Intelligent Medium Access for Mobile *Ad Hoc* Networks with Busy Tones and Power Control

Shih-Lin Wu, Yu-Chee Tseng, *Member, IEEE*, and Jang-Ping Sheu, *Senior Member, IEEE*

***Abstract*—In *mobile ad hoc networks (MANETs)*, one essential issue is how to increase channel utilization while avoiding the *hidden-terminal* and the *exposed-terminal* problems. Several MAC protocols, such as *RTS/CTS-based* and *busy-tone-based* schemes, have been proposed to alleviate these problems. In this paper, we explore the possibility of combining the concept of *power control* with the RTS/CTS-based and busy-tone-based protocols to further increase channel utilization. A sender will use an appropriate power level to transmit its packets so as to increase the possibility of channel reuse. The possibility of using discrete, instead of continuous, power levels is also discussed. Through analyses and simulations, we demonstrate the advantage of our new MAC protocol. This, together with the extra benefits such as saving battery energy and reducing cochannel interference, does show a promising direction to enhance the performance of MANET's.**

***Index Terms*—MANET, medium access control (MAC), mobile *ad hoc* network, power control, RTS/CTS, wireless network.**

I. Introduction

A *MOBILE ad hoc network (MANET)* is formed by a cluster of mobile hosts and can be rapidly deployed without any established infrastructure or centralized administration. Due to the transmission range constraint of transceivers, two mobile hosts can communicate with each other either directly, if they are close enough, or indirectly, by having other intermediate mobile hosts relay their packets. The applications of MANETs appear in places where infrastructure networks are difficult to build or unavailable (e.g., fleets in oceans, armies in march, natural disasters, battle fields, festival field grounds, and historic sites). A working group called MANET has been formed by the Internet Engineering Task Force (IETF) to stimulate research in this direction [11].

In a MANET, it is well known that the hidden-terminal problem and exposed-terminal problem can severely reduce channel utilization [15]. To relieve these problems, many protocols based on RTS/CTS dialogues have been proposed [2], [4], [8], [10], [14]. However, as shown in [3], when the traffic load is heavy, a data packet may still experience collision with probability as high as 60% due to loss of RTS or CTS packets. This is especially serious if the propagation and the transmission delays are long. To alleviate this problem, a scheme using special signals similar to carrier sense, called *busy tones*, is proposed to prevent other mobile hosts unaware of the earlier RTS/CTS dialogues from destroying the ongoing transmission [3], [15]. It is shown that the channel utilization can be doubled [3].

In this paper, we try to bring the concept of *power control* into the medium access problem in a MANET. A new MAC protocol that combines the mechanisms of power control, RTS/CTS dialogue, and busy tones is proposed. The main idea is to use the exchange RTS and CTS packets between two intending communicators to determine their relative distance. This information is then utilized to constrain the power level on which a mobile host transmits its data packets. Using lower power can increase channel reuse, and thus channel utilization. It also saves the precious battery energy of portable devices and reduces cochannel interference with other neighbor hosts. There are two ways a mobile host can predict another host's relative location. The simplest way is to use GPS (global positioning system) [7], which is very economical nowadays but is more appropriate for outdoor use. The other, which our paper is based on, is to use the signal strengths on which RTS/CTS packets are received to estimate the distance.

In this paper, we show through analyses and simulations how power control can help to increase channel utilization in a MANET. Significant gains are shown to be obtainable using power control over the *dual busy tone multiple access (DBTMA)* protocol [3]. So the outlook of using power control is promising to enhance the performance of a MANET. For practical and implementation concerns, we also consider the possibility of using *discrete*, instead of *continuous*, power levels for transmission. Specifically, given a constant k, we show how to determine k levels of power that can exploit the best channel utilization.

The rest of this paper is organized as follows. In Section II, we briefly review two existing MAC protocols. Our newly proposed protocol is presented in Section III. Section IV demonstrates the advantage of our protocol through analysis. How to use discrete power levels is discussed in Section V. Simulation results are in Section VI and conclusions are drawn in Section VII.

II. Review of Some MAC Protocols

In this section, we review the RTS/CTS-based protocol, and then the DBTMA [3].

Manuscript received September 23, 1999; revised March 3, 2000. This work was supported in part by the National Science Council of the Republic of China under Grant NSC88-2213-E-008-024 and by the Ministry of Education of the Republic of China under Grant 89-H-FA07-1-4. A preliminary version of this paper appeared in the *Proc. Int. Conf. Computer Commun. Networks*, 1999.

S.-L. Wu and J.-P. Sheu are with the Department of Computer Science and Information Engineering, National Central University, Chung-Li, 32054 Taiwan (e-mail: ken@csie.ncu.edu.tw; sheujp@csie.ncu.edu.tw).

Y.-C. Tseng is with the Department of Computer Science and Information Engineering, National Chiao-Tung University, Hsin-Chu 30050, Taiwan (e-mail: yctseng@csie.nctu.edu.tw).

Publisher Item Identifier S 0733-8716(00)07134-1.

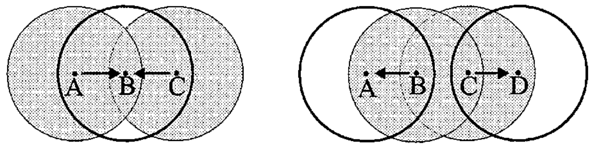

Fig. 1. Scenarios to show (a) the hidden-terminal problem and (b) the exposed-terminal problem.

A. RTS/CTS-Based Protocols

In a MANET, a MAC protocol has to contend with the *hidden-terminal* and the *exposed-terminal* problems. To see the first problem, consider the scenario of three mobile hosts in Fig. 1(a). Hosts A and B are within each other's transmission range, and so do hosts B and C. However, A and C cannot hear each other. When A is transmitting to B, since host C cannot sense A's transmission, it may falsely conclude that the medium is free and transmit, thus destroying A's ongoing packets. The problem that a station cannot detect a potential competitor because the competitor is too far away is called the *hidden-terminal* problem.

In Fig. 1(b), when B is transmitting to A, host C can sense the medium and thus will conclude that it cannot transmit. However, if C's intended recipient is D, then such transmission can actually be granted. Such inefficiency in channel use is called the *exposed-terminal* problem.

To alleviate these problems, a number of protocols have been proposed based on sending RTS (request to send) and CTS (clear to send) packets before the data transmission actually takes place [2], [4], [8], [10]. When a node wishes to transmit a packet to a neighbor, it first transmits an RTS packet. The receiver then consents to the communication by replying a CTS packet. On hearing the CTS, the sender can go on transmitting its data packet. The hidden-terminal problem in Fig. 1(a) will be eliminated when C hears the CTS packet, and the exposed-terminal problem in Fig. 1(b) will be eliminated if we grant C to transmit if it can hear B's RTS but not A's CTS. Such an approach has been accepted by the IEEE 802.11 standard [1]. In IEEE 802.11, a field called NAV (network allocation vector) is added in the RTS/CTS packets to indicate the expected transmit/receive time of the data packet.

B. RTS/CTS Dialogue Enhanced with Busy Tones

Although the RTS/CTS dialogue can alleviate some hidden- and exposed-terminal problems, as observed in [3], when propagation and transmission delays are long, the CTS packets can easily be destroyed. This will result in destruction of data packets when traffic load is heavy. Consider the scenario in Fig. 2(a). Node A sends an RTS to B, which in turn replies a CTS to A. Meanwhile, as host C cannot hear A's RTS, it may send an RTS (to start a transmission with D) or a CTS (to respond to E's RTS). In either case, D can hear neither C's nor B's RTS/CTS, but the transmission from A and B will continue as normal. If later D decides to send any packet while A is transmitting to B, the packet will be destroyed at B. As analyzed in [3], the probability of data packets experiencing collision will be as high as 60% when traffic load is high.

