A Multi-channel MAC Protocol with Power Control for Multi-hop Mobile Ad Hoc Networks

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In a mobile ad hoc network (MANET), one essential issue is Medium Access Control (MAC), which addresses how to utilize the radio spectrum efficiently and to resolve potential contention and collision among mobile hosts on using the medium. Existing works have been dedicated to using multiple channels and power control to improve the performance of MANET. In this paper, we investigate the possibility of bringing the concepts of power control and multi-channel medium access together in the MAC design problem in a MANET. Existing protocols only address one of these issues independently. The proposed protocol is characterized by the following features: (i) it follows an 'on-demand' style to assign channels to mobile hosts, (ii) the number of channels required is independent of the network topology and degree, (iii) it flexibly adapts to host mobility, (iv) no form of clock synchronization is required and (v) power control is used to exploit frequency reuse. Power control may also extend battery life and reduce signal interference, both of which are important in wireless communication. Through simulations, we demonstrate the advantage of our new protocol.

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1. INTRODUCTION

A mobile ad hoc network (MANET) is formed by a cluster of mobile hosts without fixed infrastructure provided by base stations. Due to the transmission range constraint of transceivers, two mobile hosts may communicate with each other either directly, if they are close enough, or indirectly, by having other intermediate mobile hosts relay their packets. Since no base stations are required, one major advantage of such a network is that it can be rapidly deployed. The applications of MANETs appear in places where pre-deployment of network infrastructure is difficult or unavailable (e.g. fleets in oceans, armies in action, natural disasters, battle fields, festival field grounds and historic sites). A working group called MANET [1] has been formed by the Internet Engineering Task Force (IETF) to stimulate research in this direction. Issues related to MANET have been studied intensively [2, 3, 4, 5, 6, 7, 8, 9, 10].

This paper concerns medium access control (MAC) in a MANET. A MAC protocol should address how to resolve potential contention and collision on using the communication medium. Many MAC protocols which assume a single common channel to be shared by mobile hosts have been proposed [11, 12, 13, 14, 15, 16]. We call such protocols single-channel MAC. A standard that has been widely accepted based on the single-channel model is the IEEE 802.11 [17]. One common problem with using a single channel is that the network performance will degrade seriously as the number of mobile hosts increases, due to higher contention/collision.

There are two directions that may increase the performance of a MANET. The first direction is to use a more complicated multiple-access mechanism. For example, the MAC protocol in [18, 19] empowers mobile hosts to send busy tones so as to emulate the collision detection function as that in wired Ethernet. Another example is the MAC protocol in [20], which integrates power control to increase channel reuse.

The second direction is to empower a mobile host to access multiple channels. For example, consider the currently hot CDMA technology; this may mean that a mobile host can utilize multiple codes simultaneously, or dynamically switch from one code to another as needed. We thus define a multi-channel MAC protocol as one with such capability. Using multiple channels has several advantages. First, while the maximum throughput of a single-channel MAC protocol will be limited by the bandwidth of the channel, the throughput may be increased immediately if a host is allowed to utilize multiple channels. Second, as shown in [6, 21], using multiple channels will experience less normalized propagation delay per channel than its single-channel counterpart, where the normalized propagation delay is defined to be the ratio of the propagation time over the packet transmission time. Therefore, this reduces the probability of collisions. Third, since using a single channel is difficult to support quality of service, it is easier to do so by using multiple channels [22].

In this paper, we treat channels at a logical level. A channel could be a code under the CDMA technology, or a frequency band under the FDMA technology. Disregarding the technology used, we can categorize a mobile host's transmission capability as follows.

- *Single transceiver.* A mobile host can only access one channel at a time. However, note that this is not necessarily equivalent to the single-channel model, because the transceiver is still capable of switching from one channel to another. (Under current technology, it is possible for a transceiver to switch from one channel to another in 1 μs [23, 24].) The transceiver can be simplex or duplex.
- *Multiple transceiver.* Each transceiver could be simplex or duplex. A mobile host can concurrently access multiple channels at the same time.

In this paper, we try to bring the concepts of power control and multi-channel medium access together in the MAC design problem in a MANET. Existing protocols only address one of these issues independently (see Section 2 for detailed reviews). We propose a new multi-channel MAC protocol with power control when using channels. The goal of power control is to properly reduce transmission power so as to increase channel reuse. Our protocol is characterized by the following features: (i) it follows an 'on-demand' style to access the medium and thus a mobile host will occupy a channel only when necessary, (ii) the number of channels required is independent of the network topology and (iii) no form of clock synchronization is required. In contrast, most existing protocols assign channels to a host statically even if it has no intention to transmit [25, 26, 27], requires a number of channels which is a function of the maximum connectivity [2, 25, 26, 27], or necessitates a clock synchronization among all hosts in the MANET [8, 27].

Simulation results are presented. Issues investigated include the effects of the number of available channels, the length of packets, the density of mobile hosts, the number of power levels and the mobility of mobile hosts. The results show that our protocol is very promising for improving the performance of a MANET.

The rest of this paper is organized as follows. Some reviews on multi-channel medium access and power control are in Section 2. Section 3 presents our new multi-channel MAC protocol. Simulation results are given in Section 4. Conclusions are drawn in Section 5.

2. REVIEWS

In this section, we review existing MAC protocols that address the issues of multi-channel access control and power control.

