Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2006, Article ID 36040, Pages 1–10
DOI 10.1155/WCN/2006/36040

Autonomous Power Control MAC Protocol for Mobile Ad Hoc Networks

Hsiao-Hwa Chen,[1] Zhengying Fan,[2] and Jie Li[3]

[1] *Institute of Communication Engineering, National Sun Yat-Sen University, Kaohsiung 804,Taiwan*
[2] *Tech. Department, FDC Inc. Ltd. Co., Tsuchiura 300-0873, Japan*
[3] *Graduate School of Systems and Information Engineering, University of Tsukuba, Tsukuba, 305-8573, Japan*

Received 18 July 2005; Revised 13 December 2005; Accepted 13 December 2005

Battery energy limitation has become a performance bottleneck for mobile ad hoc networks. IEEE 802.11 has been adopted as the current standard MAC protocol for ad hoc networks. However, it was developed without considering energy efficiency. To solve this problem, many modifications on IEEE 802.11 to incorporate power control have been proposed in the literature. The main idea of these power control schemes is to use a maximum possible power level for transmitting RTS/CTS and the lowest acceptable power for sending DATA/ACK. However, these schemes may degrade network throughput and reduce the overall energy efficiency of the network. This paper proposes autonomous power control MAC protocol (APCMP), which allows mobile nodes dynamically adjusting power level for transmitting DATA/ACK according to the distances between the transmitter and its neighbors. In addition, the power level for transmitting RTS/CTS is also adjustable according to the power level for DATA/ACK packets. In this paper, the performance of APCMP protocol is evaluated by simulation and is compared with that of other protocols.

1. INTRODUCTION

Recently, the research on wireless networks has gained a great amount of attention. One of the most important research areas is MANETs (mobile ad hoc networks, also called mobile multihop wireless networks) [1]. A MANET can be defined as a collection of wireless mobile nodes (e.g., portable computers or PDAs (personal digital assistances)) (or nodes for brevity) that form a dynamically changing network, without using any existing network infrastructure or centralized administration. Such a network is created as the nodes communicate with each other, with each having capability to act as a router whenever necessary. Therefore, the network topology changes dynamically as some nodes join or leave the network. In MANETs, a connection session can be established either through a single-hop transmission if the communication pairs are close enough, or through multihop relay by intermediate nodes.

Different from other types of wireless networks, a MANET does not need fixed infrastructure such as base stations or access points. Thus, a MANET can be deployed quickly and provide communications in any place where a fixed communication infrastructure is unreliable or unavailable. Now MANET has been found very useful in emergency conferences, military, and disaster rescue operations. Moreover in recent years, new applications have been developed for commercial use due to the development of mobile computing and wireless technologies.

Since mobile nodes are usually powered by batteries that provide only a limited amount of energy, how to reduce the energy consumption is of great importance for providing QoS (quality of service) assurance for MANETs. In this paper, we will focus on the design of energy-saving medium access control (MAC) sublayer protocol for MANETs.

There are two ways to reduce energy consumption in MAC protocol design. One way is to use power saving mechanisms, which allow a node to enter a doze state by powering off its wireless network interface whenever possible [2]. The other way is to use transmit power control schemes which use carefully controlled transmit power level to reduce energy consumption [3, 4]. In this paper, we are in particular interested in controlling transmit power to reduce energy consumption. It is to be noted that in MANETs transmitting power control is important for other two more reasons: (1) it affects the traffic carrying capacity of MANETs; and (2) it affects the spatial reuse.

Due to the dynamic nature of MANETs, to achieve an efficient power control for MAC protocols is a challenging issue. Especially, to design a simple, fair, and energy efficient medium access control (MAC) protocol for MANETs has become an important research topic. Recently, various energy efficient MAC schemes have been proposed, but most of them do not perform well enough. The motivation of this paper is to architect a MAC protocol with an effective power control scheme, for MANETs, that is, to propose an autonomous power control MAC protocol (APCMP), which should perform well under dynamically changing topology of MANETs. The careful computer simulation is conducted to evaluate the performance comparing with the IEEE 802.11 and an existing power control protocol by using NS-2 (network simulator version 2) [5]. It is shown that the proposed APCMP protocol offers better energy efficiency as well as throughput.

This paper is organized as follows. Section 2 introduces the related work mainly focusing on the IEEE 801.11 MAC protocol and the basic power control MAC protocol. In Section 3, we propose the novel autonomous power control MAC protocol (APCMP) for MANETs. The performance evaluation is conducted by simulation in Section 4. Section 5 concludes the paper.

2. RELATED WORK

The primary goal of a MAC protocol for MANETs is to coordinate the channel access among multiple nodes to achieve high channel utilization. In other words, the coordination of channel access should minimize or even eliminate the incidence of collisions and maximize spatial reuse at the same time. IEEE 802.11 [6] is probably the most widely used MAC protocol. In this paper all the study will focus on the IEEE 802.11 MAC protocol and its power control schemes.

2.1. IEEE 802.11 MAC protocol

IEEE 802.11 defines two MAC protocols. One is distributed coordination function (DCF) which is a fully distributed scheme. The other is point coordination function (PCF), which is a centralized scheme. The DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA) with an extension of RTS/CTS handshake mechanism to reduce packet collision and to solve the hidden terminal problem. The DCF is by far the most dominant MAC protocol for MANETs. We focus on DCF in this paper.

In the CSMA protocol, as in the case of the Ethernet, a node which wants to transmit data packet should first senses whether there is a carrier in the channel or not. If it does sense a carrier in the channel, it waits for some random interval of time and then senses the carrier again; if there is no carrier in the channel, then it starts to send its data over the channel. However, unlike the Ethernet, it is not possible for a node to detect collision at the receiver. The use of carrier sense alone causes the hidden and exposed terminal problems, as discussed below.

