國　立　中　央　大　學

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碩　士　論　文

無線行動隨建即連網路的媒介存取: 一個具動態頻道分配的 MAC 協定

指導教授： 曾 煜 棋

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中 華 民 國　八 十 九　年　六　月　九　日

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論文名稱：無線行動隨建即連網路的媒介存取: 一個具動態頻道分配的 MAC 協定

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論文題目：無線行動隨建即連網路的媒介存取: 一個具動態頻道分配的 MAC 協定

指導教授： 曾煜棋 教授、許健平 教授

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中 華 民 國 89 年 6 月 9 日

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中 華 民 國 八 十 八 年 六 月 九 日

論文名稱：無線行動隨建即連網路的媒介存取:　　　　頁數：32
一個具動態頻道分配的 MAC 協定

校所組別：國立中央大學　資訊工程　研究所

畢業時間及提要別：八十八學年度第二學期　碩士學位論文提要

研究生：林 致 宇　　　　　　指導教授：曾煜棋　許健平 教授

論文提要內容：

在這篇論文中，我們針對多頻道(Multi-Channel)環境下的無線行動隨建即連網路(Mobile Ad Hoc Network)提出一個具有動態頻道分配的 MAC (Medium Access Control)協定，此協定有下列數個特性: (i) 此協定中以 On-Demand 的方式分配頻道給行動主機，(ii) 系統提供給網路所需的頻道個數與網路的拓樸是無關的，(iii) 此協定只需要交換少數的控制訊息(Control Messages)就可以完成頻道分配與媒介存取兩個功能，(iv)在此協定中行動主機(Mobile Host)不需要任何型式的同步(Synchronization)。相較於其他的協定，以往有些協定是使用靜態的方式分配頻道，如此可能造成一個行動即使沒有資料欲傳送仍會佔用頻道，而造成浪費的情況。而有些協定其頻道的數目是最大允許的鄰居數(Maximum Connectivity)的函數，而最大允許鄰居數在具移動性的隨建即連網路中是不易掌握的。另外有些協定則需要行動主機之間做同步，這在隨建即連網路上也是不易達成的。因此前述的四個特性使得此篇論文中所提出的 MAC 協定非常適用於無線行動隨建即連網路上。最後我們利用實驗來展現其效能。

誌謝

首先，要感謝的是我的指導老師曾煜棋教授及許健平教授，由於您們的諄諄教誨以及和藹細心的督促指導才有這篇論文的問世。此外，也感謝口試指導委員黃興燦院長、連耀南教授以及陳健輝教授，由於你們的指教與導引才使得本篇論文得以更臻完善。

再來也要感謝我的家人提供我一個很好的環境，讓我能夠專心於課業上，另外也要感謝實驗室的學長同學們能夠提供專業領域上的意見。

而在研究所的生涯中，適當的休閒也是必要的，因此也特別感謝室友畹潤在寢室所養的青龍，讓我可以賞魚放鬆心情。還有以前地球科學系的同學們，讓我的研究所的生活多了許多的調劑。

兩年的研究所生涯讓自己成長了不少，好比作家三毛於「傾城」一書所說的，過去的努力化成一群一群蝴蝶，在陽光中越變越鮮明，感覺生命的神秘與極美已在蛻變中彰顯了全部的答案，而我仍將繼續的努力，只為了再生時蝴蝶的顏色。