2.1. Multi-channel MAC protocols

A multi-channel MAC protocol typically needs to address two issues: *channel assignment* (or *code assignment*) and *medium access*. The former is to decide which channels are to be used by which hosts, while the latter is to resolve the contention/collision problem when using a particular channel. There already exist many related works [2, 6, 8, 18, 20, 25, 26, 27, 28, 29, 30, 31] in the literature.

References [25, 26, 28, 29, 31] are for channel assignment in a traditional packet radio network, and thus may not be appropriate for a MANET, which has mobility. Two IEEE 802.11-like protocols are proposed in [18, 20], which separate control traffic and data traffic into two distinct channels. However, this is a special case because only one data channel is allowed. A scheme based on the Latin square is proposed in [27], which assumes a TDMA-over-FDMA technology. The channel assignment is static, and to achieve TDMA, a clock synchronization is necessary (which is difficult, especially for a large-scale MANET). Furthermore, a number of transceivers which is equal to the number of frequency bands is required, which is very costly. The protocol in [30] also assigns channels statically. It is assumed that each host has a polling transceiver and a sending transceiver. The polling transceiver hops from channel to channel to poll potential senders. Once polled, an intending sender will use its sending transceiver to transmit its packets. How to assign channels to mobile hosts is not addressed in this work. The drawbacks include a long polling time and potential collisions among polling signals. The protocol in [2] assigns channels to hosts dynamically. It mandates that the channel assigned to a host must be different from those of its two-hop neighbors. To guarantee this property, a large amount of update messages will be sent whenever a host determines any channel change on its two-hop neighbors; this is inefficient in a highly mobile system. Further, this protocol is 'degree-dependent' in that it dictates a number of channels of an order of the square of the network degree, so the protocol is inappropriate for a crowded environment.

A 'degree-independent' protocol called the multichannel-CSMA protocol is proposed in [6]. Suppose that there are n channels; the protocol requires that each mobile host have n receivers concurrently listening on all n channels, as opposed to there being only one transmitter which will hop from channel to channel and send on any channel detected to be idle. Again, this protocol has high hardware cost, and it does not attempt to resolve the hidden-terminal problem due to lack of the RTS/CTS-like reservation mechanism. A *hop-reservation* MAC protocol based on very-slow frequency-hopping spread spectrum is proposed in [8]. The protocol is also degree independent, but requires clock synchronization among all mobile hosts, which is difficult when the network is dispersed over a large area.

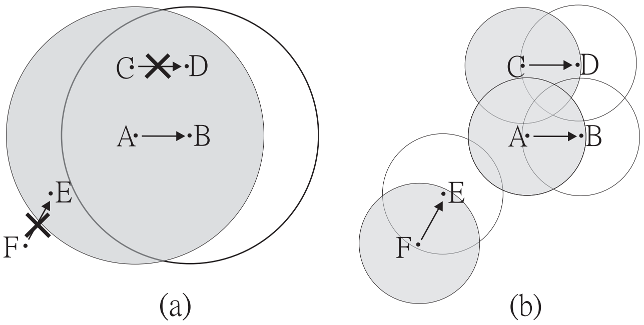

FIGURE 1. Transmission scenarios (a) when there is no power control and (b) when there is power control.

A multi-channel MAC protocol called Dynamic Channel Assignment (DCA) was proposed in [32] by the same authors. This protocol is also degree independent, and does not require any form of clock synchronization among mobile hosts. As a sequel to that work, in this paper we try to integrate the concept of power control into the DCA protocol in [32]. Through this study we hope to understand how much more benefit can be obtained on top of the DCA protocol.

2.2. MAC protocols with power control

Using power control may bring several advantages. First, the precious battery energy of portable devices may be sustained for a longer period. Second, it may reduce co-channel interference with neighboring hosts (for example, the near–far problem in CDMA systems, which can severely reduce the network throughput, can be significantly relieved by power control). Third, it may increase channel reuse in a physical area. For example, consider Figure 1a, where a communication from A to B is ongoing. The communication from C to D cannot be granted because A's signal will interfere with D's. Similarly, communication from E to F cannot be granted because E can hear A's signal as well. However, as shown in Figure 1b, if we can properly tune each transmitter's power level, all communication pairs can coexist without any interference.

A simple power-control mechanism is suggested in [20]. Suppose mobile hosts X and Y want to exchange with each other one packet. Let X send a packet with power P_t, which is heard by Y with power P_r. According to [33], the following equation holds:

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

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 the existence of obstacles. Now suppose that Y wants to reply with a packet to X such that X receives the packet with a designated power P_X. Then Y's transmission power satisfies

$$P_X = P_Y \left(\frac{\lambda}{4\pi d}\right)^n g_t g_r. \tag{2}$$

Although the values of the environment-dependent parameters d and n are unknown, one important property is that during a very short period, their values can be treated as constants. Thus, we can divide Equation (2) by Equation (1), which gives

$$\frac{P_X}{P_t} = \frac{P_Y}{P_r}. \tag{3}$$

Then Y can determine its transmission power P_Y if the other powers are known.

The MACA [13] also suggests a power control mechanism for a distributed environment. The basic idea is similar to the above formulation, but a host will gradually tune its transmission power to achieve this goal.