To resolve the above problem, a protocol called *DBTMA (dual busy tone multiple access)* is proposed [3], [5]. The single common channel is split into two subchannels: a data channel and a control channel. The control channel is to transmit RTS/CTS dialogues. Also, two narrow-band busy tones, called *transmit busy tone* (BT_t) and *receive busy tone* (BT_r), are placed on the spectrum at different frequencies with enough separation. Fig. 3 shows a possible spectrum allocation.

The purpose of busy tones is to add a capability similar to carrier sense to transceivers—BT_t is to indicate that a host is transmitting, while BT_r shows that a host is receiving. A sending host must turn its BT_t on when transmitting a data packet, and a receiving host must turn its BT_r on when it replies to the sender with a CTS. When a host wants to send an RTS, it has to make sure that there is no BT_r around it. Conversely, to reply to a CTS, a host must make sure that there is no BT_t around it. So in the scenario of Fig. 2(a), host D will be aware of, through B's BT_r, B's receiving activity. Fig. 2(b) illustrates this scenario—B's BT_r will prohibit C's RTS/CTS.

In summary, a simple rule is used in DBTMA: a host should not send if it hears any BT_r, and should not consent to send if it hears any BT_t. As a final comment, it is also possible to use busy tones to save power [13], but this is beyond the scope of this paper.

III. A New MAC Protocol with Power Control

In this section, we show how to enhance the DBTMA protocol [3], [5] with power control. Using smaller transmission power may increase channel reuse in a physical area. To motivate our work, consider Fig. 4(a), where a communication from A to B is ongoing. The communication from C to D cannot be granted because D can hear A's BT_t, and similarly that from E to F cannot be granted because E can hear B's BT_r. However, as shown in Fig. 4(b), if we can properly tune each transmitter's power level, all communication pairs can coexist without any interference.

The following discussion gives a basic idea how to incorporate power control into the original protocol. First, we should enforce A to transmit its data packet and BT_t at a minimal power level, but keep B's BT_r at the normal (largest) power level. When C wants to communicate with D, C senses no BT_r, so it can send an RTS to D. At this moment, D hears no BT_t, so D can reply with a CTS to C. Now if C appropriately adjusts its transmission power, the communication from C to D will not corrupt the transmission from A to B. The communication from E to F deserves more attention. At this time, E can sense B's BT_r. Ideally, E should send an RTS to invite F with a power level that is sufficiently large to reach F but not B. The basic idea is that E's yet-to-be-transmitted data packet should not corrupt B's reception. Host F, which must be closer to E than B is, will reply with a CTS. This causes no problem as F hears no BT_t. Then the communication from E to F can be started.

To summarize, the rules in our protocol are: 1) data packet and BT_t are transmitted with power control based on the power level of the received CTS, 2) CTS and BT_r are transmitted at the normal (largest) power level, and 3) RTS is transmitted at

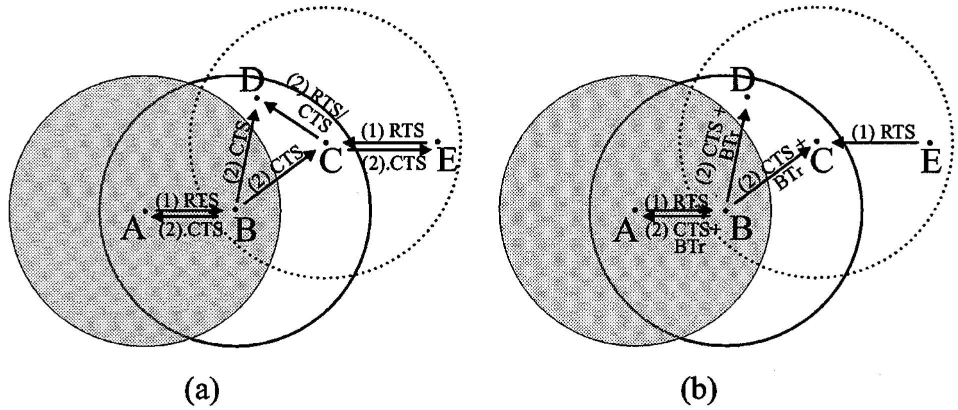

Fig. 2. (a) A scenario that B's CTS is destroyed at D by C's RTS/CTS. (b) Using busy tones to resolve the CTS destroyed problem.

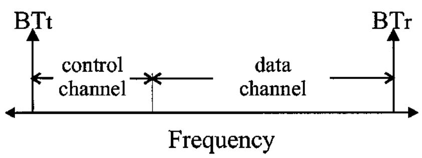

Fig. 3. Frequency chart of the DBTMA protocol.

a power level to be determined based on how strong the BT_r tones are around the requesting host.

In the following, we first demonstrate how power control can increase channel utilization under an ideal situation. Then we discuss the fundamentals to tune transmission power, followed by a formal description of our protocol.

A. Benefit of Channel Reuse by Power Control

At this point, we try to predict, under ideal situations, how much benefit power control can offer. We have developed a simple simulation without caring how the MAC protocol is designed (such as carrier sense, backoff, contention, delay, etc.). We simulated an area of size 500 $\times$ 500. On the area, we randomly generated a sender A and then randomly generated a receiver B within the circle of radius $r_{\max}$ centered at A, where $r_{\max} = 50$ is the maximum transmission distance of a host. Two models were assumed: 1) A sends to B with the maximum power, and 2) A sends to B with a smallest power such that B can receive correctly. We repeated this process to generate more sender–receiver pairs. Whenever a sender–receiver pair was generated, based on its surroundings, we then tested whether this pair will interfere any ongoing communication pair or not. If not, this pair was granted; otherwise, it was dropped.

A total of 200–1800 sender–receiver pairs were generated. We observed the number of communication pairs that were granted in the area based on the two models. The result is shown in Fig. 5, where each point is from the average of 1000 simulations. The x-axis shows the number of sender–receiver pairs being generated, and the y-axis those that were granted. In some sense, this experiment shows the number of sender–receiver pairs that can coexist in a physical area with and without power control. This can be interpreted as the amount of *channel reuse* that can be offered with and without power control. As can be seen, power control can grant about 1.5 times that of the communication pairs without power control.

B. Tuning Power Levels

In the following, we discuss how our protocol determines a power level to transmit a packet or a busy tone. We make the following assumptions.

1) *Transmission Power:* A mobile host can choose at what power level to transmit a packet. This function should be offered by the physical layer.
2) *Signal Strength:* On receiving a packet, the physical layer can offer the MAC layer the power level at which the packet was received.

Now, suppose a source host transmits a packet to a destination host. Let P_t and P_r be the power levels at which the packet is transmitted and received on the sender and receiver sides, respectively. Then the following equation holds (refer to [16, Ch. 2]):

$$P_r = P_t \left(\frac{\lambda}{4\pi d}\right)^n g_t g_r \quad (1)$$

where

λ	carrier wavelength;
d	distance between the sender and the receiver;
n	path loss coefficient;
g_t and g_r	antenna gains at the sender and the receiver, respectively.

Note that λ, g_t, and g_r are constants in normal situations. The value of n is typically 2, but may vary between 2 and 6 depending on the physical environment, such as existence of walls, cabinets, or obstacles.