林　致　宇

謹識於中央資工所
高速通訊與計算實驗室
中華民國八十九年六月九日

摘　　要

在這篇論文中，我們針對多頻道(Multi-Channel)環境下的無線行動隨建即連網路(Mobile Ad Hoc Network)提出一個具有動態頻道分配的 MAC (Medium Access Control)協定，此協定有下列數個特性: (i) 此協定中以 On-Demand 的方式分配頻道給行動主機, (ii) 系統提供給網路所需的頻道個數與網路拓樸是無關的, (iii) 此協定只需要交換少數的控制訊息(Control Messages)就可以完成頻道分配與媒介存取兩個功能，(iv)在此協定中行動主機(Mobile Host)不需要任何型式的同步(Synchronization)。相較於其他的協定，以往有些協定是使用靜態的方式分配頻道，如此可能造成一個行動即使沒有資料欲傳送仍會佔用頻道，而造成浪費的情況。而有些協定其頻道的數目是最大允許的鄰居數(Maximum Connectivity)的函數，而最大允許鄰居數在具移動性的隨建即連網路中是不易掌握的。另外有些協定則需要行動主機之間做同步，這在隨建即連網路上也是不易達成的。因此前述的四個特性使得此篇論文中所提出的 MAC 協定非常適用於無線行動隨建即連網路上。最後我們利用實驗來展現其效能。

關鍵字: 頻道分配，通訊協定，媒介存取控制，行動隨建即連網路，
行動計算，無線通訊。

第 一 章　　簡 介

無線行動隨建即連網路是由一群行動主機在沒有基地台的架構下所組成的網路。這篇論文討論此種網路下的媒介存取問題，在這一章中首先會對以往在其它論文中所提出關於多頻道的媒介存取方法做一個回顧，並說明為何那些方法都不適用於無線行動隨建即連網路，因此此篇論文的動機即提出一個適用於無線行動隨建即連網路的的多頻道媒介存取協定（Multi-Channel MAC Protocol)。

第二章　多頻道環境的考量

當我們於無線行動隨建即連網路的多頻道 (Multi-Channel) 環境下考量媒介存取問題時，相較於單一頻道 (Single-Channel) 會有許多新的問題產生，在這一章中我們提出了使用多頻道所產生的新問題，如 Missing-RTS, Missing-CTS, Channel-Deadlock 等，而我們提出的 MAC 協定可以解決這些問題。

第三章　具動態頻道分配的 MAC 協定

在這一章中我們首先對協定的硬體需求與資料結構等做一個簡單的說明，我們將頻道分成許多的子頻道 (Sub-Channel)，其中使用一個 Sub-Channel 為 Control Channel，其它則是所謂的 Data Channel，在硬體上我們需使用兩個 Transceiver，一個是 Control Transceiver，其使用 Control Channel 來收送協定中所用到的 Control Packet，而 Data Transceiver 則使用 Data Channel 來進行 Data Packet 的收送。在協定中資料結構我們會使用兩個重要的資料結構分別是 CUL 與 FCL，其中 CUL (Channel Usage List)，是記錄一個行動主機其鄰居使用 Channel 的狀況，FCL (Free Channel List)則是當欲和其它行動主機通訊時，告知對方可使用的 Channel。而整個 MAC 協定只利用 RTS/CTS/RES 的對話並配合 CUL 的更新即達成多頻道環境下的媒介存取與頻道分配。

第 四 章　　分 析 與 模 擬 結 果

在這一章中我們首先對 Channel 數做了一個簡單的分析，我們發現當 Channel 數增多時，行動主機使用 Channel 的時間 (可利用增長 Data Packet 的長度來達成) 也應該隨著增加，才能使我們的協定獲得最好的效能。

在模擬的部份我們使用 C 語言開發了一個 Simulator 來模擬 DCA MAC Protocol，我們發現當網路流量負載很大時, 我們所提出的 DCA MAC Protocol 相較於 IEEE 802.11 (Single-Channel MAC) 可以獲得較好的效能，另外我們也分別對 Data Packet 長度，Control Channel 的頻寬與傳輸半徑等變因做實驗，來驗證我們所提出的 DCA MAC Protocol 其效能。

第 五 章　　結 論

在這篇論文中提出了一個適用於無線行動隨建即連網路的 MAC 協定，協定有下列數個特性: (i) 此協定中以 On-Demand 的方式分配頻道給行動主機，(ii) 系統提供給網路所需的頻道個數與網路的拓樸是無關的，(iii) 此協定只需要交換少數的控制訊息(Control Messages)就可以完成頻道分配與媒介存取兩個功能, (iv) 在此協定中行動主機(Mobile Host)不需要任何型式的同步(Synchronization)。未來我們會將此協定加上更多有利於增進效能的機制，如 Power Control。