In Figure 1, suppose node 2 is visible to nodes 1 and 3, but node 3 is not visible to node 1 (“visible” means that within a radio range of the node). When node 1 transmits packet to node 2, node 3 does not know if node 2 is busy or not and may also transmit packets to node 2. Therefore, collision will occur at node 2. Here, node 1 has no way to detect the potential competitor node 3 because node 3 is too far away from node 1. This problem for the medium access is called *hidden terminal problem*. The hidden terminal problem in medium access of wireless networks can be solved by the MACA (medium access collision avoidance) scheme. MACA employs a RTS/CTS (request to send/clear to send) handshake between a transmitter and a receiver. In MACA, when a transmitter wants to send data packets, it begins with sending a RTS packet to the receiver. When the receiver receives RTS, it sends back a CTS packet to the transmitter. Once the transmitter receives CTS, it starts transmitting DATA packets. Then the receiver responds DATA packet with an ACK packet. When the transmitter receives an ACK packet from the receiver, the transmission can be considered as successful.

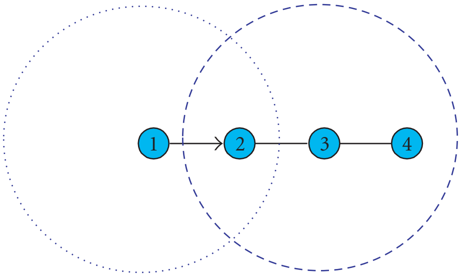


Figure 1: Illustration of the hidden terminal problem.

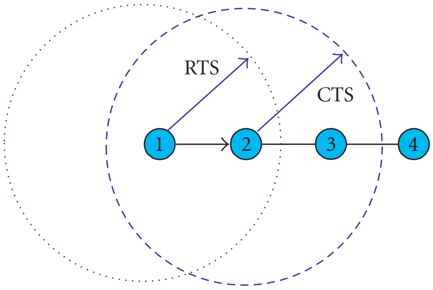


Figure 2: RTS/CTS handshake in 802.11.

IEEE 802.11 extends the CSMA by adding the RTS/CTS handshake and solves the hidden terminal problem, as shown in the following example. Suppose there are several nodes in a MANET as shown in Figure 2. When node 1 wants to transmit to node 2, it first sends a RTS packet. After receiving RTS packet, node 2 will reply with a CTS packet. CTS is also received by all neighboring nodes of node 2. Since node 3 is within the radio range of node 2, it is a neighbor of node 2 and will also receive the CTS packet. Because the duration of current transmission is recorded in the CTS packet, node 3 will know the time interval of on-going transmission and wait before the time is expired. Therefore, even if node 3 wants to transmit, it will keep silent when node 1 transmits

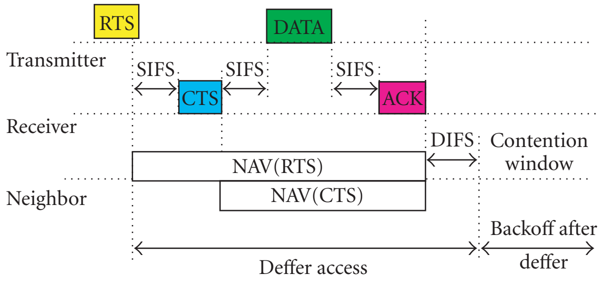


Figure 3: Timing diagram for a transmitter-receiver pair in IEEE 802.11 MAC protocol.

to node 2. Thus the problem of hidden terminal of node 3 is avoided by RTS/CTS handshake.

The timing diagram for a complete transmission cycle according to IEEE 802.11 is shown in Figure 3. In the figure, the time interval between packets is called IFS (interframe space). A node determines if the medium is idle using the carrier-sense function for the interval specified. Different IFSs are defined to provide different priority levels for access to the wireless media. Here, the shortest IFS, SIFS (short interframe space), is used to separate transmissions belonging to the same long message as shown in Figure 3. In IEEE 802.11 this value is set to 28 milliseconds. Another IFS, DIFS (distributed IFS), is used for a node to start a new transmission. It is set to 128 milliseconds. NAV (network allocation vector) is the medium reservation information stored in all nodes that received RTS or CTS packet. The current transmission duration is specified in the duration filed of RTS or CTS packet. Once neighbor nodes receive RTS or CTS, they will defer their access for the time indicated in the packets. The hidden nodes that did not detect the RTS will receive the CTS and update their NAV accordingly. Thus, collision caused by hidden terminal problem can be avoided by this method. After a transmission is finished for a transmitter or NAV is time out for a neighbor node, the nodes that want to send data will contend for the wireless medium. If the node senses a busy medium, it takes a random back-off period. After the period, the node begins to transmit. But if the medium is seized by another node, the node will set its NAV to a new value for subsequent transmission trials.

As a summary, the IEEE 802.11 MAC protocol avoids the collisions caused by hidden terminal problem in MANETs, and is widely used. However, there is no consideration of power control in the protocol at all. IEEE 802.11 consumes significant battery power since transmitters send all kinds of packets at the same transmitting power level all the time.

2.2. Basic power control MAC protocol

Recently, some power control MAC protocols that can be incorporated with the IEEE 802.11 protocol have been proposed [3, 4]. A typical scheme is to use the lowest possible power level for transmitting data packets whereas to use the maximum possible power level for control message packets. We refer to those protocols as basic power control MAC protocol (BPCMP). Next, we take a look at the BPCMP and discuss its limitations.

2.2.1. Description of BPCMP

The power control for the MAC protocols is to choose the right transmit power levels for different packets in a MANET. The transmit power levels will affect the radio range, battery life time, and capacity of the network. Some power controlled MAC protocols that can be incorporated into the IEEE 802.11 protocol have been proposed. The basic scheme allows a node to specify its current transmit power level according to different packet types. Such protocols are called the basic power control MAC protocol (BPCMP) [4]. Unlike IEEE 802.11 which sends all packets at the same power level, BPCMP sends RTS/CTS packets using the maximum possible power level but sends DATA/ACK packets at the lowest acceptable power level.