One important factor that our protocol relies on is that during a very short period, the values of d and n can be treated as constants. This makes possible choosing appropriate power levels to transmit packets, even if the values of d and n are *unknown*. For instance, suppose host X transmits an RTS with power P_t to host Y, who receives the packet with power P_r. If Y wants to reply a CTS to X at a certain power level $P_{\rm CTS}$ such that X's receiving power is the smallest possible, say $P_{\min}$, then we have

$$P_{\min} = P_{\rm CTS} \left(\frac{\lambda}{4\pi d}\right)^n g_t g_r. \quad (2)$$

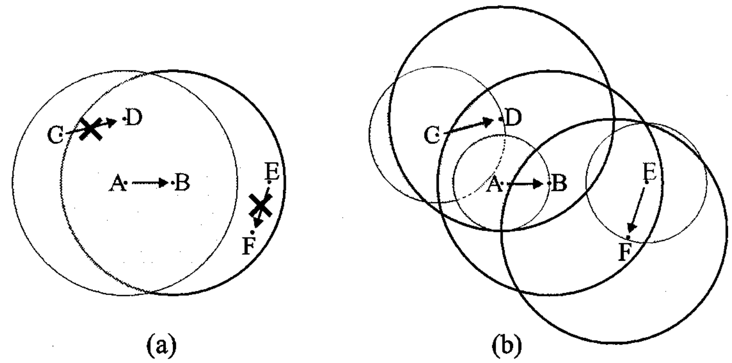

Fig. 4. Transmission scenarios (a) when there is no power control and (b) when there is power control. Transmit busy tones are shown in gray, and receive busy tones are shown in white.

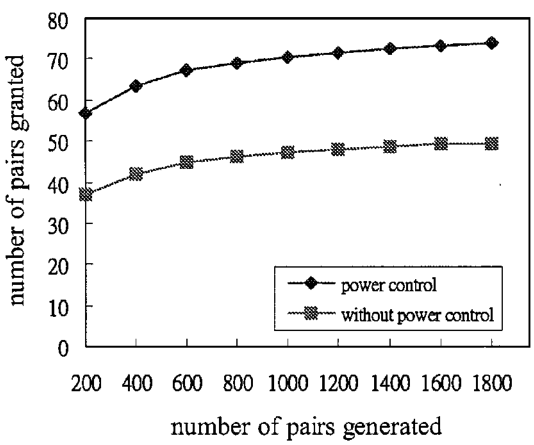

Fig. 5. Experiments on channel reuse: the number of sender–receiver pairs that can coexist in a 500 × 500 area with and without power control. The maximum transmission distance is 50 units.

Dividing (2) by (1), we have

$$\frac{P_{\min}}{P_r} = \frac{P_{\rm CTS}}{P_t}.$$

Thus, Y can determine the power level $P_{\rm CTS} = P_t P_{\min}/P_r$ even if d and n are unknown.

In practice, the level of power to transmit packets does not have to be infinitely tunable. Offering only certain discrete values may simplify hardware design. This possibility will be explored in Section V. Also, to take transmission reliability into account, the real transmission power in the above example should be larger than $P_{\rm CTS}$ by a certain level.

C. The MAC Protocol

Below, we show how to incorporate power control into the DBTMA protocol [3], [5]. The main idea is to use the exchange of RTS/CTS packets to determine which power level to transmit. The following notations regarding power levels will be used.

- $P_{\max}$: the maximum transmission power.
- $P_{\min}$: the minimum power level for a host to distinguish a signal from a noise.
- $P_{\rm noise}$: a power level under which an antenna will regard a signal as a noise ($P_{\rm noise}$ should be less than $P_{\min}$ by some constant; ideally, we assume that $P_{\min} - P_{\rm noise}$ is a very small value).

The complete protocol is formally described below.

1) On a host X intending to send an RTS to host Y, host X should sense any receive busy tone BT_r around it and send an *RTS* on the control channel at power level P_x as determined below.
   - If there is no receive busy tone, then $x = P_{\max}$.
   - Otherwise, let P_r be the power level of the BT_r that has the highest power among all BT_r's that X receives. We let

$$P_x = \frac{P_{\max} P_{\rm noise}}{P_r}. \quad (3)$$

   That is, the RTS signal should not go beyond the nearest host that is currently receiving a data packet. Note that $P_{\max}$ is used in (3) because a receive busy tone BT_r is always transmitted at the maximum power level (see rule 2 below).
2) On host Y receiving X's *RTS* packet, it should sense any transmit busy tone BT_t around it. There are two cases.
   - If there is any such busy tone, then Y ignores the *RTS* (because collision would occur if X does send a data packet to Y).
   - Otherwise, Y replies with a CTS at the maximum power $P_{\max}$ and turns on its receive busy tone BT_r at the maximum power $P_{\max}$.
3) On host X receiving Y's *CTS*, it turns on its transmit busy tone BT_t and starts transmitting its data packet, both at the power level

$$P_x = \frac{P_{\min} P_{\max}}{P_r}$$

   where P_r is the level of the power at which X receives the CTS. This power level P_x is the minimum possible to ensure that Y can decode the data packet correctly.

For instances, the reader can verify that our protocol will grant the transmissions from C to D and from E to F in Fig. 4(b).

IV. Performance Analysis

In Section III-A, we have shown the benefit of power control on channel reuse without incorporating the details of medium access control. We now present some performance analysis of our MAC protocol. Section IV-A compares the DBTMA and

TABLE I
COMPARISON OF THE PROBABILITY Prob$(C \rightarrow D|A \rightarrow B)$

	DBTMA	Ours
$\overline{BC} \leq r_{max}$	0	0.397
$r_{max} < \overline{BC} \leq 3r_{max}$	0.910	0.971

our protocols on the success possibility that two nearby communication pairs can coexist in a physical area. Section IV-B analyses the channel utilization offered by our protocol.

A. Analysis of Probability of Two Nearby Communication Pairs

We are interested in exploring how two communication pairs will interfere with each other under the DBTMA and our protocols. Specifically, the following scenario is considered. There are four hosts A, B, C, and D. Suppose that A is currently sending a packet to B. We want to find out the probability under this constraint that C can successfully initiate a transmission (through RTS/CTS dialogue) with D. Formally, we denote this probability by Prob$(C \rightarrow D|A \rightarrow B)$. We want to determine

$$\text{Prob}(C \rightarrow D|A \rightarrow B) \qquad \text{subject to} \begin{cases} \overline{AB} \leq r_{\max} \\ \overline{CD} \leq r_{\max} \\ \overline{BC} \leq 3r_{\max} \end{cases}$$

where $\overline{XY}$ denotes the distance between two hosts X and Y, and $r_{\max}$ the maximum transmission distance of an antenna (when power $P_{\max}$ is used). Note that the first two constraints are necessary because otherwise the receivers will be too far from the senders. The last constraint $\overline{BC} \leq 3r_{\max}$ is imposed because beyond this distance the two transmissions ($A \rightarrow B$ and $C \rightarrow D$) are free from interference.

To simplify the analysis, we assume that the area that a packet can reach is bounded by a circle, and that a host can tune its transmission power to a level with arbitrary accuracy. Also, we assume an ideal model that the difference $P_{\min} - P_{\text{noise}} = \epsilon$ is an arbitrarily small value (i.e., the gap to distinguish a signal and a noise is negligible).

Definition 1: Consider two points A and B on an xy-plane which are the centers of two circles of radii R_A and R_B, respectively. Define $INTC(R_A, R_B, \overline{AB})$ to be the area of the intersection of these two circles.

Definition 2: Consider three points A, B, and C on an xy-plane which are the centers of three circles of radii R_A, R_B, and R_C, respectively. Define $INTC3(R_A, R_B, R_C, \overline{AB}, \overline{AC}, \overline{BC})$ to be the area of the intersection of these three circles.

The discussion is separated into two cases depending on the value of $\overline{BC}$. Table I gives a preview of our analysis result. As can be seen, when $\overline{BC} \leq r_{\max}$, the Prob$(C \rightarrow D|A \rightarrow B)$ of our protocol is about 40%, whereas it is impossible for DBTMA to grant $C \rightarrow D$. When $r_{\max} < \overline{BC} \leq 3r_{\max}$, both protocols have a high success probability (ours is about 0.06 higher than DBTMA). This implies that our protocol is more useful when the density of mobile hosts is high.