A Multi-Channel MAC Protocol with On-Demand Channel Assignment for Mobile Ad Hoc Networks

by

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Abstract

The wireless mobile ad hoc network (MANET) architecture has received a lot of attention recently. This thesis considers the access of multiple channels in a MANET with multi-hop communication behavior. We point out several interesting issues that should be paid attention of when using multiple channels. We then propose a new multi-channel MAC protocol, which 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 and only exchanges few control messages to achieve channel assignment and medium access, and (iv) no form of clock synchronization is required. Compared to existing protocols, some assign channels to hosts statically (thus a host will occupy a channel even when it has no intention to transmit) [5, 15, 17], some require a number of channels which is a function of the maximum connectivity [5, 12, 15, 17], and some necessitate a clock synchronization among all hosts in the MANET [17, 29]. Extensive simulations are conducted to evaluate the proposed protocol.

Keywords: channel management, code assignment, communication protocol, medium access control (MAC), mobile ad hoc network (MANET), mobile computing, wireless communication.

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Chapter 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 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 march, 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 [24]. Issues related to MANET have been studied intensively [16, 20, 27, 30].

This thesis 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 [6, 10, 18, 19, 21, 23]. 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 [3]. One common problem with such protocols is that the network performance will degrade seriously as the number of mobile hosts increases, due to higher contention/collision.

One approach to relieving the contention/collision problem is to utilize multiple channels. With the advance of technology, empowering a mobile host to access multiple channels is already feasible. We thus define a *multi-channel MAC protocol* as one with such capability. Here, we use "channel" upon a logical level. Physically, a channel may be a time slot (under TDMA), a frequency band (under FDMA), or an orthogonal code (under CDMA). How to access multiple channels is a hardware-dependent issue. If TDMA is assumed, a mobile host simply needs to access multiple time slots. If FDMA or CDMA is assumed, a host may need more than one pair of transceiver.

Disregarding the transmission technology (TDMA, FDMA, or CDMA), we can classify a mobile host into several categories based on its capability in accessing multiple channels:

- *single-transceiver:* A mobile host can only access one channel at a time. The transceiver can be simplex or duplex. Note that this is not necessarily equivalent to the single-channel model, because the MAC is still capable of switching from one channel to another channel even with one transceiver.

- *multiple-transceiver:* Each transceiver could be simplex or duplex. A mobile host can access multiple channels simultaneously.

As reported in [2, 11], it is possible for a transceiver to switch from one channel to another at a short time period of $1\mu sec$. The extra hardware cost is not high.

Using multiple channels may render several advantages. First, consider CDMA, which has received a lot of attention recently and is known to be resilient to the signal fading and multi-path problems. If a protocol can only operate under one shared channel (e.g., IEEE 802.11), the maximum throughput of the network will be limited by the bandwidth of the channel. The throughput may be increased immediately if a host can utilize multiple channels with a proper multi-channel MAC protocol. Second, as shown in [4, 26], 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 guarantee quality of service, a QoS routing protocol is proposed in [22] based on multiple channels.

A multi-channel MAC 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 [5, 7, 8, 9, 12, 15, 17, 25, 26, 29, 14, 31]. References [5, 7, 9, 15, 25] 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 [8, 31], 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 [17], 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 [14] 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 that work. The drawbacks include long polling time and potential collisions among polling signals. The protocol [12] 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 [26]. 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 [29]. 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.