3. OUR MULTI-CHANNEL MAC PROTOCOL WITH POWER CONTROL

3.1. Basic idea

Our multi-channel MAC protocol is called dynamic channel assignment with power control (DCA-PC). This is an extension of our earlier DCA protocol in [32], which does not take power control into consideration. The DCA-PC protocol will resolve three problems, channel assignment, medium access and power control, in an integrated manner. It is characterized by the following features. First, it dynamically assigns channels to mobile hosts in an 'on-demand' manner. Whenever a host needs a channel, it will go through a RTS/CTS/RES dialogue to grab a channel. Once it completes its transmission, the channel will be released. Second, because of this on-demand feature, we can assume that the number of channels given to the network is a fixed number, which is independent of the network size, topology and degree. Third, we do not assume any form of clock synchronization among mobile hosts.

Our channel model is as follows. The overall bandwidth is divided into one control channel and n data channels $D_1, D_2, \ldots, D_n$. The purpose of the control channel is to assign data channels to mobile hosts and to resolve the potential contention in using data channels. Data channels are used to transmit data packets and acknowledgements. Each mobile host is equipped with two half-duplex transceivers:

- a control transceiver, which operates on the control channel to exchange control packets with other mobile hosts and to obtain rights to access data channels;
- a data transceiver, which dynamically switches to one of the data channels to transmit data packets and acknowledgements.

The notion behind our power control is as follows. The data channels will always be used with proper power control so as to exploit channel reuse. However, control packets (the

RTS/CTS/RES dialogue) will always be sent using the maximum power $P_{\max}$ because the major responsibility of control packets is to warn the neighboring environment of the future communication activity between the sender and the receiver.

We will assume that each mobile host A keeps an array called *POWER*[...]. For each host *id* neighboring A, the entry *POWER*[*id*] registers the level of power that should be used by A when sending a data packet to host *id*. For ease of presentation, we will assume *POWER*[*id*] $= \infty$ if host *id* is no longer a neighbor of A. The value of *POWER*[*id*] can be dynamically adjusted if A always monitors the communications around itself on the control channel, whether the packets are intended for it or not (this is necessary in our protocol because the control channel is to serve this purpose). Then the formulation in Section 2.2 can be used to tune the value of *POWER*[*id*]. That is, we can use the receive power level of a control packet from host *id* to determine the power level *POWER*[*id*] which A can send as a data packet to host *id*. Note that since control packets are always transmitted with the maximum power $P_{\max}$, we can replace the parameter P_t in Equation (3) by the constant $P_{\max}$. Also, let $P_{\min}$ be the minimum power level at which a mobile host can distinguish signals from noises. We can replace the expected receive power level P_X in Equation (3) by the constant $P_{\min}$. To reduce transmission error, one may also add a constant offset on top of $P_{\min}$. To keep the array *POWER*[...] up-to-date, a timeout mechanism should be included when A does not hear any communication from host *id* for a predefined period of time, in which case A simply sets *POWER*[*id*] to ∞. We comment that at the network layer, when a route is required from a source to a destination, most protocols [3, 9, 10] will broadcast network-wide route requests. We recommend that such packets be sent on the control channel with maximum power. Such packets are also helpful to establish the information in array *POWER*[...].

The above discussion gives guidelines on how to set the values in the array *POWER*[...]. Other gradual tuning schemes or lower-level hardware-supported mechanisms may also be used. However, we leave this as an independent issue in this paper, and one may incorporate any power-tuning scheme into our protocol.

3.2. The protocol

Each mobile host, say X, maintains the following data structure.

(i) *CUL*[ ]. This is the *channel usage list*. Each list entry *CUL*[i] keeps records of when a host neighboring X uses a channel. *CUL*[i] has four fields:
  (a) *CUL*[i].*host*, a neighbor host of X;
  (b) *CUL*[i].*ch*, a data channel used by *CUL*[i].*host*;
  (c) *CUL*[i].*rel_time*, when channel *CUL*[i].*ch* will be released by *CUL*[i].*host*;
  (d) *CUL*[i].*int*, whether the signals transmitted by *CUL*[i].*host* on the data channel *CUL*[i].*ch* will be overheard by X or not.

(ii) *POWER*[ ]. Each entry *POWER*[*id*] in the array records the level of power which X should use when sending a data packet to host *id*.

(ii) *FCL*. This is the *free channel list*, which is dynamically computed from *CUL* and *NL*.

TABLE 1. Meanings of variables and constants used in our protocol.

T_{SIFS}	Length of short inter-frame spacing
T_{DIFS}	Length of distributed inter-frame spacing
T_{RTS}	Time to transmit a RTS
T_{CTS}	Time to transmit a CTS
T_{RES}	Time to transmit a RES
T_{curr}	The current clock of a mobile host
T_{ACK}	Time to transmit an ACK
NAV_{RTS}	Network allocation vector on receiving a RTS
NAV_{CTS}	Network allocation vector on receiving a CTS
NAV_{RES}	Network allocation vector on receiving a RES
L_{d}	Length of a data packet
L_{c}	Length of a control packet (RTS/CTS/RES)
B_{d}	Bandwidth of a data channel
B_{c}	Bandwidth of the control channel
τ	Maximal propagation delay

Now suppose a host A wants to send a data packet to host B. The complete protocol is shown below. Table 1 lists the variables/constants used in our presentation.

Step 1. On a mobile host A having a data packet to send to host B, it first checks whether the following two conditions are true.