1) Case 1—$\overline{BC} \leq r_{\max}$: In this case, host C can hear B's receive busy tone BT_r. Our protocol may grant the transmission $C \rightarrow D$ if the following events happen: a) host C sends an RTS with a power level which reaches B with a power level P_{noise}, b) D hears C's RTS and returns a CTS. Note that event b) can succeed only if D is within the range of C's RTS, but is out of range of A's BT_t. In Fig. 6, we draw a possible relationship among hosts A, B, and C, where the circles centered at A, B, and C indicate the transmission ranges of A's BT_t, B's BT_r, and C's RTS, respectively.

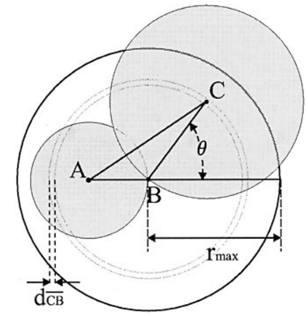

Fig. 6. Analysis of the success probability of two nearby coexisting communication pairs (case $\overline{BC} \leq r_{\max}$).

Without loss of generality, let B be a reference point, A be on B's left-hand side, and the angle between $\overrightarrow{BC}$ and the x-axis be θ (refer to Fig. 6). Note that D could be located in any place at a distance of $r_{\max}$ from C. If D is within the circle centered at C, but not in the circle centered at A, the transmission $C \rightarrow D$ will be granted. Let's denote by $p_1(\overline{AB}, \overline{CB}, \theta)$ the value of Prob$(C \rightarrow D|A \rightarrow B)$ under this instance. The success probability is

$$p_1(\overline{AB}, \overline{CB}, \theta) = \frac{\pi\overline{CB}^2 - INTC(\overline{AB}, \overline{CB}, \overline{AC})}{\pi r_{\max}^2} \quad (4)$$

where $\overline{AC} = \sqrt{(\overline{CB}\sin\theta)^2 + (\overline{AB} + \overline{CB}\cos\theta)^2}$. The numerator is the area of the circle centered at C with radius $\overline{CB}$ excluding the intersection of the gray circles centered at A and C. The denominator is the area that D may be located.

For a fixed $\overline{AB}$, the average success probability can be obtained by integrating the value in (4) for $\theta = 0 \cdots 2\pi$ and then integrating the result for $\overline{CB} = 0 \cdots r_{\max}$:

$$\int_0^{r_{\max}} \left(\frac{2\pi\overline{CB}}{\pi r_{\max}^2} \int_0^{2\pi} \left(\frac{p_1(\overline{AB}, \overline{CB}, \theta)}{2\pi} \right) d\theta \right) d\overline{CB}. \quad (5)$$

Finally, integrating the value in (5) for $\overline{AB} = 0 \cdots r_{\max}$, we obtain

$$\begin{aligned} &\text{Prob}(C \rightarrow D|A \rightarrow B) \\ &= \int_0^{r_{\max}} \left(\frac{2\pi\overline{AB}}{\pi r_{\max}^2} \int_0^{r_{\max}} \left(\frac{2\pi\overline{CB}}{\pi r_{\max}^2} \int_0^{2\pi} \right.\right. \\ &\qquad \left.\left. \cdot \frac{p_1(\overline{AB}, \overline{CB}, \theta)}{2\pi} d\theta \right) d\overline{CB} \right) d\overline{AB}. \quad (6) \end{aligned}$$

On the contrary, in the DBTMA protocol, as C can hear B's receive busy tone BT_r, the RTS/CTS dialogue will fail. So the probability Prob$(C \rightarrow D|A \rightarrow B) = 0$ for the DBTMA.

2) Case 2—$r_{\max} < \overline{BC} \leq 3r_{\max}$: In this case, host C cannot hear B's receive busy tone BT_r. So C's RTS will be sent with power level $P_{\max}$. Let's follow the model in the previous

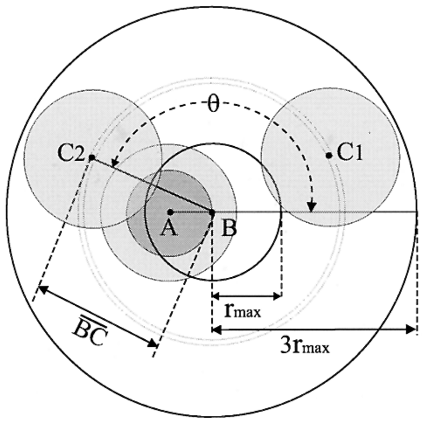

Fig. 7. Analysis of the success probability of two nearby coexisting communication pairs (case $r_{\max} < \overline{BC} \le 3r_{\max}$).

section. There is no change on the radii of the circles centered at A and B, but the radius of the circle centered at C becomes $r_{\max}$. Still, the transmission $C \to D$ will be granted if D is inside C's transmission range, but outside A's transmission range. The main difference is that the circles centered at A and C may or may not intersect. Fig. 7 illustrates this difference: when C is located at C_1, there is no intersection; but when C is at C_2, there is some intersection.

First, given fixed $\overline{AB}$, $\overline{CB}$, and θ, we recalculate the success probability

$$p_2(\overline{AB}, \overline{CB}, \theta) = \frac{\pi r_{\max}^2 - INTC(\overline{AB}, r_{\max}, \overline{AC})}{\pi r_{\max}^2}. \quad (7)$$

For a fixed $\overline{AB}$, the average success probability can be obtained by integrating the value in (7) for $\theta = 0 \cdots 2\pi$ and then integrating the result for $\overline{CB} = r_{\max} \cdots 3r_{\max}$:

$$\int_{r_{\max}}^{3r_{\max}} \left(\frac{2\pi \overline{CB}}{3^2 \pi r_{\max}^2 - \pi r_{\max}^2} \int_0^{2\pi} \cdot \left(\frac{p_2(\overline{AB}, \overline{CB}, \theta)}{2\pi} \right) d\theta \right) d\overline{CB}. \quad (8)$$

Finally, integrating the value in (8) for $\overline{AB} = 0 \cdots r_{\max}$, we obtain

$$\begin{aligned} &\text{Prob}(C \to D | A \to B) \\ &= \int_0^{r_{\max}} \left(\frac{2\pi \overline{AB}}{\pi r_{\max}^2} \int_{r_{\max}}^{3r_{\max}} \left(\frac{2\pi \overline{CB}}{3^2 \pi r_{\max}^2 - \pi r_{\max}^2} \int_0^{2\pi} \cdot \left(\frac{p_2(\overline{AB}, \overline{CB}, \theta)}{2\pi} \right) d\theta \right) d\overline{CB} \right). \end{aligned} \quad (9)$$

The main difference in the DBTMA protocol as opposed to ours is that host A will use power $P_{\max}$ to transmit its BT_t. This will reduce the probability for D to reply C's RTS. So the success probability needs to be recalculated:

$$p_3(\overline{AB}, \overline{CB}, \theta) = \frac{\pi r_{\max}^2 - INTC(r_{\max}, r_{\max}, \overline{AC})}{\pi r_{\max}^2}. \quad (10)$$

Clearly, $p_3 \le p_2$. Substituting p_3 for the p_2 in (9), we will have the Prob$(C \to D | A \to B)$ of DBTMA.

B. Analysis of Channel Utilization

The above analysis, which is from a geometrical approach, is only for two communication pairs. Extending to more communication pairs would be difficult, if not impossible. The analysis in this section will take a probabilistic approach, and the limitation on communication pairs will be eliminated. We will derive the *channel utilization* of our protocol, where channel utilization is the average aggregate time used for successful data transmission in a physical area at every instant. Our analysis follows the model in [5] and [9]. Each host is a Poisson source with a packet arrival rate of λ. Hosts are randomly distributed in an area S_{area} with density ρ. With power control, the average distance of all sender–receiver pairs can be written as $R = r_{\max}/\sqrt{2}$. To simplify the analysis, every unsuccessful data packet is destroyed by the transmitter.

