission but is able to introduce enough interference to corrupt the reception if it transmits. For example in Fig. 1, there is an ongoing transmission from A to B. C is a hidden terminal of A and may transmit during the ongoing transmission from A, which leads to collision at B. Because C does not know whether A is transmitting or not, it can occupy the channel at any time and the quality of

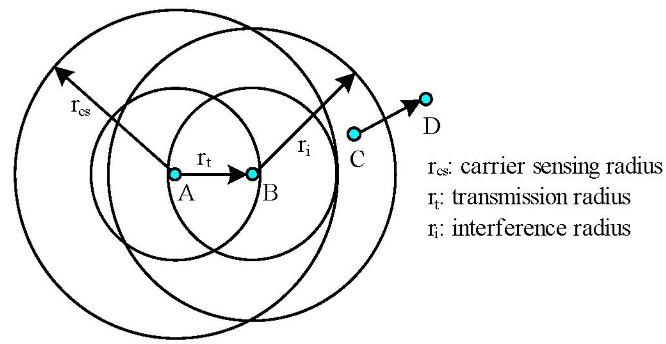

Figure 1. Hidden terminal problem

the flow from A to B cannot be guaranteed whenever there are any packets from C to D. We will illustrate more details of the hidden terminal problem and the related carrier sensing, transmission and interference ranges in Section II.

A widely studied solution to the hidden terminal problem is the out-of-band busy tone approach ([1]–[6] and references therein). Receiver sends out the busy tone signal on the busy tone channel while receiving DATA packets on the DATA channel. All nodes in the network are required to monitor the busy tone channel. If a node overhears the busy tone signal, it must keep silent to avoid possible collision. This approach can well address the hidden terminal problem, but it requires both an additional channel and an additional transceiver.

Several approaches ([6]–[9] and references therein) have also been proposed to address the hidden terminal problem without the requirement of the additional channel and transceiver. A common approach is to use a large carrier sensing range to cover the interference range around the receiver, as shown in the left part of Fig. 2. If there is no obstruct in between, all the nodes whose transmissions can interfere with the packet reception can sense the transmission from the transmitter and hence are required to keep silent to avoid collision. However, this approach decreases the spatial reuse ratio by silencing a lot of nodes that are out of the interference range of the receiver and do not interfere with the ongoing transmission and reception if

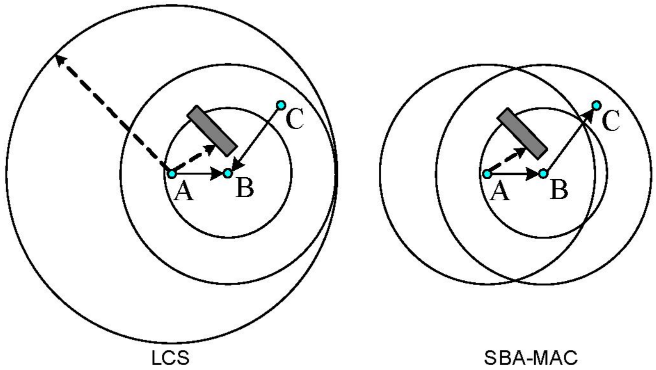

Figure 2. Carrier sensing range and interference range

they transmit. Furthermore, it does not completely solve the hidden terminal problem if there is obstruct between the nodes. For example, in Fig. 2, node C cannot sense the transmission from A for an obstruct in between and is still a hidden terminal. A variation of the approach is to maintain the same carrier sensing range but to reduce the transmission range by enforcing a higher power threshold for packet reception [7]. The basic idea is still to cover the interference range of the receiver within the carrier sensing range of the transmitter. It shares the same spatial reuse ratio and does not address the hidden terminal problem either when obstruction exists.

