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

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Abstract

In a *mobile ad-hoc networks (MANET)*, 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 co-channel interference, does show a promising direction to enhance the performance of MANETs.

Keywords: MANET, medium access control (MAC), mobile ad-hoc network, power control, RTS/CTS, wireless network.

1 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 [9].

In a MANET, it is well-known that the hidden-terminal problem and exposed-terminal problem can severely reduce channel utilization [12]. To relieve these problems, many protocols based RTS/CTS dialogues have been proposed [2, 4, 7, 8, 11]. 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 on-going transmission [3]. It is shown that the channel utilization can be increased by about twice [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 co-channel 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) [6], 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 2, we briefly review two existing MAC protocols. Our newly proposed protocol is presented in Section 3. Section 4 demonstrates the advantage of our protocol through analysis. How to use discrete power levels is discussed in Section 5. Simulation results are in Section 6 and conclu-

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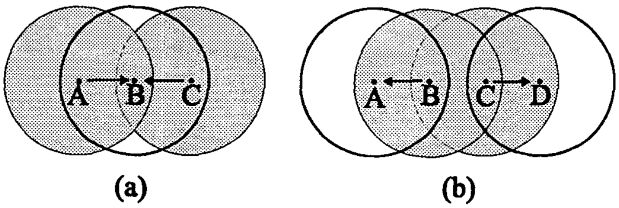

Figure 1: Scenarios to show (a) the hidden-terminal problem, and (b) the exposed-terminal problem.

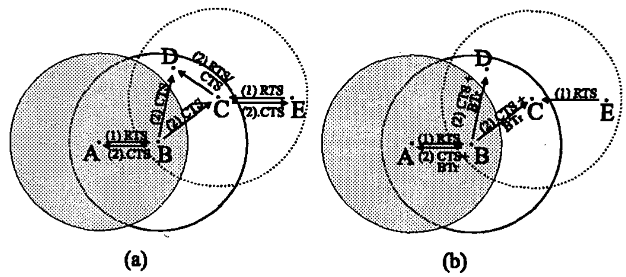

Figure 2: (a) A scenario that B's CTS is destroyed at D by C's RTS/CTS. (b) Using busy tones to resolve the CTS destroyed problem.

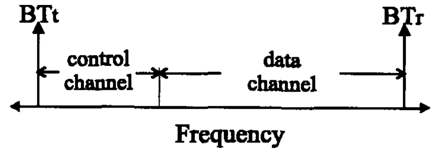

Figure 3: Frequency chart of the DBTMA protocol.

sions are in Section 7.

2 Review of Some MAC Protocols

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

2.1 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 can not hear each other. When A is transmitting to B, since host C can not 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 can not 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 can not 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 is actually taken place [2, 4, 7, 8]. When a node wishes to transmit a packet to a neighbor, it first transmits a 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.

2.2 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 destroy of data packets when traffic load is heavy. Consider the scenario in Fig. 2(a). Node A sends a RTS to B, which in turn replies a CTS to A. In the meanwhile, as host C can not hear A's RTS, it may send a 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 sub-channels: 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 does 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 the sender a CTS. When a host wants to send a RTS, it has to make sure that there is no BT_r around it. Conversely, to reply a CTS, a host must make sure that there is no BT_t around. 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 [10], but this is out of the scope of this paper.

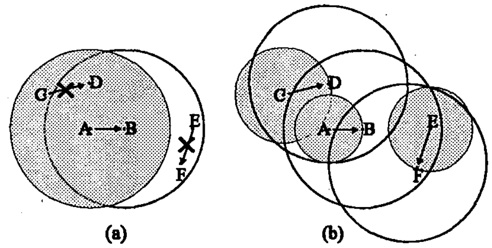

Figure 4: Transmission scenarios (a) when there is no power control, and (a) when there is power control. Transmit busy tones are shown in gray and receive busy tones are shown in white.

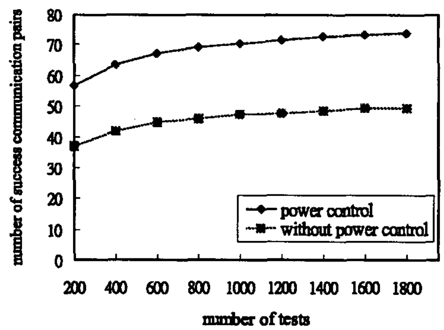

Figure 5: The potential numbers of communication pairs in a 500×500 area with and without power control. The maximum transmission distance is 50 units.