Consider a pair of hosts A and B intending to communicate. The probability Prob$(A \to B)$ can be formulated as:

$$\begin{aligned} \text{Prob}(A \to B) = &\text{Prob(RTS successful)} \\ &\cdot \text{Prob(CTS successful | RTS successful)} \\ &\cdot \text{Prob(data successful | CTS successful)}. \end{aligned}$$

Host A's RTS will succeed if there is no other transmission that can corrupt B's reception during its vulnerable period, so

$$\text{Prob(RTS successful)} = e^{-(2\gamma+\tau)\lambda(\rho\pi R^2 - 1)} \quad (11)$$

where γ is the transmission time of a control packet and τ is the propagation delay.

After receiving A's RTS, B will set its BT_r on and reply with a CTS. All nodes that are in B's BT_r range but not in A's RTS range are hidden terminals to A. The number of such hosts is

$$N_{ht} = \rho\pi r_{\max}^2 - INTC(\overline{AB}, r_{\max}, \overline{AB}).$$

So the probability that the CTS is successful depends on whether any of these hidden terminals start any transmission during the propagation period τ which can potentially corrupt the transmission $A \to B$, i.e.,

$$\begin{aligned} &\text{Prob(CTS successful | RTS successful)} \\ &= e^{-\tau\lambda N_{ht}} + (1 - e^{-\tau\lambda N_{ht}}) \\ &\quad \cdot \text{Prob(harmless hidden terminal)} \end{aligned}$$

where the first part is the probability that no hidden terminals start any transmission during a τ period, and the second part is that some hidden terminal starts a transmission but is harmless to $A \to B$.

To find Prob(harmless hidden terminal), suppose C is a hidden terminal to A. Also, let D be C's intended communication party (refer to Fig. 8, where D_1, D_2, D_3, D_4 are four possible locations of D). We analyze the effect of the hidden terminal C depending on the location of D.

1) D in A's RTS range: The transmission $C \to D$ will be prohibited by A's RTS (e.g., D_1 in Fig. 8).
2) D in B's CTS range: The transmission $C \to D$ will fail because C's RTS and B's CTS will collide in D (e.g., D_2 in Fig. 8).

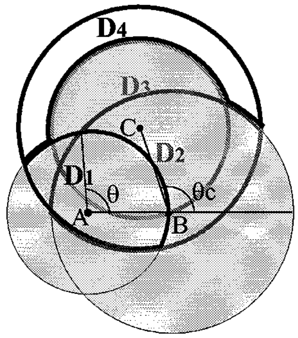

Fig. 8. Analysis of harmful/harmless hidden terminals.

3) D in the circle centered at C with radius $\overline{BC}$: The transmission $C \rightarrow D$, no matter being granted or not, will not corrupt the transmission $A \rightarrow B$ (e.g., D_3 in Fig. 8).
4) D in C's RTS range, but not falling in the above three cases: The transmission will corrupt the transmission $A \rightarrow B$ (e.g., $D4$ in Fig. 8).

So the only harmful area is what is identified in item 4, and the harmless area is the circle centered at C with radius $r_{\max}$ excluding this area

$$\begin{aligned} H_{\text{area}}(A, B, C) &= \pi\overline{CB}^2 + INTC(r_{\max}, r_{\max}, \overline{CB}) \\ &\quad - INTC(\overline{CB}, r_{\max}, \overline{BC}) + INTC(r_{\max}, \overline{AB}, \overline{AC}) \\ &\quad - INTC(\overline{CB}, \overline{AB}, \overline{AC}) \\ &\quad + INTC3(\overline{CB}, r_{\max}, \overline{AB}, \overline{BC}, \overline{AC}, \overline{AB}) \\ &\quad - INTC3(r_{\max}, r_{\max}, \overline{AB}, \overline{AB}, \overline{BC}, \overline{AC}). \qquad (12) \end{aligned}$$

Thus, C is a harmless hidden terminal with probability $(H_{\text{area}}(A, B, C)/\pi r_{\max}^2)$. Integrating this probability over all possible locations of C, we have

$$\begin{aligned} &\text{Prob(harmless hidden terminal)} \\ &= \frac{1}{\pi r_{\max}^2 - INTC(r_{\max}, \overline{AB}, \overline{AB})} \int_0^{r_{\max}} 2 \\ &\quad \cdot \left(\int_0^{\pi - \cos^{-1}(\overline{BC}^2/2\overline{AB}\cdot\overline{BC})} \right. \\ &\quad \left. \cdot \left(\frac{H_{\text{area}}(A, B, C)}{\pi r_{\max}^2} \right) d\theta_C \right) d\overline{BC} \end{aligned}$$

where θ_C is the angle shown in Fig. 8.

Once both busy tones BT_t and BT_r are set up correctly, A's data packet will be sent correctly. So Prob(data successful | CTS successful) $=$ 1. This leads to

$$\begin{aligned} &\text{Prob}(A \rightarrow B) \\ &= e^{-\lambda(2\gamma+\tau)\lambda(\rho\pi R^2 - 1)} \\ &\quad \cdot \left(e^{\tau\rho R(\pi R + \overline{AB}\sin\theta - 2R\theta)} \right. \\ &\quad + \left(1 - e^{\tau\rho R(\pi R + \overline{AB}\sin\theta - 2R\theta)}\right) \\ &\quad \left. \cdot \text{Prob(harmless hidden terminal)} \right). \end{aligned}$$

Let's define a busy period as the period between two consecutive idle periods. There are two types of busy periods: successful transmission period and unsuccessful transmission period. The expected time of a busy period is then

$$\overline{B} = T_s \,\text{Prob}(A \rightarrow B) + T_f(1 - \text{Prob}(A \rightarrow B))$$

where T_s is the expected time of a successful transmission period, and T_f is the expected time of an unsuccessful transmission period. A successful transmission time consists of an RTS packet transmission time, a CTS packet transmission time, and a data packet transmission time (δ), each followed by propagation time τ:

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

An unsuccessful transmission period consists of an RTS packet transmission time followed by τ and a collision time before the channel becomes idle again [9]:

$$T_f = \gamma + 2\tau - \frac{1 - e^{-\tau\lambda\rho\pi R^2}}{\lambda\rho\pi R^2}.$$

An idle period is the time between two consecutive busy periods. According to the property of a Poisson process, the expected time of an idle period is

$$\overline{I} = \frac{1}{\lambda\rho\pi R^2}.$$

So the average utilization period can be expressed as

$$\overline{U} = \delta \,\text{Prob}(A \rightarrow B)$$

which gives the effective channel utilization ratio

$$T(A \rightarrow B) = \frac{\overline{U}}{\overline{B} + \overline{I}}.$$

As the above analysis is only for a particular value of $\overline{AB}$ (which may range from 0 to R), taking this into consideration through integration, we have the average channel utilization

$$\overline{T} = \frac{1}{\lambda\rho\pi R^2} \int_0^R \left(\rho 2\pi\overline{AB} \cdot T(A \rightarrow B)\right) d\overline{AB}. \qquad (13)$$

In the area S_{area}, the *maximum number of concurrent transmission pairs* can be conservatively approximated by $m = S_{\text{area}}/(3\sqrt{3}R^2/2)$, where the denominator is the area of a hexagon of side length R. So the aggregated channel utilization in the area S_{area} is $m\overline{T}$.

V. Discrete Power Control

In practice, the levels of power provided by the physical layer may not be infinitely tunable. A more reasonable assumption is that only a certain number of (discrete) power levels are offered. In this section, we try to answer the question: given a fixed integer k, how do we determine k power levels to maximize channel utilization?