Figure 4 illustrates the timing of sending RTS/CTS using the maximum power level, $p_{\max}$, and DATA and ACK packets using the lowest possible power level, p_{desired}. Figure 5 shows an example of radio range, where the transmit power level for RTS/CTS is 30 mW and the lowest acceptable transmit power level for DATA/ACK is 1 mW.

In BPCMP, the desired power level for transmitting DATA/ACK is determined after RTS/CTS handshake. The procedures for a complete transmission cycle are described as follows.

(1) The transmitter sends RTS packets using the maximum possible power level $p_{\max}$.

(2) The receiver receives the RTS at signal power p_{rec}, and calculates the minimum desired transmit power level p_{data} for transmitting data packets as follows:

$$p_{\text{data}} = \frac{p_{\max}}{p_{\text{rec}}} \times Rx_{\text{thresh}}, \qquad (1)$$

where Rx_{thresh} is the lowest acceptable received signal strength. Then, the receiver marks the minimum desired transmit power level in the control message field of CTS and sends CTS back to the transmitter.

(3) Once having received CTS, the transmitter begins to transmit data packet using the power level p_{data}.

(4) The receiver sends back an ACK as soon as it receives DATA. The transmitting power level for sending ACK is determined in a similar way as done for DATA.

2.2.2. Problems with BPCMP

There are several problems with BPCMP. (1) Using the fixed transmitting power level, $p_{\max}$, for RTS/CTS is not energy efficient since the distance between the transmitter and the receiver may change from time to time. (2) The transmission at maximum possible power level causes to interfere other existing radio applications. (3) Different transmitting power levels result in asymmetric topologies, and thus may consume more energy [4]. Furthermore, the BPCMP was proposed under the assumption that signal attenuation between transmitters and receivers is kept the same in both

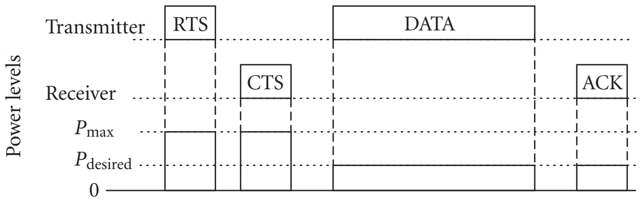


Figure 4: Timing diagram of different power level in BPCMP.

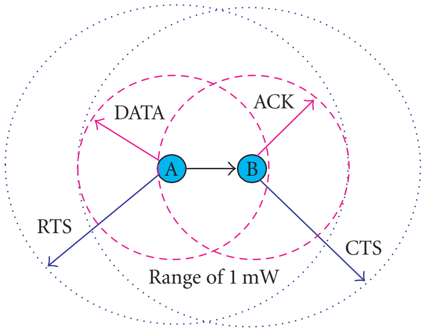


Figure 5: Ranges of different power levels in BPCMP.

transmission directions. It may make the communications unreliable if the assumption is not held.

In summary, the BPCMP adopts the maximum possible transmitting power level for sending RTS/CTS packets and the minimum desired transmitting power level for sending DATA/ACK packets for implementing power control in MANETs. As indicated by our simulation results, it does not work so well in terms of energy efficiency. In addition, it degrades the overall network capacity.

3. AUTONOMOUS POWER CONTROL MAC PROTOCOL

In this section, we propose a novel autonomous power control MAC protocol that can adjust the transmitting power for DATA/ACK packets as well as RTS/CTS packets according to the current network condition in order to reduce the energy consumption whereas the performance of the whole network should not be much sacrificed. The main idea for the protocol is to use an appropriate power levels for transmitting DATA/ACK packets and the RTS/CTS packets followed. We will show through simulation that the new protocol is more energy efficient and more spatial reusable than BPCMP (basic power control MAC protocol), and at the same time it is simple to be implemented. In the sections below, we explain the consideration and the design of the proposed MAC protocol.

One of the salient features of a MANET is its dynamic network topology. As mobile nodes may move randomly in a MANET, the distances between transmitters and receivers may change arbitrarily. The transmitting power level should be adjustable depending on the distance. Existing BPCMP adjusts the transmitting power for sending DATA and ACK packets to a minimum required level. However, it still needs a fixed maximum possible power level to transmit RTS and CTS packets. Since the network topology changes dynamically, the power level for sending RTS and CTS also needs to be adjusted according to the current node density. The appropriate power level brings in several advantages, such as energy saving, spatial reuse, and collisions reduction.

Using the adjustable transmitting power level, however, may result in different power levels used by different transmitters in the network. It may in turn cause excessive collisions. Furthermore, it seems that it is impossible to have the optimal transmitting power level according to global network condition dynamically. Here we try to adjust the transmitting power level locally within a local neighboring node group and to have an approximately similar power level for all the neighboring nodes. In the proposed protocol, transmitting power level for a local node group is adjusted to an approximately similar value in two ways. One is to adopt an appropriate power level for transmitting DATA/ACK, depending on the average distance from the transmitter to all current neighbors. The other one is to adjust the power level for transmitting next RTS/CTS to a value proportional to the DATA/ACK power level. Thus the energy consumption can be reduced by collisions avoidance.

In a MAC protocol, we note that the distance can be estimated by using the transmitting power level at a transmitter and the actual received signal power level at a receiver. Thus, bidirectional links between transmitters and receivers can be ensured, as long as the transmitters/receivers transmit packets using some suitable power level, at which the receivers/transmitters can receive the same signal power level. Using the estimated distance information, the adjust power level could be calculated.