In this thesis, we propose a new multi-channel MAC protocol which can be applied to both FDMA and CDMA technology. The protocol requires two simplex transceivers per mobile host. Based on a RTS/CTS-like reservation mechanism, our protocol does not require any form of clock synchronization among mobile hosts. It dynamically assigns channels to mobile hosts in an "on-demand" fashion and is also a degree-independent protocol. Both the channel assignment and medium access problems are solved in an integrated manner with light control traffic overhead. In Table 1.1, we summarize and compare the above reviewed protocols and ours. Extensive simulation results are presented based on two bandwidth models: *fixed-channel-bandwidth* and *fixed-total-bandwidth*. Observations and analysis are given to explain under what condition our multi-channel MAC protocol can outperform its single-channel counterpart. The results also indicate that using our protocol will experience less degradation when the network is highly loaded.

The rest of this thesis is organized as follows. In Chapter 2, we present a simple MAC protocol based on a static channel assignment, through which we then discuss several important issues that should be addressed by a multi-channel MAC protocol. Chapter 3 presents

Table 1.1: Comparison of multi-channel MAC protocols.

protocol	assignment	no_transceivers	no_channels	clock sync.	info. collected
[8, 31]	no need	2	2	no	none
[5, 7, 9, 15, 25]	static	1	deg.-dep.	no	global
[17]	static	*n*	deg.-indep.	yes	none
[14]	N/A	2	N/A	no	N/A
[12]	dynamic	2	deg.-dep.	no	2-hop
[26]	dynamic	*n*	deg.-indep.	no	none
[29]	dynamic	1	deg.-indep.	yes	none
ours	dynamic	2	deg.-indep.	no	1-hop

our multi-channel MAC protocol. Some analysis and simulation results are given in Chapter 4. Conclusions are drawn in Chapter 5.

Chapter 2

Concerns with Using Multiple Channels

The purpose of this section is to motivate our work. We will show that care must be taken if one tries to directly translate a single-channel MAC (such as IEEE 802.11) to a multi-channel MAC. To start with, we will introduce a multi-channel MAC protocol based on a static channel assignment strategy. Then several interesting observations with using multiple channels, as opposed to using single channel, will be raised.

2.1 SM: A Simple Multi-channel Protocol

Below, we present a simple multi-channel MMAC protocol, which we cal *SM*. The protocol uses a static channel assignment, and on each channel the transmission follows IEEE 802.11. We assume that there are an arbitrary number of hosts in the MANET, but the system only offers a fixed number, n, of channels. Each mobile host is equipped with a half-duplex transceiver Thus, when $n = 1$, this converges to the IEEE 802.11 Standard.

In SM, channels are assigned to mobile hosts in a random, but static, manner. One simple way is to use hosts' IDs (e.g., IP address or network card's MAC address). Supposing that channels are numbered $0, 1, \ldots, n-1$, we can statically assign channel $i = ID \bmod n$ to host ID. The basic idea is: when a host X needs to send to a host Y, X should tune to Y's channel. Then, X follows IEEE 802.11 [3] to access the medium. A host operates between two states, RECEIVE and SEND, as described below.

- *RECEIVE*:

    1. When the host has nothing to send, it tunes its transceiver to its channel, listening for possible intending senders.
    2. On receiving a RTS (request-to-send) packet, it follows IEEE 802.11 to reply a CTS (clear-to-send) packet using its own channel. Then it waits for the data packet, still on the same channel.

- *SEND*:

    1. When the host is not expecting any data packet (under the RECEIVE mode) and has a packet to send, it switches to the SEND mode and transmits a RTS to the receiver using the receiver's channel. Then it waits for the receiver's reply.
    2. On receiving the replied CTS, it starts to transmit the data packet, following the IEEE 802.11 style, using the receiver's channel. Then it waits for the receiver's ACK, on which event it will return to the RECEIVE mode.

2.2 Some Observations

Below, we make some observations associated with the above SM protocol. Two traditional problems in a single-channel system are the *hidden-terminal* and *exposed-terminal* problems, as illustrated in Fig. 2.1. In Fig. 2.1(a), when host A is sending to B, because host C can not sense the signals from A, it is likely that C's transmission activity will be overheard by B and thus destroy B's receiving activity. In Fig. 2.1(b), host A is sending to B. Later, host C intends to send to host D, but since C can sense A's signals, C will wait until A's transmission activity terminates. In fact, the communications from A to B and from C to D can happen concurrently.