Throughout this section, our development is based on (1), and we will assume that $n = 2$. Observe that channel utilization is proportional to the number of concurrent transmitting hosts in the MANET, which is in turn proportional to number of nonoverlapping circles of radius $r_{\rm avg}$ that can coexist in a physical area, where $r_{\rm avg}$ is the average transmission distance in our protocol. Since the average of power levels, $P_{\rm avg}$, used for transmission is proportional to $r_{\rm avg}^n$, to maximize channel utilization we should minimize the expected value $E(P_{\rm avg})$.

In the following, when $n = 2$ we show that evenly spreading the k power levels is the best choice.

Lemma 1: When $n = 2$ in (1), given an integer k, the k power levels, $(1/k)P_{\max}$, $(2/k)P_{\max}$, $\ldots$, and $(k/k)P_{\max}$, will give the minimum $E(P_{\rm avg}) = ((k+1)/2k)P_{\max}$.

Proof:

Induction Basis: When $k = 2$, assume that a power P_x is offered other than the maximum power $P_{\max}$. Let r_x and $r_{\max}$ be the radii of the circles that can be covered by these two power levels, respectively. By (1), we have $P_x/P_{\max} = r_x^2/r_{\max}^2$. As a receiver is randomly distributed around a sender within a distance $r_{\max}$, the sender has a probability $(\pi r_x^2/\pi r_{\max}^2)$ to use power P_x, and $(\pi r_{\max}^2 - \pi r_x^2)/\pi r_{\max}^2$ to use $P_{\max}$. So the expected power level being used is

$$E(P_{\rm avg}) = P_x \frac{\pi r_x^2}{\pi r_{\max}^2} + P_{\max}\frac{\pi r_{\max}^2 - \pi r_x^2}{\pi r_{\max}^2} = P_x \frac{P_x}{P_{\max}} + P_{\max}\left(1 - \frac{P_x}{P_{\max}}\right).$$

Letting the differentiation $E'(P_{\rm avg}) = 0$, we have $E'(P_{\rm avg}) = (2P_x/P_{\max}) - 1 = 0$. So $P_x = (P_{\max}/2)$, which gives $E(P_{\rm avg}) = (3/4)P_{\max}$.

Induction Hypothesis: Assume that with the $k-1$ power levels, $(1/(k-1))P_{\max}$, $(2/(k-1))P_{\max}$, $\ldots$, $((k-1)/(k-1))P_{\max}$, the $E(P_{\rm avg}) = (k/2(k-1))P_{\max}$ is the minimum.

Induction Step: Now assume that the second largest power level is P_x. By the induction hypothesis, the power levels should be arranged as $(1/(k-1))P_x$, $(2/(k-1))P_x$, $\ldots$, $((k-1)/(k-1))P_x$, $P_{\max}$. Again, let r_x be the radius of the circle that can be covered by power P_x. A sender has a probability $(\pi r_x^2/\pi r_{\max}^2)$ to use power levels $\leq P_x$, and $(\pi r_{\max}^2 - \pi r_x^2)/\pi r_{\max}^2$ to use $P_{\max}$. So the expected power level being used is

$$E(P_{\rm avg}) = \frac{kP_x}{2(k-1)} \cdot \frac{\pi r_x^2}{\pi r_{\max}^2} + P_{\max}\frac{\pi r_{\max}^2 - \pi r_x^2}{\pi r_{\max}^2} = \frac{kP_x}{2(k-1)} \cdot \frac{P_x}{P_{\max}} + P_{\max}\left(1 - \frac{P_x}{P_{\max}}\right).$$

Letting the differentiation $E'(P_{\rm avg}) = 0$, we have $E'(P_{\rm avg}) = (P_x k)/((k-1)P_{\max}) - 1 = 0$. So we have $P_x = ((k-1)/k)P_{\max}$, which gives $E(P_{\rm avg}) = ((k+1)/2k)P_{\max}$. As $E(P_{\rm avg}) \to (P_{\max}/2)$ as $k \to \infty$, this also tells us that the theoretical upper bound for channel utilization improvement is at most two times that without power control. □

We comment that when n is of other values, the derivation will be similar.

VI. Simulation Results

We have developed a simulator to verify the performance of our scheme and compare our result to the DBTMA protocol. We mainly focus on the channel utilization (note that the discussion here can be compared to the channel utilization analysis in Section IV-B, but should not be confused with the interference analysis in Section IV-A and the channel reuse analysis in Section III-A).

A MANET with a certain number of mobile hosts which may roam around in a physical area was simulated. The simulation parameters are listed below.

- Physical area = 8 km × 8 km
- Maximum transmission distance $(r_{\max}) = 0.5$–2.0 km
- Number of mobile hosts = 600
- Speed of mobile host = 0 or 125 km/hr
- Length of control packet = 100 bits
- Link speed = 1 Mbits/s
- Transmission bit error rate = 10^{-5}/bit.

Data packets were generated to the MANET by a Poisson distribution. For each packet, we randomly chose one of the mobile host as the source node and a neighbor host within distance $r_{\max}$ as the receiver. We varied the number of data packets injected into the MANET and observed the channel utilization in the area.

Fig. 9 shows the channel utilization of the DBTMA and our protocols at different traffic loads when $r_{\max} = 0.5$ km. Data packets length is fixed at 1000 bits. From Fig. 9(a), we see that the DBTMA protocol will saturate at around load = 600 packets/ms, while our protocol will saturate at around load = 800 packets/ms. Also, our protocol can deliver a channel utilization about 2 times that of the DBTMA. Moving to Fig. 9(b) and (c), where $r_{\max} = 1.0$ and 2.0 km, respectively, we observe that both protocols will saturate at lower loads. This is reasonable because a larger transmission distance means a more crowded environment (signals are more likely to overlap with each). By comparing these three figures, we further see that a larger transmission distance $r_{\max}$ will slightly favor our protocol (the gap between DBTMA and our protocols enlarges slightly). Hence, power control is of more importance in more crowded environments.

Next, we observe the effect of packet length. Fig. 10 shows our simulation results when $r_{\max} = 1.0$ km. As can be seen, longer data packets can deliver higher channel utilization. This shows an interesting result that longer packets are less vulnerable with busy tones and power control. This is perhaps because the hidden-terminal problem is less serious (less interruption/interference from hidden terminals).

The above simulations have used infinite power levels. We also simulated discrete power levels and observed its effect on channel utilization. Setting $r_{\max} = 1$ km, arrival rate = 200 or 400 packets/ms, and packet length = 1 or 2 kbits, Fig. 11 shows the channel utilization using different numbers of power levels. Apparently, more power levels enable a host to transmit with less interference to its surroundings, thus giving higher channel utilization. However, using 4 to 6 power levels can already deliver a channel utilization close to that of using infinite power levels. So it makes little sense to have too many power levels. This shows the practical value of our result.

The previous simulations are based on no host mobility. Fig. 12 demonstrates the effect of host mobility. We compare

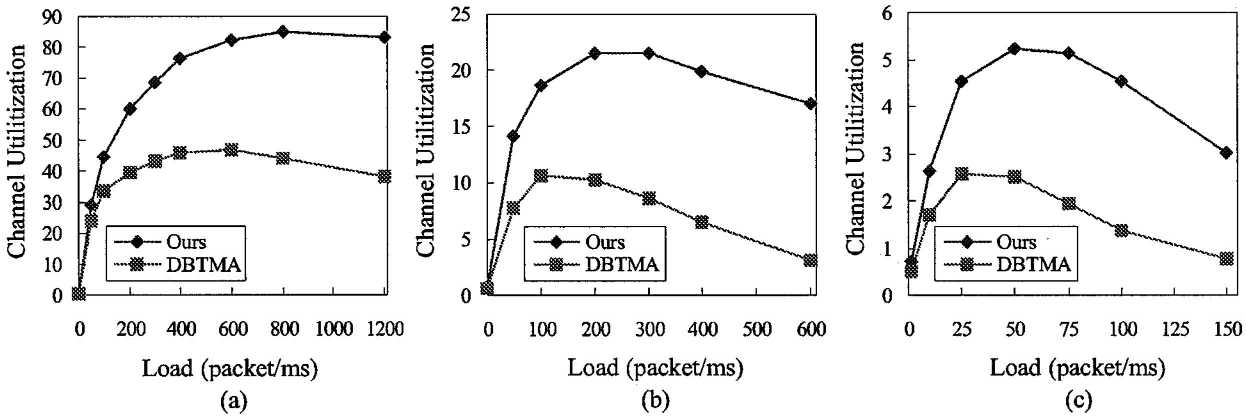

Fig. 9. Channel utilization versus traffic load when (a) $r_{\max} = 0.5$ km, (b) $r_{\max} = 1.0$ km, and (c) $r_{\max} = 2.0$ km.

