A Multi-Channel MAC Protocol with Power Control for Multi-Hop Mobile Ad Hoc Networks *

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Abstract

In a mobile ad-hoc networks (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 dedicated to using multiple channels [4, 6, 9, 10, 12, 18, 20] and power control [7, 13, 21] 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.

1 Introduction

A *mobile ad-hoc network (MANET)* is formed by a cluster of mobile hosts without fixed infrastructure provided by base stations. The applications of MANETs appear in places where predeployment of network infrastructure is difficult or unavailable (e.g., natural disasters, battle fields, and festival field grounds). 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 [9, 11, 15, 18, 19, 20, 24].

This paper concerns *MAC (medium access control)* 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 [5, 8, 13, 14, 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 [2]. 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 [6] 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 [25], 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 [3, 18], 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 (QoS), it is easier to do so by using multiple channels [17].

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. Our protocol is characterized by the following features: (i) it follows an "on-demand" style to ac-

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cess 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. On the contrary, most existing protocols assign channels to a host statically even if it has no intention to transmit [4, 10, 12], require a number of channels which is a function of the maximum connectivity [4, 9, 10, 12], or necessitate a clock synchronization among all hosts in the MANET [12, 20]. Simulation results are presented. The results show that our protocol is very promising to improve the performance of a MANET.

2 Reviews

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 to be used by which hosts, while the later is to resolve the contention/collision problem when using a particular channel. There already exist many related works [4, 6, 9, 10, 12, 18, 20, 25] in the literature.

References [4, 10] 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 [6, 25], 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 *Latin square* is proposed in [12], 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 [9] 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 *multichannel-CSMA* protocol is proposed in [18]. Suppose that there are n channels. The protocol requires that each mobile host have n receivers concurrently listening on all n channels. On the contrary, there is 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 [20]. The protocol is also degree-independent, but requires clock synchronization among all mobile hosts, which is difficult when the network is dispersed in a large area.

A multi-channel MAC protocol called *DCA (Dynamic Channel Assignment)* was proposed in [23] 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 of that work, in this paper we try to integrate the concept of power control into the DCA protocol in [23]. 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 sustain for longer time. 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 relieved by power control significantly). Third, it may increase channel reuse in a physical area.

A simple power control mechanism is suggested in [25]. 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 [22], the following equation holds:

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

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

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

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

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

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

3.1 Basic Idea

Our multi-channel MAC protocol is called *DCA-PC (dynamic channel assignment with power control)*. This is an extension of our earlier DCA protocol in [23], which does not take power control into consideration. 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. Control transceiver will operate on the control channel to exchange control packets with other mobile hosts and to obtain rights to access data channels. Data transceiver will dynamically switch 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 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 assume that each mobile host A keeps an array called $POWER[...]$. For each host id neighboring to 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 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, no matter the packets are intending for it or not. Then the formulation in Section 2.2 can be used to tune the value of $POWER[id]$. That is, we can used the receive power level of a control packet from host id to determine the power level $POWER[id]$ by which A can send 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 Eq. (3) by the constant P_{max}. Also, let P_{min} be the minimum power level that a mobile host can distinguish signals from noises. We can replace the expected receive power level P_X in Eq. (3) by the constant P_{min}. To reduce the transmission errors, one may also add a constant offset on top of P_{min}. In addition, 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 ∞.

The above discussion gives a guideline 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.

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

3.2 The Protocol

Each mobile host, say X, maintains three data structures. $CUL[\,]$ is called the *channel usage list*. Each list entry $CUL[i]$ keeps records of when a host neighboring to X uses a channel. $CUL[i]$ has four fields: $CUL[i].host$ records a neighbor host of X, $CUL[i].ch$ is a data channel used by $CUL[i].host$, $CUL[i].rel\_time$ is when channel $CUL[i].ch$ will be released by $CUL[i].host$, and $CUL[i].int$ records whether the signals transmitted by $CUL[i].host$ on the data channel $CUL[i].ch$ will be overheard by X or not. The second data structure is $POWER[\,]$. Each entry $POWER[id]$ in the array records the level of power by which X should use when sending a data packet to host id. The third data structure FCL is called the *free channel list*, which is dynamically computed from CUL and NL.

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.

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

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

   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:

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

   Intuitively, this is to ensure that if D_j is currently in use, then either (i) D_j will be freed after a successful

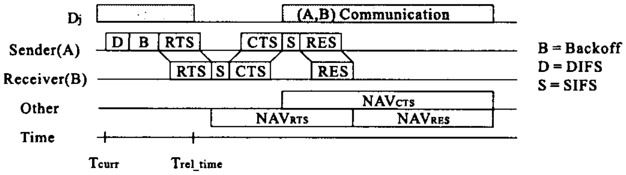


Figure 1: Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

   exchange of RTS and CTS packets (Fig. 1 shows how the above timing is calculated), or (ii) the signals from host $CUL[i].host$ on channel D_j does not interfere A and the yet-to-be-transmitted signals from A to B will not interfere 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.

   Then A puts all D_j's satisfying condition b) into its FCL. Otherwise, A must wait at step 1 until these conditions become true.

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.

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:

   $$(CUL[i].ch = D_j) \Longrightarrow \{CUL[i].rel\_time \leq T_{curr} + (T_{SIFS} + T_{CTS})\} \vee \{(CUL[i].int = 0) \wedge (POWER[CUL[i].host] > POWER[A])\}$$

   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 2b; 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 host $CUL[i].host$). Then B picks the first such channel D_j and replies a $CTS(D_j, NAV_{CTS}, P_{CTS})$ to A, where

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

   Then B tunes its data transceiver to D_j waiting for A's packet. Otherwise, B replies a $CTS(T_{est})$ 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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

   On the contrary, if C receives B's $CTS(T_{est})$, it ignores this packet.