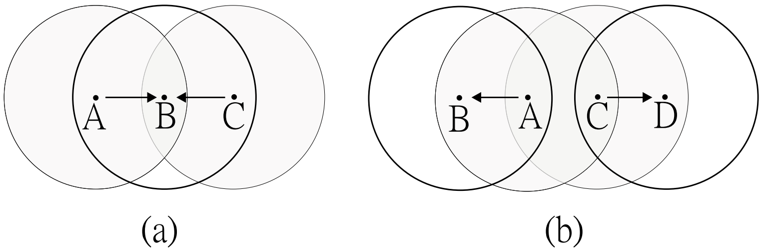

Figure 2.1: Two traditional problems in a single-channel system: (a) the hidden-terminal problem, and (b) the exposed-terminal problem.

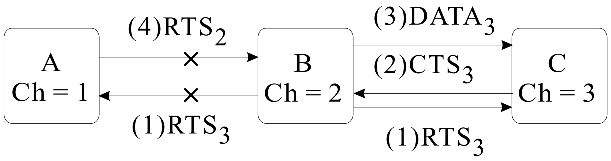

Figure 2.2: The problem of missing RTS in a multi-channel MAC. (The leading number on each message shows the message sequence; the subscript shows the channel on which the corresponding message is sent.)

We would like to know how these problems affect the SM protocol, which has multiple channels. As shown below, the hidden-terminal problem will become more serious, the exposed-terminal problem will become less serious, and some new problems may appear.

- *Missing RTS:* In Fig. 2.2, host *B* initiates a communication with *C* using *C*'s channel 3. Host *A* later intends to communicate with *B* and thus sends a RTS on channel 2. Since *B* is busy in sending, this RTS will not be heard by *B*. Furthermore, since *A* can not sense the carrier from *B* (on channel 3), multiple RTSs may be sent at a *short* period of time until the maximal number of retrials expires. On the contrary, in a single-channel MAC, the carrier from *B* can be detected by *A* and thus *A* will inhibit its next RTS unless the common carrier is free. Thus, *A*'s RTS has a higher chance to succeed in a single-channel MAC.

- *False Connectivity Detection:* The above failure in RTS will lead to a dilemma that *A* can not tell whether *B* is at its neighbor or not. Thus, *A* may easily and falsely conclude

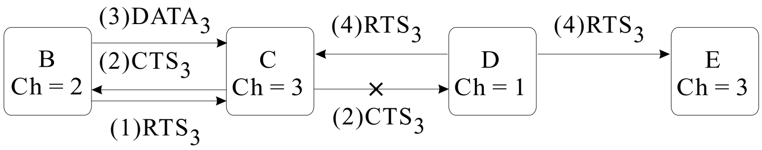

Figure 2.3: The problem of missing CTS in a multi-channel MAC.

that the link from *A* to *B* is broken. This may give the upper network layer a false signal and lead to a disaster. For instance, consider the many routing protocols for MANET [13, 16, 28]. If the link from *A* to *B* is a part of a route, then a ROUTE_ERROR packet will be reported to the source of the route, causing the source host to initiate a new, but unnecessary, round of ROUTE_DISCOVERY. In fact, the original route still exists. According to [27], ROUTE_DISCOVERY will lead to a *broadcast storm* problem, thus causing serious redundancy, contention, and collision on the medium. Because of this, the network may be flooded by many control packets.