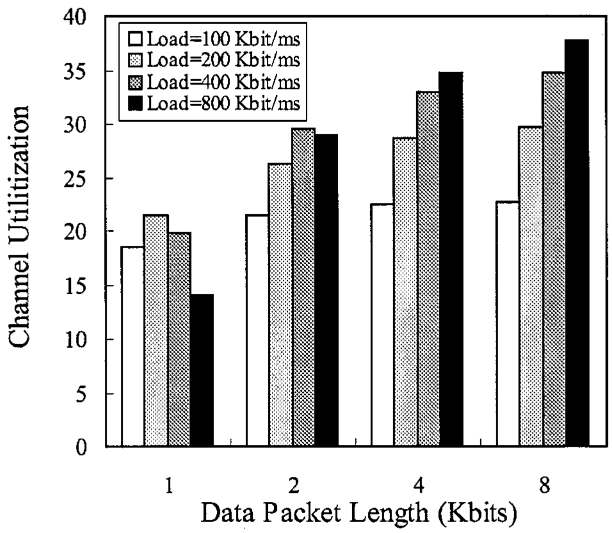

Fig. 10. Channel utilization versus data packet length at various traffic loads.

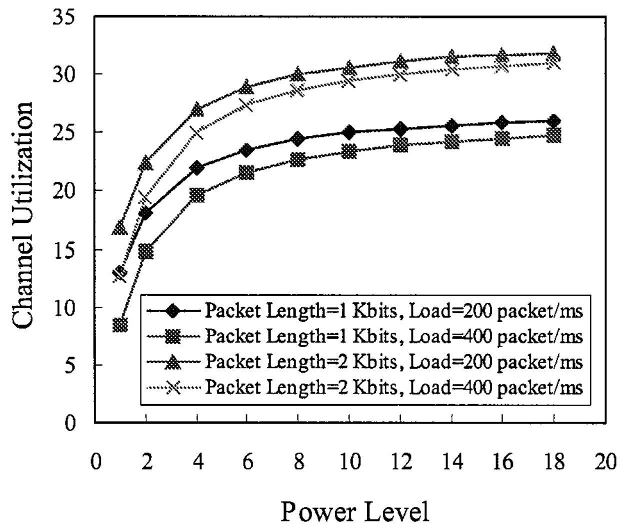

Fig. 11. Channel utilization versus number of power levels at $r_{\max} = 1$ km, arrival rate = 200 or 400 packets/ms, and packet length = 1 or 2 kbits.

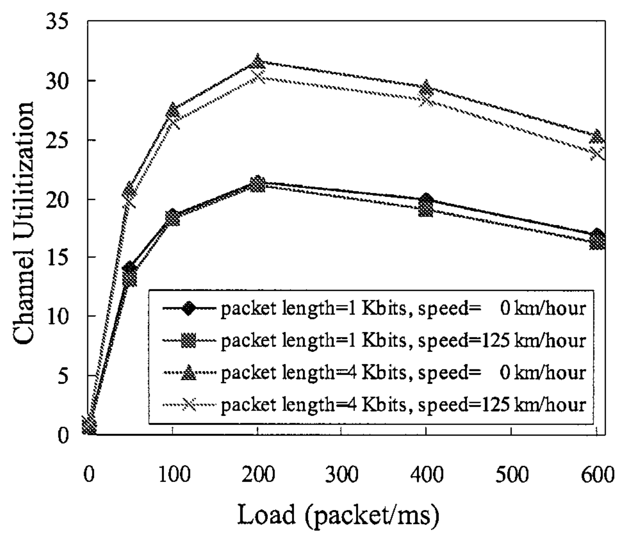

Fig. 12. Channel utilization versus traffic load when hosts have no mobility and when hosts move at 125 km/h. The transmission distance $r_{\max} = 1$ km.

the channel utilization when hosts have no mobility and when hosts move at 125 km/h with random direction. (A speed of 125 km/h means a very fast vehicle, such as cars on highways.) The results show that the effect of host mobility to channel utilization is very limited and thus negligible at the MAC layer, which is the same as the observation in [3].

Finally, Fig. 13 compares the channel utilization obtained from our simulation to that from our analysis in Section IV-B (i.e., $m\overline{T}$). The results in Fig. 13(a) are obtained from a physical area of size 1 km × 1 km with 50 mobile hosts each with a transmission distance of $r_{\max} = 0.5$ km. This case represents a small value of $m = 3.07$ (recall that this is an estimation on the number of concurrent transmission pairs). The purpose here is to reduce the effect of error induced by m on the overall channel utilization. We can see that the peak theoretical utilization is slightly higher than the peak simulated utilization. We believe that this is because the theoretical analysis does not consider some timing factors (such as backoff, transmission delays, message preambles, etc.) which are considered in our simulations. However, as the load exceeds the throughput of the network, we see that the simulated utilization will outperform the theoretical utilization. We believe that this is because the probability Prob(RTS successful) in (11) is too conservative when the traffic load is high. This probability is to estimate the number of

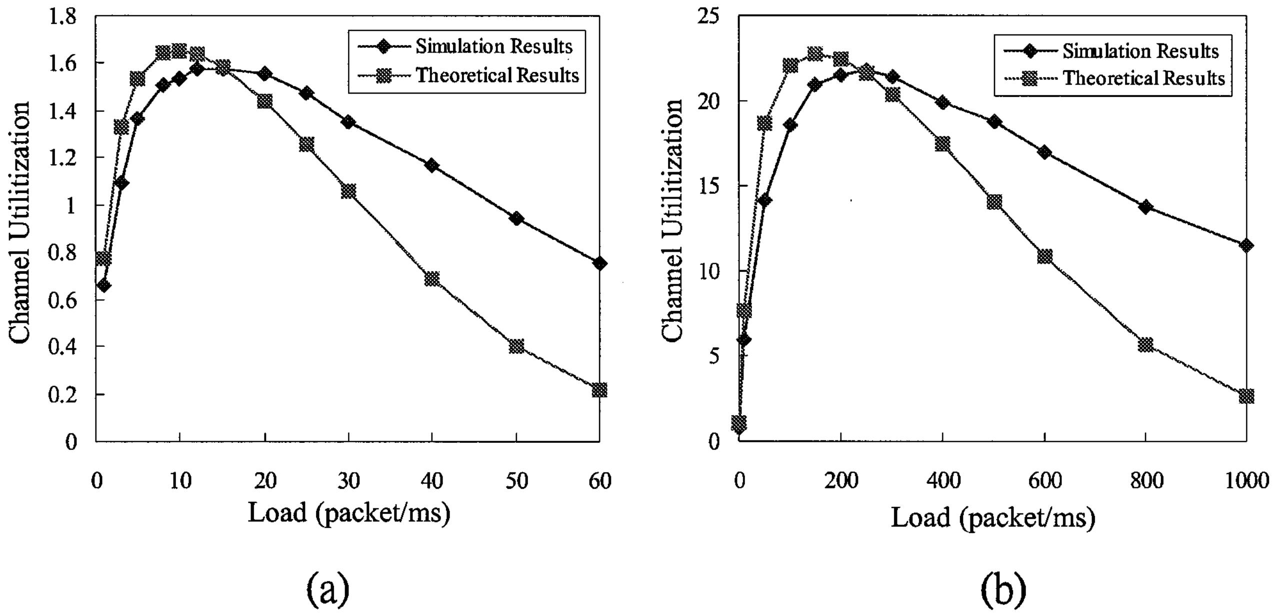

Fig. 13. Simulated channel utilization versus theoretical channel utilization: (a) in a 1 km ×1 km area with 50 mobile hosts and (b) in an 8 km × 8 km area with 600 mobile hosts.