To address the shortcomings of the above approaches, a hidden terminal has to defer their transmissions according to a received or sensed signal/packet from the current receiver on the same channel for DATA transmission. Fullmer and Garcia-Luna-Aceves proposed a scheme FAMA in [10] to use a "CTS dominance" mechanism to ensure collision-free data packet reception. This mechanism requires nodes sensing any noise to defer their transmission long enough for a maximum-length data packet to be received. However, it may mistakenly treat collisions and any undecodable transmissions of frames other than CTS to be "CTS dominancee" and then waste the channel in the long deferral time. Yeh proposed CSMA/IB in [11] to require the receiver to transmit a short signal or inband busy tone between the received data fragments. Any nodes overhearing the signal have to defer their transmissions for a duration equal to the transmission time for a maximum data fragment. Compared to FAMA, CSMA/IB can reduce the deferral time significantly if the length of a maximum data fragment is much less than a maximum-length data packet. However, busy tone periods increase the total transmission time of a data packet. Data fragments also introduce more control overhead, like the physical and MAC layer headers [12]. The performance of CSMA/IB has not been well evaluated. How to set the length of busy tone signal and maximum data fragment, and what their impact is on the performance deserve careful studies.

In this paper, we propose a new MAC scheme using dummy bits and short busy advertisement (SBA) signals based on the CSMA/CA (carrier sense multiple access with collision avoidance) or the IEEE 802.11 MAC scheme. In the basic SBA-MAC scheme, several short periods of dummy bits are inserted in the DATA frame. During these periods, the receiver switches to the transmission mode and transmit a short busy advertisement consisting of synchronization symbols, and then switches back to continue the packet reception. A node defers its transmission for a BIFS (interframe spacing due to busy advertisement) period after detecting a SBA signal or any noise. We analyze the performance of the SBA-MAC scheme and study the impact of the length of BIFS on the system performance. The results show that SBA-MAC can significantly outperform the previous approaches using a single channel.

The rest of this paper is organized as follows. Section II details various ranges and the hidden terminal problem. The SBA-MAC scheme is proposed in Section III. We analyze and evaluate the performance of the proposed scheme in Section IV. Finally, we conclude the paper in Section V.

VARIOUS RANGES AND THE HIDDEN TERMINAL PROBLEM

In this section, we illustrate the definitions of carrier sensing range, transmission or communication range, and interference range, and what is their impact on the hidden terminal problem. Notice that all these ranges are determined by some thresholds of the power level of the received or sensed signal.

A. Communication, Carrier Sensing, and Interference Ranges

Communication range sometimes is also called as *transmission range*. It indicates an area around one node where all other nodes can correctly receive the packet transmitted by this node if there is no other interference signals. It is determined by the receiver sensitivity P_{se}. At the edge of the range, the received signal from the node in the center has a power level equal to the receiver sensitivity.

Carrier sensing range indicates an area around one node where all other nodes can sense the transmission from this node. It is determined by the carrier sensing threshold P_{cs}. At the edge of the range, the received signal from the node in the center has a power level equal to the carrier sensing threshold. Any node other than the intended receiver in this range which sense the transmission from the node at the center of the range indicates a busy channel to the MAC layer and hence is required not to transmit.

Interference range indicates an area around one node where another transmission can interfere with reception at this node so that it fails to receive the packet correctly from the intended transmitter. This range is determined by both received power of the intended packet and the signal to interference plus noise ratio (SNR). If there is no other transmission in this range and interference only comes from a transmission outside of this range, the receiver should have an SNR larger than the requirement for correct reception. The larger the received power of the intended signal is, the smaller the range is. We refer to the range as a *typical interference range* when the received power is equal to the receiver sensitivity. Apparently, the typical interference range is larger than the interference range for a received power larger than the receiver sensitivity. The interference range can be determined by the maximum allowable interference power P_i (or P_i^* for the typical interference range) and

$$P_i = \frac{P_r}{SNR}, \ P_i^* = \frac{P_{se}}{SNR} \tag{1}$$

where P_r is the received power of the intended packet at the current receiver. If we assume that every node uses the same transmission power, under the protocol model [13] we have

$$d_i = d_h SNR^{\frac{1}{\gamma}}, \ d_i^* = d_t SNR^{\frac{1}{\gamma}} \tag{2}$$

where d_i is the radius of the interference range, d_h is the distance between the current transmitter and its intended receiver or simply hop distance of the current hop/link, d_i^* is the radius of the typical interference range, γ is the path loss exponent, and d_t is the maximum communication distance.