(a) B is not equal to any *CUL*[i].*host* such that

$$CUL[i].rel\_time > T_{\mathrm{curr}} + (T_{\mathrm{DIFS}} + T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}}).$$

If so, this means that B will still be busy (in using data channel *CUL*[i].*ch*) after a successful exchange of RTS and CTS packets.

(b) There is at least a channel D_j such that for all i,

$$\begin{aligned}(CUL[i].ch = D_j) \Longrightarrow\ & \{CUL[i].rel\_time \leq T_{\mathrm{curr}} \\ & + (T_{\mathrm{DIFS}} + T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}})\} \vee \\ & \{(CUL[i].int = 0) \wedge (POWER[CUL[i].host] \\ & > POWER[B])\}.\end{aligned}$$

Intuitively, this is to ensure that if D_j is currently in use, then either (i) D_j will be freed after a successful exchange of RTS and CTS packets (Figure 2 shows how the above timing is calculated), or (ii) the signals from host *CUL*[i].*host* on channel D_j do not interfere with A and the yet-to-be-transmitted signals from A to B will not interfere with host *CUL*[i].*host*. Note that condition (ii) is determined by the power levels for A to send to hosts *CUL*[i].*host* and B.

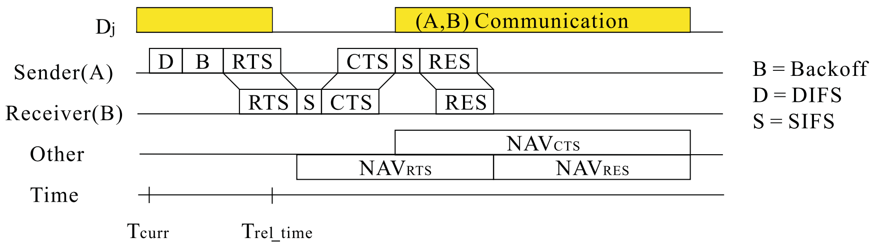

FIGURE 2. Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

Then A puts all D_js satisfying condition (b) into its *FCL*. Otherwise, A must wait at Step 1 until these conditions become true.

Step 2. Then A can send a $RTS(FCL, L_d)$ to B with power $P_{\max}$, where L_d is the length of the yet-to-be-sent data packet. Also, following the IEEE 802.11 style, A can send this RTS only if there is no carrier on the control channel in a T_{DIFS} plus a random backoff time period. Otherwise, it has to go back to Step 1.

Step 3. On a host B receiving the $RTS(FCL, L_d)$ from A, it has to check whether there is any data channel $D_j \in FCL$ such that for all i,

$$\begin{aligned}&(CUL[i].ch = D_j) \Longrightarrow\\ &\quad \{CUL[i].rel\_time \le T_{\mathrm{curr}} + (T_{\mathrm{SIFS}} + T_{\mathrm{CTS}})\} \vee\\ &\quad \{(CUL[i].int = 0) \wedge (POWER[CUL[i].host]\\ &\quad > POWER[A])\}.\end{aligned}$$

If so, D_j is a free channel that can be used by B (the philosophy for the above conditions is similar to that in Step 1b; we ensure that D_j is a free channel after a CTS duration and the yet-to-be-transmitted signals from B to A will not interfere with host $CUL[i].host$). Then B picks the first such channel D_j and replies with a $CTS(D_j, NAV_{\mathrm{CTS}}, P_{\mathrm{CTS}})$ to A, where

$$\begin{aligned}NAV_{\mathrm{CTS}} &= L_d/B_d + T_{\mathrm{ACK}} + 2\tau\\ P_{\mathrm{CTS}} &= POWER[A].\end{aligned}$$

Then B tunes its data transceiver to D_j waiting for A's packet. Otherwise, B replies a $CTS(T_{\mathrm{est}})$ with power $P_{\max}$ to A, where T_{est} is the minimum estimated time that B's *CUL* will change minus the time for an exchange of a CTS packet:

$$T_{\mathrm{est}} = \min\{\forall i, CUL[i].rel\_time\} - T_{\mathrm{curr}} - T_{\mathrm{SIFS}} - T_{\mathrm{CTS}}.$$

Step 4. On an irrelevant host $C \ne B$ receiving A's $RTS(FCL, L_d)$, it has to inhibit itself from using the control channel for a period

$$NAV_{\mathrm{RTS}} = 2T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + T_{\mathrm{RES}} + 2\tau.$$

This is to avoid C from interrupting the RTS → CTS → RES dialogue between A and B.

Step 5. Host A, after sending its RTS, will wait for B's CTS with a timeout period of $T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + 2\tau$. If no CTS is received, A will retry until the maximum number of retries is reached.

Step 6. On host A receiving B's $CTS(D_j, NAV_{\mathrm{CTS}}, P_{\mathrm{CTS}})$, it performs the following steps.

(a) Append an entry $CUL[k]$ to its *CUL* such that

$$\begin{aligned}CUL[k].host &= B\\ CUL[k].ch &= D_j\\ CUL[k].rel\_time &= T_{\mathrm{curr}} + NAV_{\mathrm{CTS}}\\ CUL[k].int &= 1.\end{aligned}$$

(b) Broadcast $RES(D_j, NAV_{\mathrm{RES}}, P_{\mathrm{RES}})$ with power $P_{\max}$ on the control channel, where

$$\begin{aligned}NAV_{\mathrm{RES}} &= NAV_{\mathrm{CTS}} - T_{\mathrm{SIFS}} - T_{\mathrm{RES}}\\ P_{\mathrm{RES}} &= POWER[B].\end{aligned}$$

(c) Send its DATA packet to B on the data channel D_j with power $POWER[B]$. Note that this step happens concurrently with step (b).