potential attackers on an RTS packet. The estimation has considered all potential attackers at a certain distance (R) from the receiver of this RTS. However, as the traffic load is high, many attackers will be prohibited by the earlier RTS/CTS dialogues in the surroundings. Similarly, the Prob(CTS successful | RTS successful) might be conservative, too, when the traffic load is high. This explains why, after the peak utilization, our simulated result will outperform the theoretical analysis in Fig. 13(a). The results in Fig. 13(b) are obtained from a physical area of size 8 km × 8 km with 600 mobile hosts each with a transmission distance of $r_{\max} = 1.0$ km. This represents a larger value of $m = 49.27$. The trend is very similar to that in Fig. 13(a).

VII. Conclusion

The main objective of MAC protocols is to arbitrate the accesses of communication medium among multiple mobile hosts. This is of more challenge in a MANET environment since radio signals from different antennas are likely to overlap with each other in many areas, thus seriously wasting the medium. In this paper, we have proposed a new MAC protocol for MANETs that utilize the intelligence of power control on top of the RTS/CTS dialogues and busy tones. Channel utilization can be significantly increased because the severity of signal overlapping is reduced. Analyses and simulation results have all shown the advantages of using our protocol. As to future work, RTS/CTS is only one of the many possibilities to access wireless medium. Future research could be directed to applying the power-control concept to other domains. Recently, some works have addressed the possibility of using an intermediate relay node to transmit a packet in an indirect manner [6], [12], instead of transmitting a packet directly. It will be interesting to further investigate applying power control on this issue.

References

[1] *IEEE Std 802.11–1997: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Inst. Elec. Electron. Eng., New York, USA, 1997.

[2] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A medium access protocol for wireless LANs," in *Proc. SIGCOMM'94*, 1994, pp. 212–225.

[3] J. Deng and Z. J. Hass, "Dual busy tone multiple access (DBTMA): A new medium access control for packet radio networks," in *Proc. Int. Conf. Universal Personal Commun.*, Oct. 1998.

[4] C. L. Fullmer and J. Garcia-Luna-Aceves, "Floor acquisition multiple access (FAMA) for packet-radio networks," in *Proc. SIGCOMM'95*, Nov. 1995.

[5] Z. J. Hass and J. Deng, "Dual busy tone multiple access (DBTMA): Performance evaluation," in *Proc. 49th Annu. Int. Veh. Technol. Conf.*, Oct. 1998.

[6] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. Hawaii Int. Conf. Syst. Sci.*, 2000.

[7] E. D. Kaplan, Ed., *Understanding GPS: Principles and Applications*. Boston, MA: Artech House, 1996.

[8] P. Karn, "MACA—A new channel access method for packet radio," in *Proc. ARRL/CRRL Amateur Radio 9th Computer Networking Conf.*, 1990, pp. 134–140.

[9] L. Kleinrock and F. A. Tobagi, "Packet switching in radio channels: Part I—Carrier sense multiple access modes and their throughput-delay characteristics," *IEEE Trans. Commun.*, vol. 23, pp. 1417–1433, 1975.

[10] C. R. Lin and M. Gerla, "MACA/PR: An asynchronous multimedia multihop wireless network," in *Proc. IEEE INFOCOM'97*, Apr. 1997.

[11] J. P. Macker and M. S. Corson, "Mobile *ad hoc* networking and the ETF," *Mobile Computing Commun. Rev.*, vol. 2, pp. 7–9, July 1998.

[12] V. Rodoplu and T. H. Meng, "Minimum energy mobile wireless networks," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1333–1344, Aug. 1999.

[13] S. Singh and C. S. Raghavendra, "Power efficient MAC protocol for multihop radio networks," in *Proc. Int. Symp. Personal, Indoor Mobile Commun.*, 1998.

[14] F. Talucci and M. Gerla, "MACA-BI (MACA By Invitation) A wireless MAC protocol for high speed *ad hoc* networking," in *Proc. ICUPC'97*, Nov. 1997.

[15] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part II—The hidden terminal problem in carrier sense multiple access modes and the busy tone solution," *IEEE Trans. Commun.*, vol. 23, pp. 1417–1433, 1975.

[16] E. K. Wesel, *Wireless Multimedia Communicaions: Networking Video, Voice, and Data*. Reading, MA: Addison-Wesley, 1998.

Shih-Lin Wu received the B.S. degree in computer science from the Tamkang University in 1987.

Since September 1997, he has been a Ph.D. student at the Department of Computer Science and Information Engineering, National Central University. His advisors are Prof. J.-P. Sheu and Prof. Y.-C. Tseng. He is a member of High-Speed Communication and Computing Laboratory of NCU. His current research interests include mobile computing, wireless communication, parallel, and distributed computing.

Yu-Chee Tseng (S'91–M'95) received the B.S. and M.S. degrees in computer science from the National Taiwan University and the National Tsing-Hua University in 1985 and 1987, respectively.

He worked for the D-LINK Inc. as an Engineer in 1990. He obtained his Ph.D. in computer and information science from the Ohio State University in January of 1994. From 1994 to 1996, he was an Associate Professor at the Department of Computer Science, Chung-Hua University. He joined the Department of Computer Science and Information Engineering, National Central University in 1996, and has become a Professor since 1999. In August 2000, he became a Professor at the National Chiao-Tung University. He served as a Program Committee Member in the International Conference on Parallel and Distributed Systems, 1996, the International Conference on Parallel Processing, 1998, the International Conference on Distributed Computing Systems, 2000, and the International Conference on Computer Communications and Networks 2000. He was a Workshop Co-Chair of the National Computer Symposium, 1999. His research interests include mobile computing, wireless communication, network security, parallel and distributed computing, and computer architecture.

Dr. Tseng is a member of the IEEE Computer Society and the Association for Computing Machinery.

Jang-Ping Sheu (S'85–M'86–SM'98) received the B.S. degree in computer science from Tamkang University, Taiwan, Republic of China, in 1981, and the M.S. and Ph.D. degrees in computer science from the National Tsing Hua University, Taiwan, Republic of China, in 1983 and 1987, respectively.

He joined the Faculty of the Department of Electrical Engineering, National Central University, Taiwan, Republic of China, as an Associate Professor in 1987. He is currently a Professor of the Department of Computer Science and Information Engineering, National Central University. From March to June of 1995, he was a Visiting Researcher at the IBM Thomas J. Watson Research Center, New York. From July 1999 to April 2000, he was a Visiting Scholar in the Department of Electrical and Computer Engineering, University of California, Irvine. His current research interests include parallelizing compilers, interconnection networks, and mobile computing.

Dr. Sheu is a member of the ACM and Phi Tau Phi Society. He is an Associate Editor of Journal of Information Science and Engineering, Journal of the Chinese Institute of Electrical Engineering, and Journal of the Chinese Institute of Engineers. He received the Distinguished Research Awards of the National Science Council of the Republic of China in 1993–1994, 1995–1996, and 1997–1998.