Normally, SNR is required to be larger than $0dB$ for correct reception. Therefore, a typical interference range is larger than the communication range. In the default settings in the widely used simulation tools ns2, the carrier sensing radius is 2.2 times of the transmission radius, and the interference radius is about 1.78 times of the transmission radius when the capture threshold is set as 10dB.

B. Hidden Terminal Problem

A hidden terminal of a transmitter cannot sense the transmission, but its transmission interferes with the packet reception at the current receiver. Therefore, if a hidden terminal begins to transmit during the ongoing transmission, the current receiver will fail to receive the packet. That is to say, there is a collision at the receiver. Hidden terminal problem is the collision problem due to transmissions from one or more hidden terminals.

Now it is clear that in Fig. 1 and 2, node C is a hidden terminal of node A. It cannot sense A's transmission and hence it is allowed to transmit. However, it is in the interference range of node B and therefore it will interfere with the packet reception at B if it transmits.

ADDRESSING HIDDEN TERMINAL PROBLEM WITH SHORT BUSY ADVERTISEMENT SIGNAL

In this section, we introduce the SBA-MAC scheme. We first explain the basic operations at a transmitter, a receiver and other neighboring nodes. Then we study how to construct a short busy advertisement signal and how to set various parameters in the SBA-MAC scheme. Finally, we discuss why this scheme can greatly increase the spatial reuse ratio.

A. Basic Operations in the SBA Procedure

In the SBA procedure a transmitter divides the payload of the DATA frame into several parts or fragments and inserts a small block of bits between two adjacent fragments. These bits are dummy bits and can be equal to any values. A transmission period of these dummy bits is referred to as *an intra-data-frame spacing* or *an inter-data-fragment spacing* (IDFS).

During an IDFS period, the intended receiver ignores the received signal, sends out a *busy advertisement signal* over the same channel to notify its hidden terminals of the ongoing transmission, and then switches back to continue the packet reception. The corresponding message sequence is shown in Fig. 3.

To protect the data fragments, any device sensing the busy advertisement signal in the typical interference range (i.e. the sensed power is larger than P_i^*, refer to Section II-A) should keep silent for a certain period. We refer to this period as a BIFS period, or *an interframe spacing due to a busy advertisement signal*. Apparently, to guarantee an error-free reception of the data fragment, BIFS should be large enough for a maximum-length data fragment to be received. Since the busy advertisement is also subject to collision, a node sensing any interference signal with a power larger than P_i^* is also required to defer its transmission for at least a BIFS period.

B. Parameters in SBA Procedure

Let T_{IDFS} denote the length of an IDFS period. T_{IDFS} must be large enough for the receiver to switch from receiving mode to transmitting mode, to send out a busy advertisement signal, and to switch back to receiving mode.

$$\begin{aligned} T_{IDFS} &= T_{RT} + T_{BA} + T_{TR} \\ T_{RT} &\leq T_{SIFS} \\ T_{BA} &\geq T_{aCCATime} \\ T_{TR} &\leq T_{SIFS} \end{aligned} \tag{3}$$