On the contrary, if A receives B's $CTS(T_{\mathrm{est}})$, it has to go back to Step 1 at time $T_{\mathrm{curr}} + T_{\mathrm{est}}$ or when A knows that there is a newly released data channel, whichever happens earlier.

Step 7. On an irrelevant host $C \ne A$ receiving B's $CTS(D_j, NAV_{\mathrm{CTS}}, P_{\mathrm{CTS}})$, C updates its *CUL*. This is the same as Step 6(a) except that

$$\begin{aligned}CUL[k].rel\_time &= T_{\mathrm{curr}} + NAV_{\mathrm{CTS}} + \tau\\ CUL[k].int &= \begin{cases}0, & \text{if } POWER[B] > P_{\mathrm{CTS}}\\ 1, & \text{if } POWER[B] \le P_{\mathrm{CTS}}.\end{cases}\end{aligned}$$

In contrast, if C receives B's $CTS(T_{\mathrm{est}})$, it ignores this packet.

Step 8. On a host C receiving $RES(D_j, NAV_{\mathrm{RES}}, P_{\mathrm{RES}})$, it appends an entry $CUL[k]$ to its *CUL* such that

$$\begin{aligned}CUL[k].host &= A\\ CUL[k].ch &= D_j\\ CUL[k].rel\_time &= T_{\mathrm{curr}} + NAV_{\mathrm{RES}}\\ CUL[k].int &= \begin{cases}0, & \text{if } POWER[A] > P_{\mathrm{RES}}\\ 1, & \text{if } POWER[A] \le P_{\mathrm{RES}}.\end{cases}\end{aligned}$$

Step 9. On B completely receiving A's data packet, B replies with an ACK on D_j with power $POWER$[A].

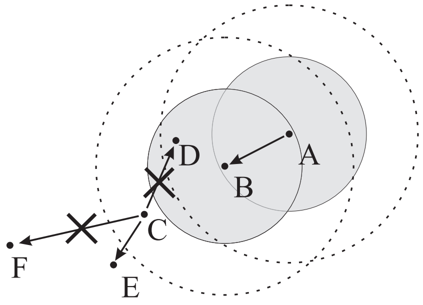

FIGURE 3. An example of our DCA-PC protocol.

Below, we show an example of our power control mechanism. In Figure 3, the areas bounded by dotted circles represent the transmission ranges of the control packets from hosts A and B. The circles in gray are the transmission ranges of A's data packet and B's ACK packet, respectively. Note that control packets are sent without power control, and data packets are sent with power control. So the RTS/CTS/RES dialogue between A and B will be overheard by hosts C and D. Now, if host C intends to perform some communication, it may be allowed to use the data channel that A and B are using if its transmission power is properly controlled (there will be an entry in C's data structure such that $CUL[k].host = B$ and $CUL[k].int = 0$). If C's intended receiver is D, D will reject C's request to use the same channel used by A and B (there will be an entry in D's data structure such that $CUL[k].host = B$ and $CUL[k].int = 1$). If C's intended receiver is E, C will be allowed to use the same channel that A and B are using (this can be determined by C's $POWER[B]$ and $POWER[E]$). E may or may not grant C's request in using that channel depending on its neighboring status. However, if C's intended receiver is F, C will try to find a channel other than that used by A and B (again, this can be determined by C's $POWER[B]$ and $POWER[F]$).

4. SIMULATION RESULTS

We have implemented a simulator to compare the performance of the proposed DCA-PC and our earlier DCA [20] protocols. In our simulation, we consider two bandwidth models.

- *Fixed-channel-bandwidth.* Each channel (data and control) has a fixed bandwidth. Thus, with more channels, the network can potentially use more bandwidth.
- *Fixed-total-bandwidth.* The total bandwidth offered to the network is fixed. Thus, with more channels, each channel will share less bandwidth.

We comment that the first model may reflect the situation in CDMA, where each code has the same bandwidth, and we may utilize multiple codes to increase the actual bandwidth of the network. In contrast, the second model may reflect the situation in FDMA, where the total bandwidth is fixed, and our job is to determine an appropriate number of channels to best utilize the given bandwidth. As a reference point, we also include the performance of IEEE 802.11 under the fixed-total bandwidth model. The purpose is to see the benefit of using multiple channels.

TABLE 2. Simulation parameters.