Furthermore, the power control should also be conducted in conjunction with routing, since it needs to keep connectivity. Conversely, routing depends on power control since the available coverage of transmitters depends on the transmitting power levels. A key feature of a wireless channel is that it is a shared medium. An excessively high power level causes excessive interference. This consequently reduces the traffic carrying capacity of the network in addition to reduced battery life time. Therefore, it is desirable to use a transmitting power level as low as possible [7].

Based on aforementioned considerations, in our protocol the transmitting power for sending RTS/CTS packets should be adjusted to a level just slightly higher than that required for transmitting DATA/ACK packets. On the other hand, to guarantee connectivity of the network, we increase the transmitting power level gradually if it is too low to reach any other node.

3.1. *Calculation of transmitting power level*

In the proposed power control MAC protocol, the distance information is used to determine the transmitting power level. Assume that the noise level at a receiver is lower than the signal level. It is common to model signal attenuation by $d^{1/k}$, where d is the distance between a transmitter and a receiver and k is a coefficient for $k \geq 2$. Thus, the distance d can be estimated by

$$d = \sqrt[k]{\frac{p^{*}_{\mathrm{RTS/CTS}}\alpha}{p_{\mathrm{rec}}}}, \tag{2}$$

where $p_{\mathrm{RTS/CTS}}$ is the transmitting power level for the RTS/CTS packet, p_{rec} is the received signal power level, and α is a constant depended on the antenna gain, system loss, and wavelength, and so forth. For brevity, we set $\alpha = 1$ in the paper.

For a given transmitter, suppose that there are already $m - 1$ mobile nodes being its neighboring nodes (i.e., it can send data directly without passing through a relaying neighboring nodes). For the implementation, we can let the transmitter to keep the most current $m-1$ records of the estimated distances to its $m - 1$ neighbor nodes, respectively. Now consider that the transmitter wants to send a data packet to another mobile node, namely, the mth node. At first, the distance from the transmitter to the mth mobile node is estimated. Then, the average estimated distance from the transmitter to the m mobile nodes (neighbors) is calculated as follows:

$$\overline{d} = \frac{1}{m}\sum_{i=1}^{m} d_i, \tag{3}$$

where d_i is the estimated distance from the transmitter to the ith neighbor.

The power level for transmitting DATA or ACK, $p_{\mathrm{data/ack}}$, from the transmitter to the mth neighbor is determined by

$$p_{\mathrm{data/ack}} = \overline{d}^{k} \times Rx_{\mathrm{thresh}}, \tag{4}$$

where Rx_{thresh} is the minimum necessary received signal strength.

Note that in the proposed protocol, $p_{\mathrm{data/ack}}$ from the transmitter to the mth neighbor is determined depending on average estimated distance $\overline{d}$ instead of d_m. For the case $d_m > \overline{d}$, the transmitter may have to cancel the transmission to the mth mobile node directly due to the insufficient transmitting power level and the data packet has to be transmitted via one of its neighbors, which is closer to it. The reason for using the average estimated distance $\overline{d}$ is trying to obtain a similar power level for the data packet transmission to all m mobile nodes and the packet is routed by shorter hops.

In the proposed protocol, the transmitting power level for the next RTS/CTS, $p'_{\mathrm{RTS/CTS}}$ is given as follows:

$$p'_{\mathrm{RTS/CTS}} = p_{\mathrm{data/ack}} \times c, \tag{5}$$

where c is a parameter related with the network situation, and $c > 1$.

It is to be noted that changing the power level for RTS/CTS will affect the number of neighbors seen by each transmitter, and thus the number of neighbors it has to contend with for medium access. At the same time, changing the radio coverage range of a transmitter will change the number of hops in routing, and consequently the amount of traffic that each node has to carry. The parameter c may depend on the local node density and traffic load. When the node density is larger, for example $m > 5$, it is reasonable to have a smaller value of c. Otherwise, we should set a larger value for c.

3.2. *APCMP algorithm*

The algorithm carried out in the APCMP consists of four major steps as introduced below.

(1) First, a transmitter sets the values of $p_{\mathrm{RTS/CTS}}$ (also denoted by p_{RTS_T}) and p_{ack_R}, which is stored in the routing table, into the RTS packet, where p_{ack_R} is the transmitting power level for the receiver to transmit ACK. If the value of p_{RTS_T} is NULL (which means that it is not available), it will be set to the value of the current transmitter's power level for transmitting DATA (i.e., p_{data}). Then the transmitter will send the RTS using the transmitting power level $p_{\mathrm{RTS/CTS}}$.

In the receiver's side, the receiver will receive the RTS packet by power level p_{rec} and obtain p_{RTS_T} and p_{ack_R} carried in RTS packet. With these values, it can calculate the desired power level p_{data_T} for transmitting DATA packets as follows:

$$p_{\mathrm{data}_T} = \frac{p_{\mathrm{RTS}_T}}{p_{\mathrm{rec}}} \times Rx_{\mathrm{thresh}}. \tag{6}$$

The receiver estimates the distance from the current transmitter by using p_{ack_R}. With the estimated distance information, new power level $p_{\mathrm{data/ack}}$ and $p'_{\mathrm{RTS/CTS}}$ for the receiver is calculated from (4) and (5). The value $p'_{\mathrm{RTS/CTS}}$ is set as the new $p_{\mathrm{RTS/CTS}}$ for the receiver. Then, the receiver sends the values of $p_{\mathrm{RTS/CTS}}$ (as p_{CTS_R}) and p_{data_T} in the CTS packet to the transmitter with the new power level $p_{\mathrm{RTS/CTS}}$.