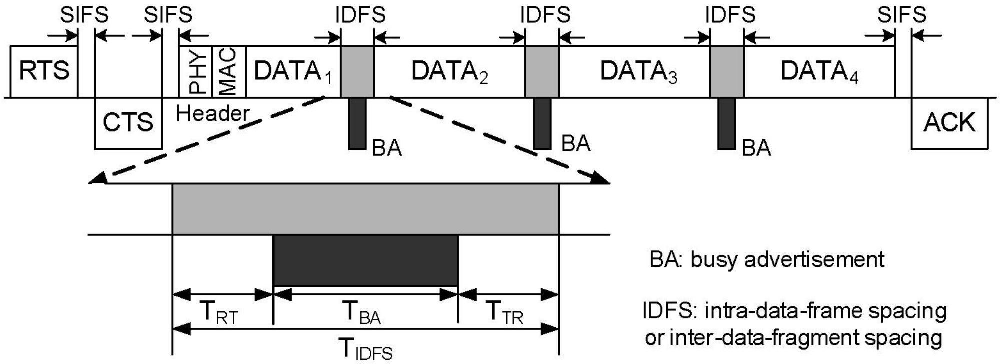

Figure 3. Four-way handshake with busy advertisement signals

T_{RT} is the time that the MAC and PHY (physical layer) require to switch from receiving mode to transmitting mode. T_{BA} is the time that the device requires to send out a busy advertisement which is long enough for other devices to sense. T_{TR} is the time that the MAC and PHY require to switch from transmitting mode to receiving mode. As defined in the IEEE 802.11 standards, $T_{aCCATime}$ is the minimum time for the CCA (clear channel assessment) mechanism to assess the medium and to determine whether the medium is busy or idle. A short interframe space (SIFS), also defined in the IEEE 802.11 standards, is long enough for a T_{RT} or a T_{TR} between an incoming frame and an outgoing frame or vice versa. Since the receiver does not need any response from other devices during an IDFS period, which is required in SIFS in the original four-way handshake, it is possible for T_{RT} or T_{TR} to be less than $SIFS$, which depends on implementation of the physical layer ([12], [14]–[16]).

Let T_{BIFS} be the length of a BIFS period. Notice that an EIFS procedure is adopted in the IEEE 802.11 MAC protocol. A node is required to keep silent for at least an EIFS period if it detects some undecodable signal. The EIFS period is used to protect the reception of an ACK frame. To provide the same function, the BIFS procedure replaces the original EIFS procedure, but T_{BIFS} should be larger than or equal to T_{EIFS}. Since a node only knows that it is the intended receiver after it receives the physical and MAC headers, BIFS should be large enough to protect the reception of these headers. So

$$T_{BIFS} \geq max(T_{EIFS}, T_{PHY} + T_{MAC} + T_{SIFS} + 2T_{prop} + T_{RT}) \tag{4}$$

where T_{PHY} and T_{MAC} are the transmission time for the physical header and the MAC header, respectively. T_{prop} is the maximum propagation delay between two communicating nodes. On the another hand, T_{BIFS} must be larger than or equal to the maximum transmission time of a data fragment. Notice that between two consecutive busy advertisement signals, the receiver needs to consume time T_{TR} and T_{RT} besides the time for reception of a DATA fragment. Therefore, to keep a hidden terminal silent, the transmission time for a DATA fragment T_{frag} must satify

$$T_{frag} \leq T_{BIFS} - T_{RT} - T_{TR} \tag{5}$$

if it is not the last fragment, and

$$T_{frag} \leq T_{BIFS} - T_{TR} \tag{6}$$

otherwise. Accordingly, a transmitter divides a data frame into one or more fragment and places some dummy bits in between as shown in Fig. 4. The number of IDFS periods should be as small as possible while satisfying the above equations. Details of the algorithm to calculate the positions of IDFS periods are omitted here due to page limit.

C. Busy Advertisement Signal

The busy advertisement signal can be the training symbols in a physical layer preamble, as long as it is longer enough for other devices to sense, i.e. larger than or equal to $T_{aCCATime}$. Since the preamble is transmitted with the lowest basic rate following a certain pattern, it is much easier to detect it than many other signals. The busy advertisement signal can also be any other well defined signals to facilitate the detection and differentiation of it from other signals.