Number of mobile hosts (except for part C)	200
Number of power levels (except for part D)	5
Maximum speed of a mobile host (except for part E)	36 km h^{-1}
Physical area	1 km × 1 km
Transmission range	0.3 km
Maximum number of retrials to send a RTS	6
Length of DIFS	50 μs
Length of SIFS	10 μs
Backoff slot time	20 μs
Signal propagation time	5 μs
Control packet length L_c	300 bits
Data packet length L_d	A multiple of L_c

The parameters used in our simulations are listed in Table 2. Mobile hosts were generated randomly in a physical area of size 1 km × 1 km. Each mobile host had a roaming pattern as follows. It first moved in a randomly chosen direction at a randomly chosen speed for a random period; this was repeated indefinitely. Packets arrived at each mobile host with an arrival rate of λ packets/s. For each packet arriving at a host, we randomly chose a host at the former's neighborhood as its receiver. If the fixed-channel-bandwidth model is assumed, each channel's bandwidth is 1 Mbit s^{-1}. If the fixed-total-bandwidth model is assumed, the total bandwidth is 1 Mbit s^{-1}. Also, to take signal interference and degradation into consideration, we have used discrete power levels, as opposed to continuous power levels suggested in the protocol. For example, in future experiments, we will use 5 levels of power: $P_{\max}/5, 2P_{\max}/5, \ldots, P_{\max}$. When transmitting, a mobile host must choose the smallest power level that is not less than the minimal possible level to reach its destination. In the following, we present our simulation results from several aspects.

Simulation A. Effect of the number of channels

In this experiment, we vary the number of channels to observe its effect. Figure 4 shows the result under the fixed-total-bandwidth model. As can be seen, the peak throughput of DCA-PC does outperform that of DCA. One interesting phenomenon is that although DCA-PC outperforms DCA in most points, the gap between DCA-PC and DCA actually decreases as more channels are used. In other words, the effect of power control is less significant as the number of channels is too large (e.g. see the gap at 15 channels). So, under the fixed-total-bandwidth model, one must carefully pick the number of channels to maximize the benefit of

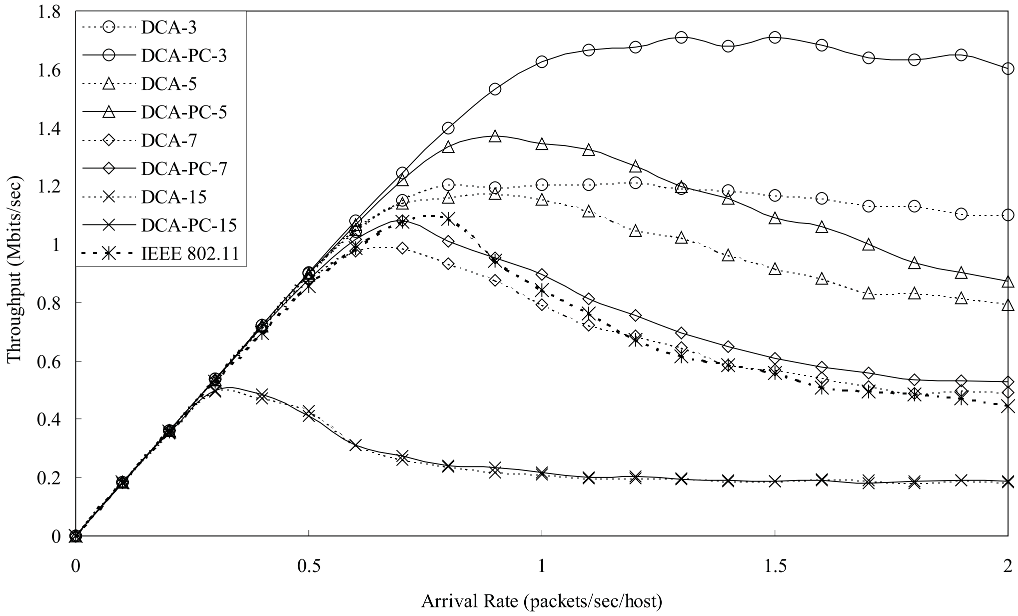

FIGURE 4. Arrival rate vs. throughput under the fixed-total-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

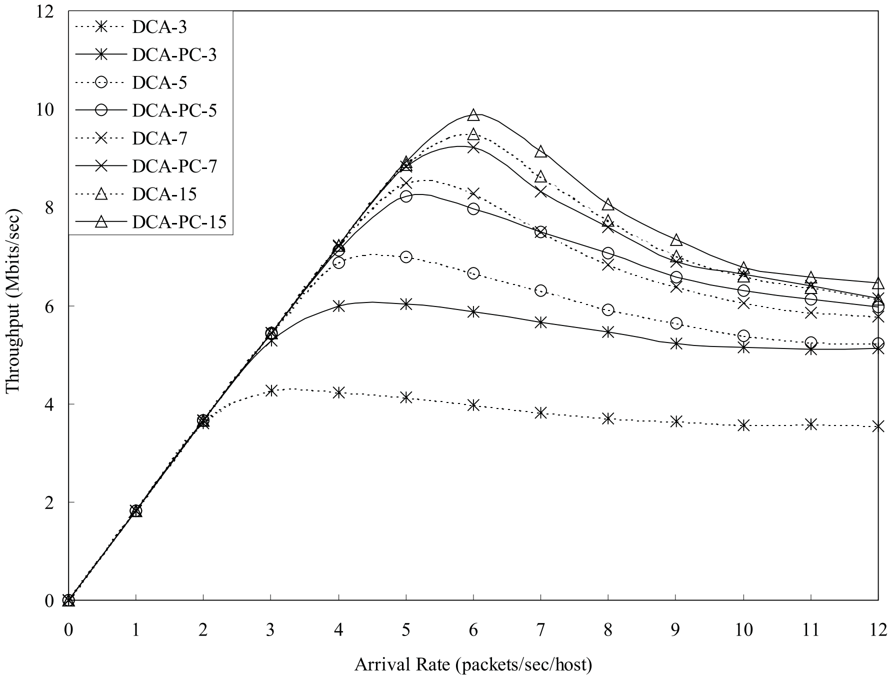

FIGURE 5. Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels.

our protocol. This is perhaps because the control channel is overloaded (it cannot function well in distributing data channels to mobile hosts; the reason will become clear from simulation B).