(2) The transmitter receives the CTS packet by p_{rec} and obtains the values of p_{CTS_R} and p_{data_T} carried in the CTS packet. The desirable power level p_{ack_R} for the receiver to transmit ACK packet is obtained from

$$p_{\mathrm{ack}_R} = \frac{p_{\mathrm{CTS}_R}}{p_{\mathrm{rec}}} \times Rx_{\mathrm{thresh}}. \tag{7}$$

The transmitter calculates and saves the estimated distance to the current receiver d_r. The average distance $\overline{d}$ to all the neighbors that have been stored recently is calculated. Then, it can calculate $p_{\mathrm{data/ack}}$, $p'_{\mathrm{RTS/CTS}}$ and set $p'_{\mathrm{RTS/CTS}}$ as the new $p_{\mathrm{RTS/CTS}}$. After that, the transmitter begins to transmit data using $p_{\mathrm{data/ack}}$.

Table 1: The network components and parameters for a mobile node using a modified CMU's wireless model.

phyType Phy	WirelessPhy
antType	Antenna/OminiAntenna
ifqType	Queue/DropTail/PriQueue
MacType	Set to 3 MAC protocols, respectively
addressType	Flat
adhocRouting	DSDV (destination-sequenced distance vector)
Max. transmit power	281.8 mW
Radio range of Max power	250 m
Max packet in ifq	50
Channel width	2 Mbps

(3) If the transmitter does not receive CTS packet after a time out, it will increase the power level for transmitting RTS/CTS to a predefined value and send RTS again.

(4) The receiver will send back the ACK packet using the power level $p_{\text{data/ack}}$ after receiving the data packet. When the transmitter receives ACK before the time out expires, the transmission cycle is finished successfully. Otherwise, the transmitter will transmit again in a similar way up to the maximum retransmission times.

4. PERFORMANCE EVALUATION

The performance of APCMP is evaluated through computer simulation. At first, we implement autonomous power control MAC protocol by NS-2 (network simulator version 2) [5] (v2.27), which is a discrete event-driven simulator. The NS-2 is widely used for MANETs research. Some existing MAC protocols used in MANETs, such as IEEE 802.11, have been also implemented in it. The NS-2 was developed in two languages, C++ and OTcl. C++ language runs faster but is difficult to debug, making it suitable mostly for detailed protocol implementation. On the other hand, the OTcl runs much slower but is easier to modify, making it ideal for simulation configuration and setup. Currently, the NS-2 runs in Unix/Linux operating system. In our simulation it was installed into a Linux-like environment on Windows XP operating system, which is provided by Cygwin [8].

4.1. Simulation models

A modified CMU's wireless model [9] for MANETs was used as a basic wireless interface model. The network components and parameters for a mobile node are listed in Table 1.

In order to thoroughly simulate a new protocol for MANETs, it is important to use a mobility model that accurately represents the mobile nodes. In our simulation, the node movements are modeled by the random waypoint (RWP) model [10], which was developed by CMU and has been popularly used in the simulation of MANETs. The RWP is a simple synthetic mobility model based on random directions and speeds to realistically represent the behaviors of mobile nodes.

In the RWP model, each node chooses uniformly at random a destination node in a rectangular region. A node moves to this destination with a velocity chosen at random uniformly in the predefined interval (i.e., (min. speed, max. speed)). When it reaches the destination, it remains static for a pause time and then starts moving again according to the same rule. It has been observed in [11, 12] that the spatial distribution of mobile nodes according to the RWP model is nonuniform. For the cases where a node can remain static for the entire simulation time, the pause time is predefined as a constant in our simulation.

The traffic is modeled by CBR (constant bit rate) packet flows with fixed generation rate of ten packets per second. The size of a CBR packet is 512 kB, and it becomes 20 kB larger after a routing header is added in case of DSDV (destination-sequenced distance vector) routing. The maximum packet number for a session is set to 10 000. And the transmitter and the receiver of a CBR session are chosen randomly among the nodes. The starting time of a session is also randomly chosen between 0 and 200 seconds, so a session always finishes at the end of the simulation. The traffic load varies by increasing the number of CBR sessions. For example, 10 CBR sessions will be generated when the number of nodes is set to 20.

4.2. Performance metrics

To judge the merit of a protocol for MANETs, three common qualitative metrics are used in our performance evaluation as explained below.

(i) Delivery ratio: it is ratio of the number of data packets correctly delivered out of the total number of data packets sent. In fact it is an external measure of connectivity performance. This value (always less than one) should be as large as possible.
(ii) Throughput: it is the number of data bits delivered per second. It also implies the performance of network capacity. The higher the value is, the better the performance becomes.
(iii) Rate of energy efficiency: it is the number of data bits delivered per joule energy consumed, which indicates the energy efficiency. The higher the rate means the more energy efficient.

4.3. Simulation results

The proposed APCMP protocol has been compared with IEEE 802.11 and BPCMP based on the aforementioned three metrics for performance evaluation. The effects of the number of nodes and the maximum moving speeds are studied. The results are plotted in the figures with respect to the above three performance metrics.

4.3.1. Effects of number of nodes

First, we study the effects of number of nodes in a MANET. The parameter setting is generated as follows. Nodes are placed in a 500 m × 500 m square area. The constants, k, c,

Table 2: The number of nodes and traffic sessions for simulation runs in scenario 1.

Number of nodes	2	4	6	8	10
Number of CBR sessions	1	2	3	4	5

and m used in the proposed protocol are set to be 2, 1.2, and 5, respectively. The random waypoint model with pause time being two seconds was used to model the node movements. And the maximum speed of each node is set to be zero and ten m/s, respectively. Total simulation time for each scenario is 221 seconds. The number of nodes and traffic sessions are listed in Table 2.

The simulations were carried out for IEEE 802.11 MAC protocol, BPCMP, and APCMP, respectively. Figures 6, 7, and 8 plot the results when nodes do not move, while Figures 9, 10, and 11 provide results when the maximum node moving speed is 10 m/s. All the simulation results were obtained with 95% confidence interval.