D. Synchronization Issue

When the receiver receives the first DATA fragment, it is synchronized with the physical layer preamble of the fragment. It needs to keep the synchronized clock information or store it somehow during $IDFS$, and uses it to decode subsequent data fragments after an IDFS period. This clock signal can be used to send out the busy advertisement signal. As long as it is still synchronized with the received signal when it switches back to receiving mode. This means that the subsequent data fragments do not need to carry a physical and MAC layer header like at the head of the whole data frame. The transmitter can also choose to insert a short

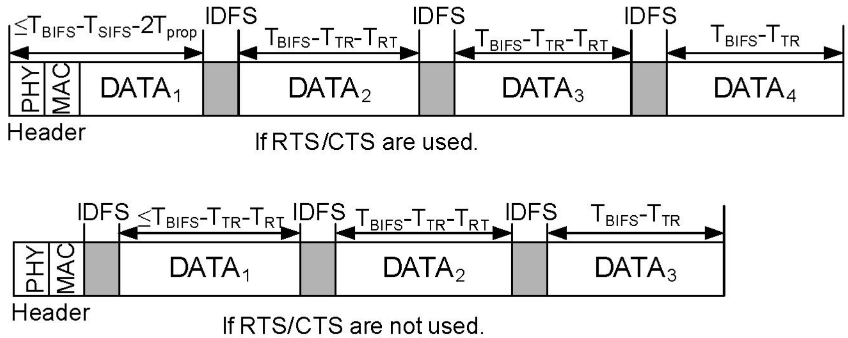

Figure 4. Positions of IDFS Periods in the DATA Frame

period of training symbols before each fragment to facilitate the receiver to be synchronized again after the transmission of a busy advertisement signal. All the data fragments share the same information in the physical and MAC layer header at the beginning of the data frame.

A transmitter can choose not to send the dummy bits during IDFS periods to save a little energy as long as the silent periods do not result in the loss of synchronization information for the subsequent data fragments to be received at the receiver.

E. Carrier Sensing Range

In the proposed scheme, we set the carrier sensing range with the same size as that of the typical interference range (refer to Section II-A) as shown in the right part of Fig. 2.

$$P_{cs} = P_i^* \tag{7}$$

Any node senses a signal with a power level larger than the typical interference power P_i^* should indicate a busy channel and defer its transmission. If one node senses an undecodable signal or a busy advertisement signal with a power level larger than P_i^*, it is required to keep silent for at least a BIFS period after the signal is finished.

In this way, a busy advertisement signal only silences those hidden terminals interfering with the current packet reception. On the other hand, nodes outside of the typical interference range of the transmitter are allowed to initiate a new transmission. Compared to the approach using a large carrier sensing range as shown in the left part of Fig. 2, our approach allows more concurrent transmissions and hence can significantly increase the spatial reuse.

Virtual carrier sensing mechanism is still being used. That is to say, if one node overhears and correctly decode a MAC frame, like RTS, CTS, DATA, and ACK frames, it keeps silent during the period indicated in the duration field of the frame.

F. CTS Dominance

A hidden terminal problem may transmit a RTS frame at the same time when the current receiver transmits a CTS frame. Since the length of a RTS frame is larger than that of a CTS frame [12], the header part of the data frame may collide with the tail part of the RTS frame from a hidden terminal at the current receiver if the transmission of these two frames begin at the same time. To avoid this type of hidden terminal problem and ensure an error-free data reception, a new CTS frame longer than a RTS frame should be used like that in the FAMA scheme [10]. Thus in the above scenario, the hidden terminal can sense the tail part of a CTS frame and hence defer its own transmission according to the carrier sensing mechanism.

PERFORMANCE ANALYSIS AND PARAMETERS SELECTION

A. Spatial Reuse Ratio

Due to the carrier sensing requirement, there is a certain area around the transmitter and the receiver where no other communication is allowed. In SBA-MAC, this area is the interference range around the transmitter and the receiver. It is easy to show that the area S_{ba} is equal to

$$S_{ba} = 2(\pi - \arccos(\frac{d_h}{2d_i}))d_i^2 + d_i d_h \sqrt{1 - (\frac{d_h}{2d_i})^2} \tag{8}$$

In the approach using a large carrier sensing range as shown in the left side of Fig. 2, the area occupied by each transmission is S_{lcs} and

$$S_{lcs} = \pi d_{cs}^2 = \pi(d_t + d_i)^2 \tag{9}$$

B. Protocol Overhead

In the subsection, we only discuss four-way handshake with RTS/CTS. Similar analysis can be applied to two-way handshake without RTS/CTS.