3 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 can not be granted because D can hear A's BT_t, and similarly that from E to F can not 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 a RTS to D. At this moment, D hears no BT_t, so D can reply 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 a 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: (i) data packet and BT_t are transmitted with power control, (ii) CTS and BT_r are transmitted at the normal (largest) power level, and (iii) RTS is transmitted at 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.

3.1 Benefits of Power Control

At this point, it deserves to predict, under ideal situations, how much benefit power control can offer. We have developed a simple simulation without caring how MAC protocols are designed. We simulated an area of size 500×500. 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: (i) A sends to B with the maximum power, and (ii) A sends to B with a smallest power such that B can receive correctly. Based on the surroundings, we then checked whether the transmission from A to B will interfere any ongoing communication pair or not. If not, the transmission from A to B was granted; otherwise, it was dropped. We then repeated the above process a number of times (ranging from 200 to 1800), trying to add more communication pairs to the area.

We observed the numbers 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. As can be seen, power control can offer about 1.5 times more communication pairs than that without power control.

3.2 Tuning Power Levels

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

- *Transmission Power:* A mobile host can choose on what power level to transmit a packet. This function should be offered by the physical layer.
- *Signal Strength:* On receiving a packet, the physical layer can offer the MAC layer the power level on 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 on which the packet is transmitted and received on the sender and receiver sides, respectively. Then the following equation holds (refer to the Chapter 2 of [13]):

$$P_r = P_t(\frac{\lambda}{4\pi d})^n g_t g_r, \tag{1}$$

where λ is the carrier wavelength, d is the distance between the sender and the receiver, n is the path loss coefficient, and g_t and g_r are the 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 a 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_{CTS} such that X's receiving power is the smallest possible, say P_{min}, then we have

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

Dividing Eq. (2) by Eq. (1), we have

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

Thus, Y can determine the power level $P_{CTS} = P_t P_{min}/P_r$ 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 5. Also, to take transmission reliability into account, the real transmission power in the above example should be larger than P_{CTS} by a certain level.

3.3 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_{noise}: a power level under which an antenna will regard a signal as a noise (P_{noise} should be less than P_{min} by some constant; ideally, we assume that $\leq P_{min} - P_{noise}$ is a very small value.)

The complete protocol is formally described below.

1. On a host X intending to send a RTS to host Y, host X should sense any receive busy tone BT_r around it and send a 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
   $$P_x = \frac{P_{max} P_{noise}}{P_r}. \quad (3)$$
   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 Eq. (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).

4 Performance Analysis

This section we will compare the DBTMA and our protocols on the success possibility that two nearby communication pairs can coexist in a MANET. We are interested in how much benefit our protocol can offer over the DBTMA by allowing more communication pairs to exist in a small physical area. Specifically, the following scenario is considered: There is a MANET of 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 such constraint that C can successfully initiate a transmission (through RTS/CTS dialogue) with D. Formally, denote the probability by $Prob(C \to D)$. We want to determine

$$Prob(C \to D) \text{ subject to } \begin{cases} A \text{ sending a data packet to } B \\ \overline{AB} \leq r_{max} \\ \overline{CD} \leq r_{max} \\ \overline{BC} \leq 3r_{max} \end{cases}$$

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 constraint $\overline{BC} \leq 3r_{max}$ is imposed because beyond this distance the two transmissions ($A \to B$ and $C \to D$) 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

Table 1: Comparison on the probability $Prob(C \to D)$ given the condition that another communication $A \to B$ is ongoing.

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

accuracy. Also, we assume an ideal model that the difference $P_{min} - P_{noise} = \epsilon$ is an arbitrarily small value (i.e., the gap to distinguish a signal and a noise is negligible).

The discussion is separated into two cases depending on the value of $\overline{BC}$. Table 1 summarizes of our analysis result. The detailed derivation is in [14]. As can be seen, when $\overline{BC} \le r_{max}$, the $Prob(C \to D)$ of our protocol is about 40%, whereas it is impossible for DBTMA to grant $C \to D$. When $r_{max} < \overline{BC} \le 3r_{max}$, both protocols have a high success probability. This implies that our protocol is more useful when the density of mobile hosts is high.

5 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 to determine k power levels to maximize channel utilization.

Throughout this section, our development is based on Eq. (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 non-overlapping circles of radius r_{avg} that can coexist in a physical area, where r_{avg} is the average transmission distance in our protocol. Since we assume $n = 2$ in Eq. (1), the average of power levels, P_{avg}, used for transmission is proportional to r_{avg}^2. Therefore, to maximize channel utilization, we should minimize the expected value $E(P_{avg})$.

The following show that evenly spreading the k power levels is the best choice. The proof of the following Lemma is in [14].