Figure 6 shows that when nodes keep static and the number of nodes and traffic increase, our protocol (denoted by the line for "proposed") keeps a high delivery ratio that can be higher than 0.99, which is very close to IEEE 802.11. Whereas the BPCMP performs the worst in delivery ratio, which can reach to about 0.94. For the throughput, there is not much difference among the three protocols as shown in Figure 7. Figure 8 shows that the proposed protocol is the most energy efficient one, where the energy consumption of APCMP protocol is about 83% of the BPCMP protocol, and only about 49% of the 802.11 protocol.

When the node moving speed is 10 m/s, the delivery ratio of the proposed protocol is a little lower than that of the 802.11 MAC protocol, especially when the number of nodes increases to 10, as shown in Figure 9. The reason is that, as the number of nodes increases, the node density also increases and thus transmitting power level will be adjusted autonomously to a smaller value, leading to a temporary disconnection between the transmitter-receiver pair, which is too far away from each other. Therefore, the unsuccessful delivery will increase if compared with the 802.11, which uses a fixed maximum transmitting power. Nevertheless, APCMP still performs better than the BPCMP, which is just 95%. Although the 801.11 performs a little bit better than APCMP on the delivery ratio, it performs much worse than APCMP on the energy efficiency rate, as shown in Figure 11. From Figure 11, the rate of energy efficiency of the 802.11 is still the worst one. For more details, it is shown that the energy efficiency of APCMP is about 20% higher than that of BPCMP and 120% higher than that of 802.11 protocol. Figure 10 plots that the throughput of three protocols is close to each other.

4.3.2. Effects of the maximum node moving speed

Here we study the effects of the maximum node moving speed as it increases from zero to 21 m/s. The parameter setting is the same as that in Section 4.3.1 except the followings: (1) nodes are placed in a 1000 m × 1000 m square area;

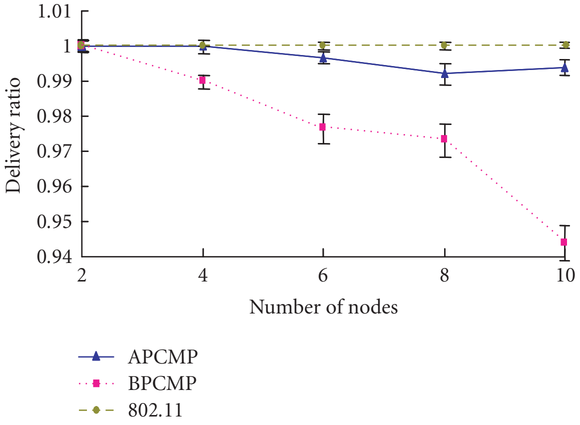


Figure 6: Comparison of delivery ratio (max. moving speed = 0).

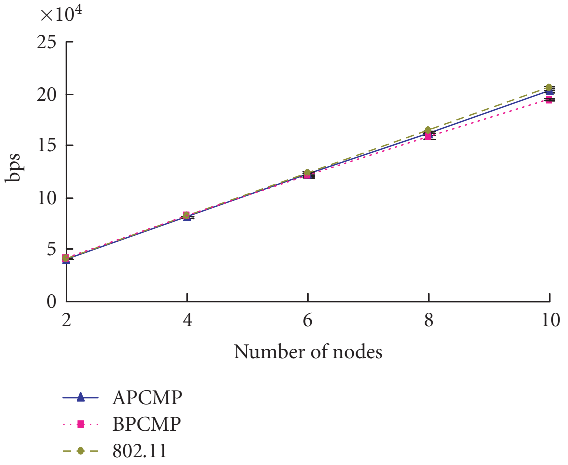


Figure 7: Comparison of throughput (moving speed = 0).

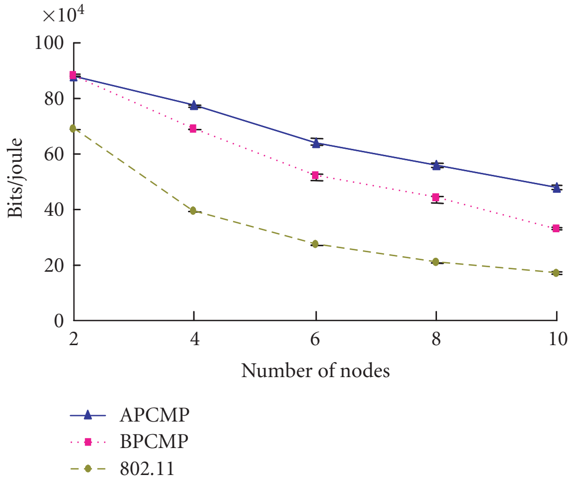


Figure 8: Comparison of energy efficiency (moving speed = 0).

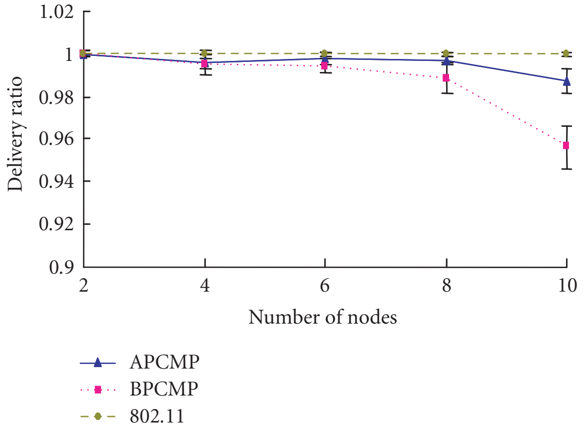


Figure 9: Comparison of delivery ratio (max. moving speed = 10 m/s).