In SBA-MAC, the transmission time of a data packet is increased due to the inserted dummy bits. Let N_{ba}

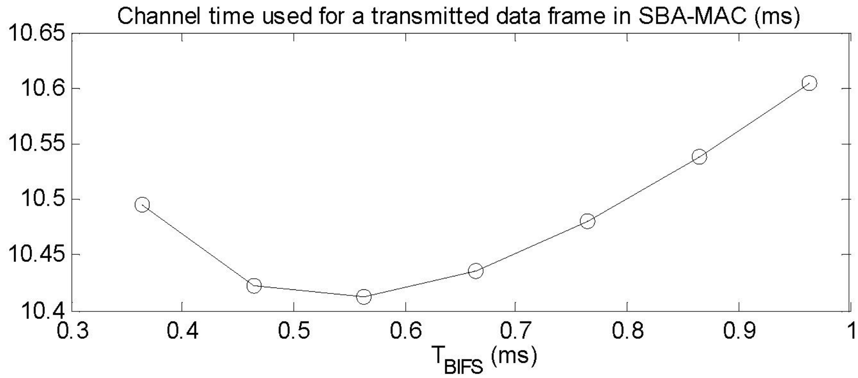

Figure 5. Channel time for a transmitted packet in SBA-MAC

be the number of inserted IDFS periods. Notice that the channel time T_{pba} used for each data packet also includes the backoff period and the deferral time T_{BIFS} due to the sensed undecodable signals, which is also increased if BIFS is longer than EIFS. Let p_{ba} be the probability that a node near the current transmission defers T_{BIFS}, successfully contends for the channel and begins to transmit after the current transmission is finished. Then $1 - p_{ba}$ is the probability that the transmission opportunity is obtained by the current transmitter or receiver, or any another node that correctly overhears the current transmission. Now, we can obtain

$$\begin{aligned} T_{pba} &= T_{backoff} + T_{RTS} + T_{CTS} + T_{ACK} + 3T_{SIFS} + \\ & \quad T_{DIFS} + N_{ba}T_{IDFS} + T_{DATA} + p_{ba}T_{BIFS} \end{aligned} \quad (10)$$

According to the procedure in Section III-B, we have

$$N_{BA} \approx \frac{T_{DATA} - T_{PHY} - T_{MAC}}{T_{BIFS} - T_{RT} - T_{TR}} \quad (11)$$

It is easy to show that when

$$T_{BIFS} = \sqrt{\frac{(T_{DATA} - T_{PHY} - T_{MAC})T_{IDFS}}{p_{ba}}} \quad (12)$$

T_{pba} is minimized, and the minimum value is

$$\begin{aligned} min(T_{pba}) = T_{backoff} + T_{RTS} + T_{CTS} + T_{ACK} + \\ 3T_{SIFS} + T_{DIFS} + T_{DATA} + \\ 2\sqrt{p_{ba}(T_{DATA} - T_{PHY} - T_{MAC})T_{IDFS}} \end{aligned} \quad (13)$$

In the FAMA scheme [10], we assume that FAMA uses the same carrier sensing range to obtain good spatial reuse ratio as in SBA-MAC. Similarly with p_{ba}, we define it as p_{fama} in FAMA. The channel time T_{pfama} used for each data packet in FAMA is

$$\begin{aligned} T_{pfama} = T_{backoff} + T_{RTS} + T_{CTS} + T_{ACK} + \\ 3T_{SIFS} + T_{DIFS} + T_{DATA} + p_{fama}max\{T_{DATA}\} \end{aligned} \quad (14)$$

Similarly, the channel time T_{plcs} used for each data packet in the approach using a large carrier sensing range is equal to

$$\begin{aligned} T_{lcs} &= T_{backoff} + T_{RTS} + T_{CTS} + T_{ACK} + 3T_{SIFS} + \\ & \quad T_{DIFS} + T_{DATA} + p_{lcs}T_{EIFS} \end{aligned} \quad (15)$$