Lemma 1 *Given an integer k, the k power levels, $\frac{1}{k}P_{max}$, $\frac{2}{k}P_{max}$, ..., and $\frac{k}{k}P_{max}$, give the minimum $E(P_{avg}) = \frac{k+1}{2k}P_{max}$.*

6 Simulation Results

We have developed a simulator to verify the performance of our scheme and compare our result to the DBTMA protocol. 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 = $8km \times 8km$
- maximum transmission distance (r_{max}) = 0.5 or 1.0 km
- number of mobile hosts = 600
- speed of mobile host = 0 or 125 Km/hr.

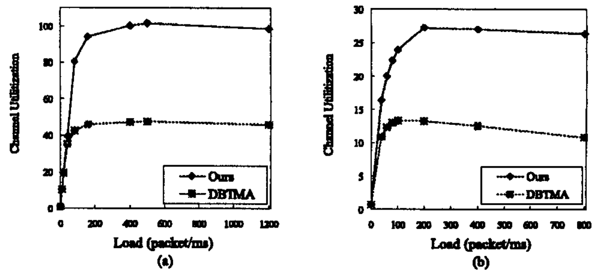

Figure 6: Channel utilization vs. traffic load when (a) r_{max} = 0.5 Km and (b) r_{max} = 1.0 Km.

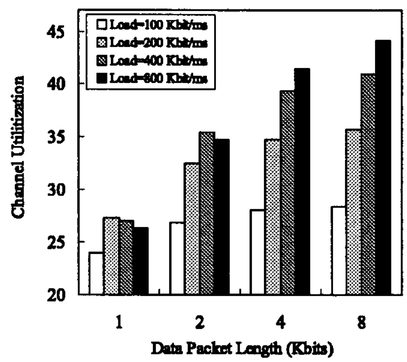

Figure 7: Channel utilization vs. data packet length at various traffic loads.

- length of control packet = 100 bits
- link speed = 1 Mbps
- 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. 6 shows the channel utilization of the DBTMA and our protocols at different traffic loads when r_{max} = 0.5 Km. Data packets are fixed at 1000 bits in length. From Fig. 6(a), we see that at low traffic load ($\le$ 20 packets/ms) both protocols deliver about the same channel utilization. However, at higher traffic load ($\ge$ 80 packets/ms), our protocol can deliver about 2 times channel utilization that of the DBTMA. Moving to Fig. 6(b), we further observe more benefit of power control as r_{max} is enlarged to 1 km. Hence power control is of more importance when radio signals are more likely overlap with each other.

Next, we observe the effect of packet length. Fig. 7 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.

The above simulations use infinite power levels. We also simulated discrete power levels and observed its effect on

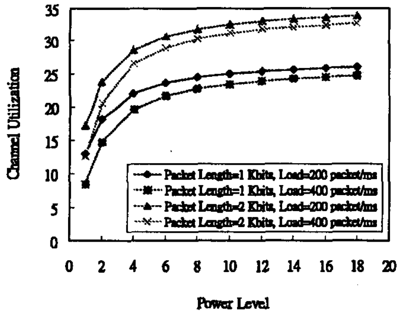

Figure 8: Channel utilization vs. number of power levels at $r_{max} = 1$ Km, arrival rate = 200 or 400 packets/ms, and packet length = 1 or 2 Kbits.

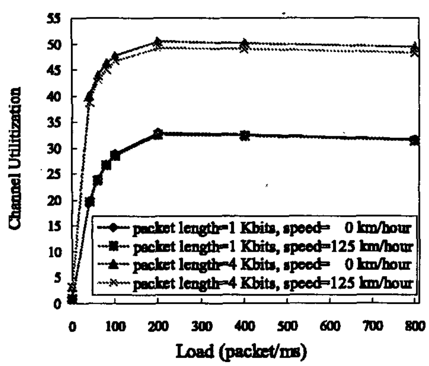

Figure 9: Channel utilization vs. traffic load when hosts have no mobility and when hosts move at 125 Km/hr. The transmission distance $r_{max} = 1$ Km.

channel utilization. Setting $r_{max} = 1$ Km, arrival rate = 200 or 400 packets/ms, and packet length = 1 or 2 Kbits, Fig. 8 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. But using 4 to 6 power levels can deliver a channel utilization close to that of using infinite power levels. This shows the practical value of our result.

The previous simulations are based on no host mobility. Fig. 9 demonstrates the effect of host mobility. We compare the channel utilization when hosts have no mobility and when hosts move at 125 Km/hr with random direction. The results show that the effect of host mobility to channel utilization is negligible at the MAC layer, which is the same as the observation in [3].

7 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 serious wasting the medium. In this paper, we have proposed a new MAC protocol for MANETs that utilizes 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. 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.

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