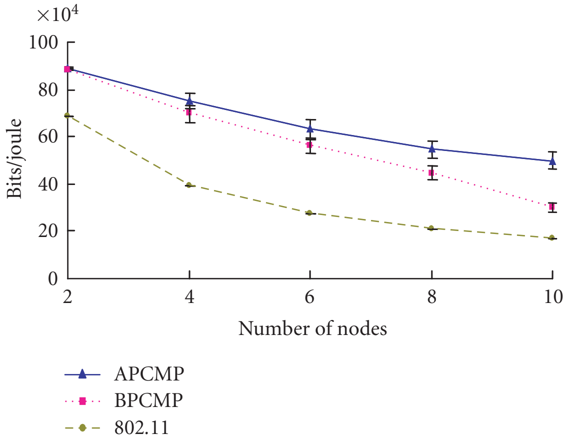


Figure 11: Comparison of energy efficiency (max. moving speed = 10 m/s).

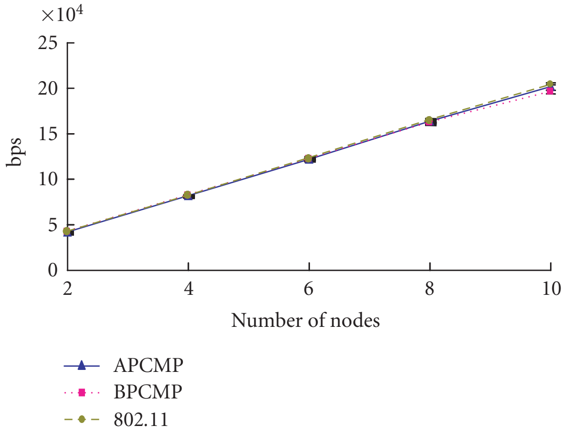


Figure 10: Comparison of throughput (max. moving speed = 10 m/s).

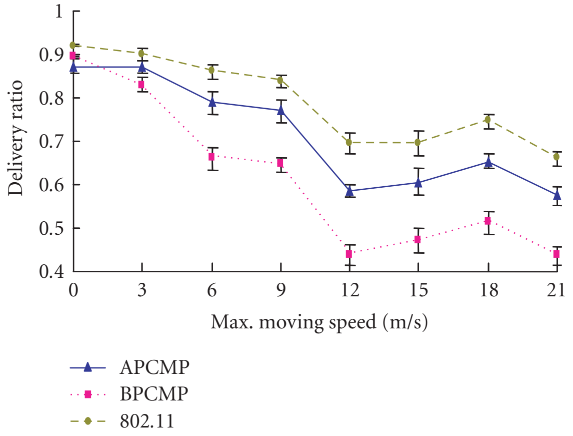


Figure 12: Comparison of delivery ratio (number of nodes: 20, CBR: 10).

(2) the number of nodes is set to be 20; and (3) the number of CBR sessions is set to be ten. The simulation results of delivery ratio, throughput, and rate of energy efficiency are shown in Figures 12, 13, and 14, respectively. The confidence interval is 95% in the simulations.

It is known from Figures 12 and 13 that the delivery ratio and throughput of our protocol is better than BPCMP but worse than 802.11, being about 118% of BPCMP and 90% of 802.11. In addition, it is to be noted that the delivery ratio and throughput decrease in general as node moving speed increases from zero to 12 m/s, as shown in Figures 12 and 13. However, when speed increases further from 12 m/s to 18 m/s, all the three protocols perform better. It is reasonable as faster node movements may generate more successful transmissions [13].

Figure 14 shows the ratio energy efficiency as node moving speed increases. APCMP protocol performs again the best, being about 60% of that for BPCMP and 73% of that for 802.11. It it seen from Figure 14 that BPCMP performs really badly as node moving speed increases and the number of nodes increases. It consumes more energy even than IEEE 802.11; whereas APCMP protocol is very robust in such a network scenario and provides the best energy saving performance.

In summary, the proposed APCMP protocol offers superb performance in terms of energy efficiency and mobility support and in particular suits applications in MANETs. Besides, APCMP protocol is simple to implement and can be incorporated easily into popular IEEE 802.11 protocol.

5. CONCLUSION

To reduce energy consumption is of great importance for providing QoS assurance in MANETs. The focus of this paper is on the design of power control MAC protocol for MANETs. A brief introduction of IEEE 802.11 MAC protocol and basic power control MAC protocol for MANETs motivated us to propose a simple and yet efficient autonomous

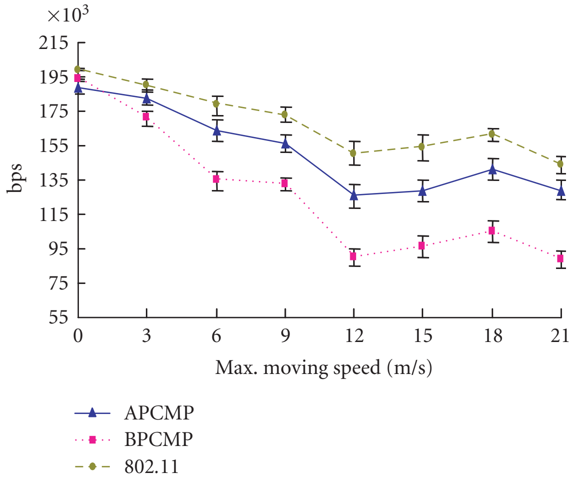


FIGURE 13: Comparison of throughput (number of nodes: 20, CBR: 10).