Since $S_{lcs} > S_{ba}$, there are more nodes that sense undecodable signals. That is to say,

$$p_{lcs} \geq p_{ba} \quad (16)$$

Now we can calculate the gain of SBA-MAC compared with the approach using a large carrier sensing range is

$$K_{sba-lcs} = \frac{S_{lcs}}{S_{ba}}\frac{T_{lcs}}{T_{pba}}, \; K_{sba-fama} = \frac{T_{fama}}{T_{pba}} \quad (17)$$

C. Numerical Results

In this subsection, we adopt the system parameters in the IEEE 802.11b standard. $T_{aCCATime} \leq 15\mu s$, SNR requirement is 10dB, $T_{IDFS} = 2T_{SIFS} + T_{aCCATime} = 35\mu s$, $T_{EIFS} = 364\mu s$, $T_{RTS} = 352\mu s$, $T_{CTS} = 304\mu s$, and $T_{ACK} = 304\mu s$.

We set $p_{ba} = p_{fama} = p_{lcs} = 1$, $max\{T_{DATA}\} = 10ms$, and $d_h = d_t$. Fig. 5 shows the channel time for a transmitted data packet in SBA-MAC when $T_{DATA} = 8ms$. We can see that T_{pba} only changes by up to 1.9% when T_{BIFS} is from 364 μs to 964 μs although there is apparently an optimal value of T_{BIFS}. When $T_{BIFS} = T_{EIFS} = 364\mu s$, we plot the performance gain $K_{sba-lcs}$ and $K_{sba-fama}$ in the Figure 6. We can see that SBA-MAC can improve the throughput by 44% to 53% when T_{DATA} is from 10 to 1 ms compared to the approach using a large carrier sensing range. The improvement is about 68% to 344% compared to the FAMA scheme.

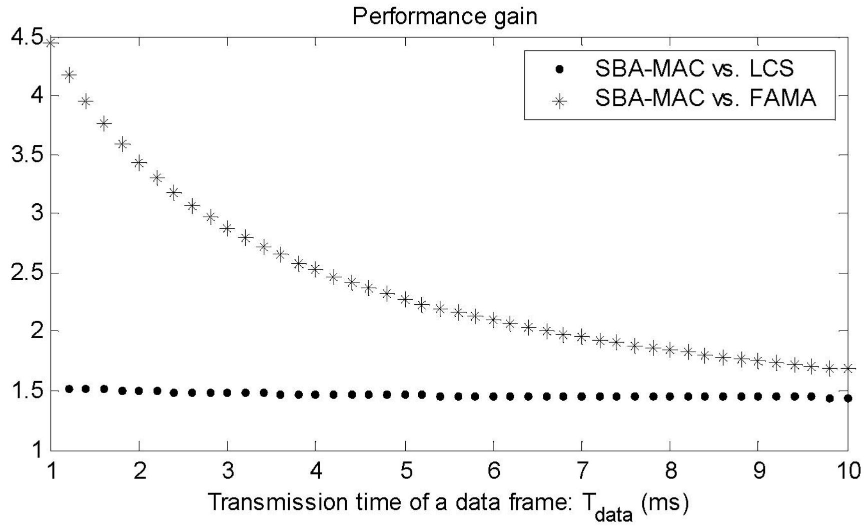

Figure 6. Performance gain of SBA-MAC compared to the approach using a large carrier sensing range and the FAMA scheme

CONCLUSIONS

In this paper, we propose a new SBA-MAC scheme to solve the hidden terminal problem without using out-band signaling. The new scheme is based on the CSMA/CA or the IEEE 802.11 MAC scheme. Some dummy bits are inserted in the data frame. During the periods of these dummy bits, the receiver sends out short busy advertisement signals to notify hidden terminals of the current transmission so that the latter defer their transmissions to avoid collision. Although SBA-MAC protocol increases the transmission time of each data frame, it greatly increases the spatial reuse ratio and well address the hidden terminal problem. The performance results show that SBA-MAC noticeably outperforms the existing approaches addressing the hidden terminal problem.

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