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

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

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

4 Simulation Results

We have implemented a simulator to compare the performance of the proposed DCA-PC and our earlier DCA [25] protocols. In our simulation, we consider two bandwidth models. *Fixed-channel-bandwidth* means that each channel (data and control) has a fixed bandwidth. Thus, with more channels, the network can potentially use more bandwidth. *Fixed-total-bandwidth* means that the total bandwidth offered to the network is fixed. Thus, with more channels, each channel will share less bandwidth.

The parameters used in our experiments are: physical area = 100 × 100, no. of hosts = 200 (except for part B), transmission range $r = 30$, max. speed of a mobile host = 36 km/hr (except for part D), $DIFS = 50\mu sec$, $SIFS = 10\mu sec$, backoff slot time = $20\mu sec$, control packet length L_c = 300 bits, data packet length L_d = 9000 bits. 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. After this period, it made the next roaming based on the same model. Packets arrived at each mobile host with an arrival rate of λ packets/sec. For each packet arrived 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 Mbits/sec. If the fixed-total-bandwidth model is assumed, the total bandwidth is 1 Mbits/sec. We use 5 levels of power (except for part C): $\frac{P_{max}}{5}, \frac{2P_{max}}{5}, \ldots, P_{max}$.

A) Effect of the Number of Channels: In this experiment, we vary the number of channels to observe its effect. Fig. 2 shows the result under the fixed-total-bandwidth model. As can be seen, the peek 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). This is perhaps because the control channel is overloaded (it can not function well to distribute data channels to mobile hosts; the reason was explained clearly in our early paper [23]).

Also, as a reference point, we observe that the performance of IEEE 802.11 is about same as our DCA and DCA-PC protocols with 7 channels. Using less than 7 channels is beneficial, but using more than 7 channels is disadvantageous.

Fig. 3 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 improvement is becoming less significant as too many channels are used (the reason was explained clearly in our early paper [23]).

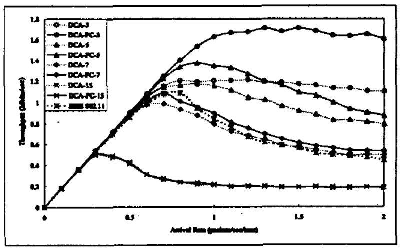


Figure 2: Arrival rate vs. throughput under the fixed-total-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

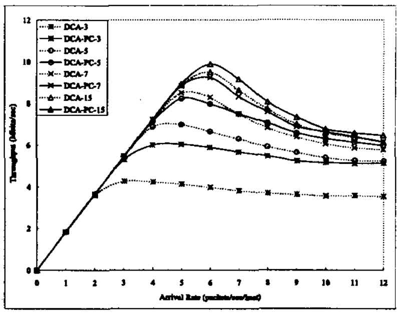


Figure 3: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels.

B) Effect of Host Density: In this experiment, we vary the number of mobile hosts. The result is in Fig. 4, where a fixed number of 15 channels are 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 crowded area.

C) Effect of the Number of 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. Fig. 5 (a) and (b) 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.

D) Effect of Host Mobility: In this experiment, we enlarge the maximal speed that mobile hosts could take. In Fig. 6, The trend does show that our DCA-PC protocol will degrade slightly faster than the DCA protocol, as reasoned above. Even so, DCA-PC

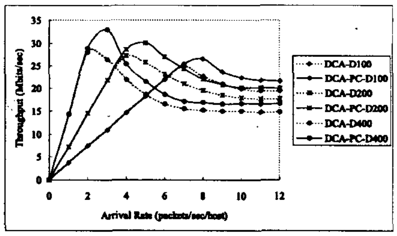
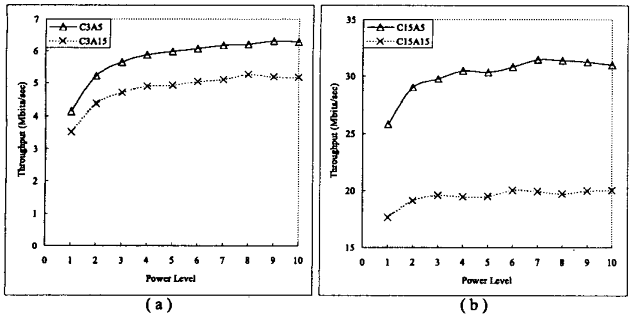


Figure 4: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different numbers of mobile hosts. (Di means i mobile hosts.)



(a) (b)

Figure 5: Number of power levels vs. throughput: (a) 3 channels with $L_d/L_c = 30$ and (b) 15 channels with $L_d/L_c = 120$. 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.

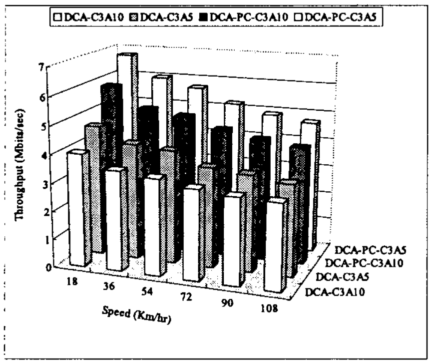


Figure 6: Mobility vs. throughput. The peak throughput appears at around A5, while the saturated, but stable, throughput appears at around A10.

still outperforms DCA at highly mobile environment.

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 many factors, such as channel bandwidth models, number of channels, host density, and host mobility, into consideration. The result shows a promising direction to improve the performance of MANET.

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