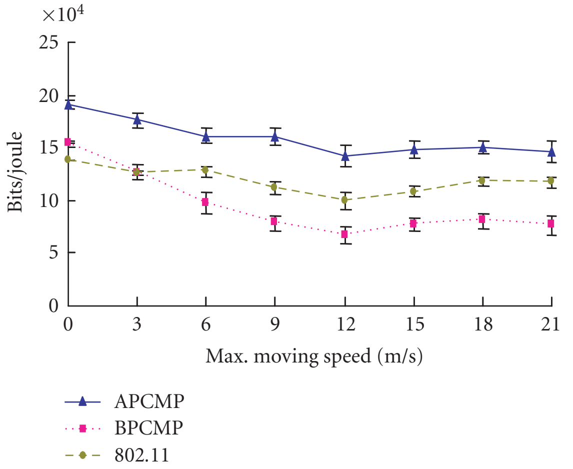


FIGURE 14: Comparison of energy efficiency (number of nodes: 20, CBR: 10).

power control MAC protocol (APCMP), in which transmitting power can be adjusted autonomously to an appropriate level according to network condition. The APCMP protocol has been evaluated by simulations under NS-2 and compared with other MAC protocols. It has been shown from the simulation results that APCMP protocol offers a very good energy efficiency and throughput under various mobility scenarios and is in particular suitable for the applications in MANETs.

ACKNOWLEDGMENTS

The work reported in this paper was supported partly by Research Grants NSC 94-2213-E-110-014 and NSC 94-2213-E-110-013. The work of Jie Li has been supported in part by JSPS under Grant-in-Aid for Scientific Research.

REFERENCES

[1] Internet Engineering Task Force (IETF) Mobile Ad Hoc Networks Working Group Charter, http://www.ietf.org/html.charters/manet-charter.html.

[2] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks," in *Proceedings of 7th Annual International Conference on Mobile Computing and Networking (MOBICOM '01)*, pp. 85–96, Rome, Italy, July 2001.

[3] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian, "Conserving transmission power in wireless ad hoc networks," in *Proceedings of the 9th International Conference on Network Protocols (ICNP '01)*, pp. 24–34, Riverside, Calif, USA, November 2001.

[4] E.-S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," in *Proceedings of the 8th Annual International Conference on Mobile Computing and Networking (MOBICOM '02)*, pp. 36–47, Atlanta, Ga, USA, September 2002.

[5] The Network Simulator—NS-2, 2004, http://www.isi.edu/nsnam/ns/.

[6] Institute of Electrical and Electronics Engineers, USA, IEEE 802.11 Draft Standard for Wireless LAN: Medium Access Control and Physical Layer Specification, draft p802.11d5.0 edition, July 1996.

[7] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, 2000.

[8] http://www.cygwin.com.

[9] The CMU Monarch Project, The CMU Monarch Project's Wireless and Mobility Extensions to NS.

[10] C. Bettstetter, G. Resta, and P. Santi, "The node distribution of the random waypoint mobility model for wireless ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 2, no. 3, pp. 257–269, 2003.

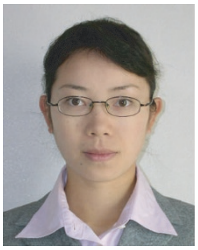
[11] C. Bettstetter, "Mobility modeling in wireless networks: categorization, smooth movement, and border effects," *ACM Mobile Computing and Communications Review*, vol. 5, no. 3, pp. 55–67, 2001.

[12] C. Bettstetter and O. Krause, "On border effects in modeling and simulation of wireless ad hoc networks," in *Proceedings of IEEE International Conference on Mobile and Wireless Communication Networks (MWCN '01)*, Recife, Brazil, August 2001.

[13] M. Grossglauser and D. N. C. Tse, "Mobility increases the capacity of ad hoc wireless networks," *IEEE/ACM Transactions on Networking*, vol. 10, no. 4, pp. 477–486, 2002.

Hsiao-Hwa Chen is currently a Full Professor in National Sun Yat-Sen University, Taiwan. He has authored or coauthored over 150 technical papers in major international journals and conferences, and four books, and three book chapters in the areas of communications. He served as a TPC Member and Symposium Chair of major international conferences, including IEEE VTC, IEEE ICC, IEEE Globecom, IEEE WCNC, and so forth. He served or is serving as an Editorial Broad Member or/and Guest Editor for IEEE Communications Magazine, IEEE Transactions on Wireless Communications, IEEE Vehicular Technology Magazine, Wireless Communications and Mobile Computing (WCMC) Journal and International Journal of Communication Systems, and so forth.

He has been a Guest Professor of Zhejiang University, Shanghai Jiao Tung University, China.



Zhengying Fan was born in Shaanxi, China. She received her B.S. degree in electronic sciences from Northwest University, China, in 1999, and her M.S. degree in information sciences and electronics from the University of Tsukuba, Japan, in 2005. Currently she is with the Tech. Department of FDC Inc. Ltd. Co, Japan.

Jie Li received the B.E. degree in computer science from Zhejiang University, Hangzhou, China, in 1982, the M.E. degree in electronic engineering and communication systems from China Academy of Posts and Telecommunications, Beijing, China, in 1985. He received the Dr. Eng. degree from the University of Electro-Communications, Tokyo, Japan, in 1993. Since April 1993, he has been with University of Tsukuba, Japan. He has been an Associate Professor since 1997. His research interests are in mobile distributed multimedia computing and networking, OS, network security, modeling, and performance evaluation of information systems. He received the Best Paper Award from IEEE NAECON'97. He is a Senior Member of IEEE, and a Member of ACM. He has served as a secretary for the Study Group on System Evaluation of the Information Processing Society of Japan (IPSJ) and on several editorial boards for IPSJ (Information Processing Society of Japan) Journal, and so on, and on Steering Committees of the SIG of System EVALuation (EVA) of IPSJ, the SIG of DataBase System (DBS) of IPSJ, and the SIG on Mobile Computing and Ubiquitous Communications of IPSJ. He has also served on the program committees for several international conferences such as IEEE Infocom, IEEE Globecom, and IEEE Mass.