Also, as a reference point, we observe that the performance of IEEE 802.11 is about the same as our DCA and DCA-PC protocols with seven channels. Using less than seven channels is beneficial, but using more than seven channels is disadvantageous.

Figure 5 shows the same simulation under the fixed-channel-bandwidth model. The trend of the gap between DCA-PC and DCA is about the same as the earlier case. The only difference is that when we look at the performance of DCA-PC (or similarly DCA) individually, the throughput will keep on improving as more channels are used. This is quite reasonable because under the fixed-channel-bandwidth model, a larger number of channels means more total bandwidth that can be used potentially. However, the

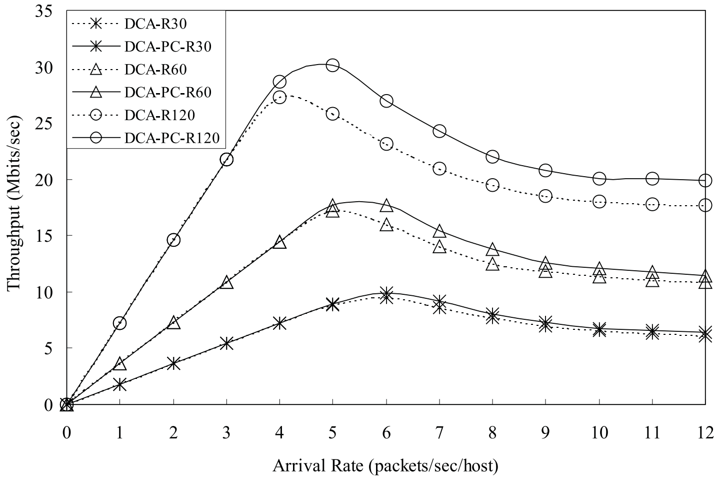

FIGURE 6. Arrival rate vs. throughput under the fixed-channel-bandwidth model at different $L_\mathrm{d}/L_\mathrm{c}$ ratios (Rj means the ratio $L_\mathrm{d}/L_\mathrm{c} = j$).

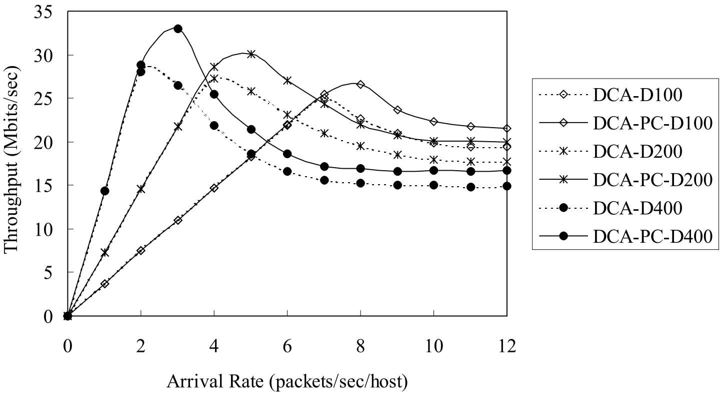

FIGURE 7. Arrival rate vs. throughput under the fixed-channel-bandwidth model at different numbers of mobile hosts. (Di means i mobile hosts.)

improvement is becoming less significant as too many channels are used (the reason will become clear from the following simulation).

Simulation B. Effect of data packet length

As observed in the previous experiment, the gap between DCA-PC and DCA will become less significant as more channels are used. We speculated that this is because the control channel is saturated (with too many data channels, the control channel will be overloaded). One way to verify the conjecture is to increase the length of data packets (each successful RTS/CTS/RES dialogue can schedule more data bits to be sent). In this experiment, we keep the number of channels a constant of 15, and vary the ratio $L_\mathrm{d}/L_\mathrm{c}$ under the fixed-channel-bandwidth model. The result is shown in Figure 6, from which we see a clear trend that a larger ratio $L_\mathrm{d}/L_\mathrm{c}$ is beneficial. We also observe that the gap between DCA-PC and DCA actually increases as the ratio $L_\mathrm{d}/L_\mathrm{c}$ increases. This justifies our earlier reasoning. Also, note that in the experiment we did not take transmission error rate into consideration, so the actual benefit may be saturated at a certain point of the $L_\mathrm{d}/L_\mathrm{c}$ ratio.

Simulation C. Effect of host density

In the earlier experiments, we used a fixed number of 200 hosts. In this experiment, we vary the number of mobile hosts. The result is shown in Figure 7, where a fixed number of 15 channels is used. We see that the gap between DCA and DCA-PC is slightly larger with more hosts. Since more hosts means a denser environment, this indicates that power control is more important in a crowded area.

Simulation D. Effect of the number of power levels

The above simulations all used a fixed number of five power levels. In this experiment, we vary the number of power levels to observe its effect. Apparently, using more power levels enables a mobile host to transmit with less interference to its surroundings, thus giving higher channel utilization. Figures 8a and 8b show that using 4–6 and 2–3 power levels, respectively, can already deliver a satisfactory throughput, so it makes not much sense to have too many power levels. This also shows the practical value of our result.

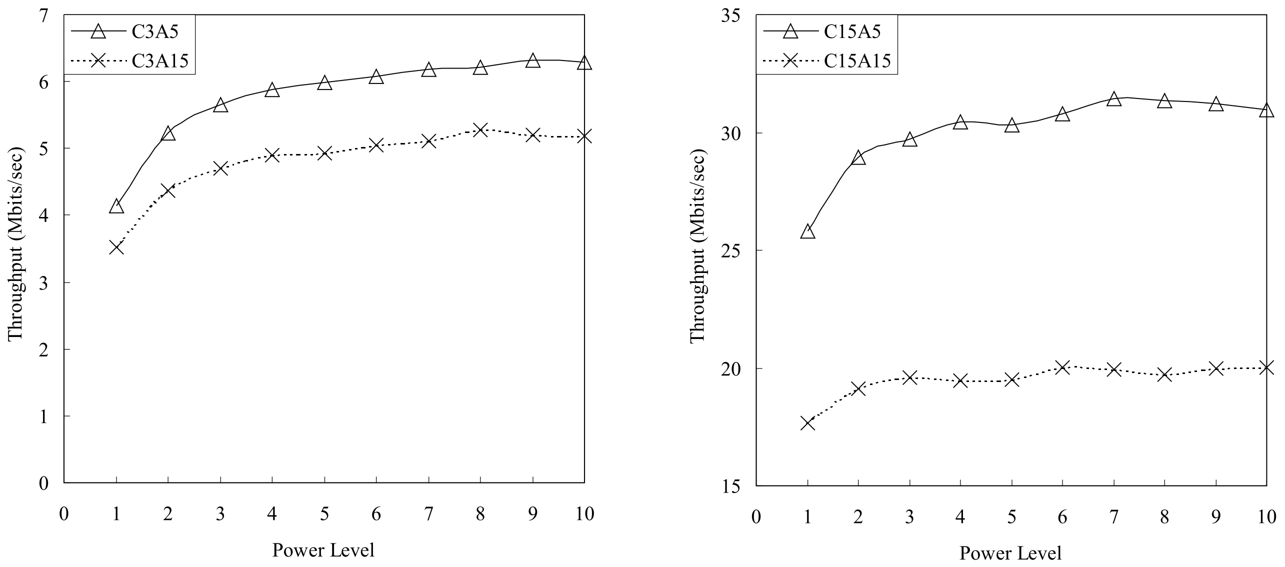

FIGURE 8. Number of power levels vs. throughput: (a) 3 channels with $L_\mathrm{d}/L_\mathrm{c} = 30$ and (b) 15 channels with $L_\mathrm{d}/L_\mathrm{c} = 120$. The number after 'A' is the arrival rate (packets/sec/host). The peak throughput appears at around A5, while the saturated, but stable, throughput appears at around A15.

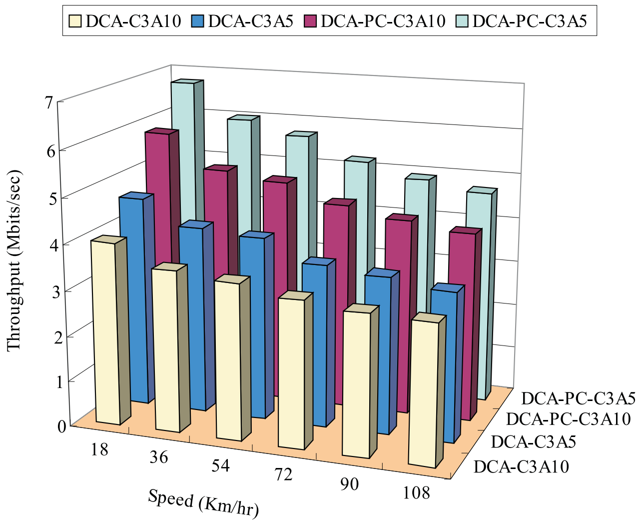

FIGURE 9. Mobility vs. throughput. The peak throughput appears at around A5, while the saturated, but stable, throughput appears at around A10.

Simulation E. Effect of host mobility

In all the above experiments, mobile hosts roam at a speed randomly chosen between 0 to 36 km h^{-1}. Higher mobility may reduce the effectiveness of RTS/CTS/RES dialogues (a successful one may be disrupted by an ignorant host with higher chance). Moreover, with power control, this effect may be magnified, since we have reduced the power to transmit data packets. In this experiment, we enlarge the maximal speed that mobile hosts could take. The result is shown in Figure 9. The trend does show that our DCA-PC protocol will degrade slightly faster than the DCA protocol, as reasoned above. Even so, DCA-PC still outperforms DCA in a highly mobile environment (such as 108 km h^{-1}).

5. CONCLUSIONS

We have proposed a new multi-channel MAC protocol that solves the channel assignment, multiple access, and power control problems in an integrated way. Extensive simulation results have been conducted, which take into consideration many factors, such as channel bandwidth models, number of channels, data packet length, host density and host mobility. The result shows a promising direction to improve the performance of MANET. As one referee pointed out, the work in this paper does not take into consideration how our protocol can interact with power saving (such as shooting down a receiver into a sleep mode). This would be an interesting problem deserving further investigation.

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