- *Missing CTS:* In Fig. 2.3, similar to the earlier scenario, *B* initiates a communication with *C* on channel 3. Later on, host *D* wants to send to *C* and initiates a RTS on channel 3, thus destroying *C*'s receiving activity. This is similar to the hidden-terminal problem. However, in a single-channel MAC, this RTS will be prohibited by *C*'s earlier *CTS*. Unfortunately, in a multi-channel MAC, *C*'s earlier CTS may not be heard by *D* because *D* will tune its transceiver to channel 3 only after there is a transmission need. Thus, using CTS is less effective in a multi-channel MAC as opposed to that in a single-channel MAC. In addition, as shown in the right-hand part of Fig. 2.3, even if *D*'s intending receiver is *E* instead of *C*, as long as *E*'s channel is the same as *C*'s, *C*'s receiving activity will still be destroyed. Hence, the hidden-terminal problem will become more serious unless sufficient care has been taken. If it is guaranteed that no two hosts within a distance of two hops will use the same channel to send (such as [5, 12]), this problem can be alleviated.

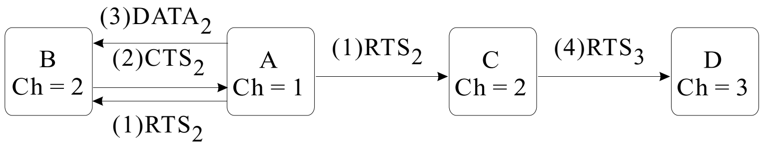

Figure 2.4: The exposed-terminal problem in a multi-channel MAC.

- *Exposed-Terminal Problem:* Consider the exposed-terminal problem in Fig. 2.4, which is redrawn from Fig. 2.1(b) by assigning a channel to each host. In this case, *C* may hear *A*'s earlier RTS (on channel 2). However, *C* is still allowed to use *D*'s channel 3 to send a RTS. Thus, the transmission from *C* to *D* may be granted. So the exposed-terminal problem can be somehow relieved in a multi-channel MAC.

- *Channel Deadlock Problem:* In Fig. 2.5, we show a scenario that there is a circle of hosts, *A*, *B*, *C*, and *D*, each intending to communicate with the host next to it by sending a RTS. Since each host tunes its transceiver to the SEND mode, these RTSs are likely to be missed. This will form a circular dependence relation, thus creating a deadlock scenario. As time passes by, the deadlock may be resolved automatically. However, we conjecture that such scenarios may be common, especially when the network load is high, and multiple deadlocks may exist. This may significantly degrade channel utilization, and thus the system's performance.

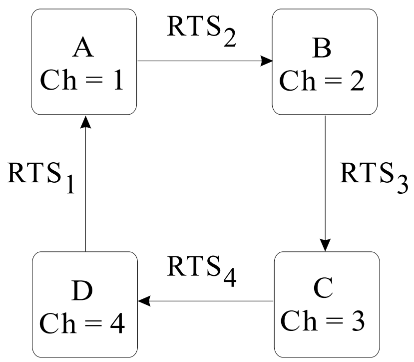

Figure 2.5: The channel deadlock problem in a multi-channel MAC.

Chapter 3

DCA Multi-Channel MAC Protocol

This section presents our multi-channel MAC protocol, which we call *DCA (dynamic channel assignment)*. The proposed protocol has the following features. First, it assigns channels to mobile hosts in an "on-demand" manner in that only those hosts intending to send will own channels. Once a host completes its transmission, the channel will be released. Second, we assume that the MANET is given a fixed number of channels, which is independent of the network size, topology, and degree. Third, we do not assume any form of clock synchronization among mobile hosts.

We first describe our channel model. The overall bandwidth is divided into one control channel and n data channels $D_1, D_2, \ldots, D_n$. This is exemplified in Fig. 3.1, based on a FDMA model. (If CDMA is used, the control channel may occupy one or more codes.) Each data channel is equivalent and has the same bandwidth. The purpose of the control channel is to resolve the contention on data channels and assign data channels to mobile hosts. Data channels are used to transmit data packets and acknowledgements. Each mobile host is equipped with two half-duplex transceivers, as described below.

- *control transceiver:* This 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:* This transceiver will dynamically switch to one of the data channels

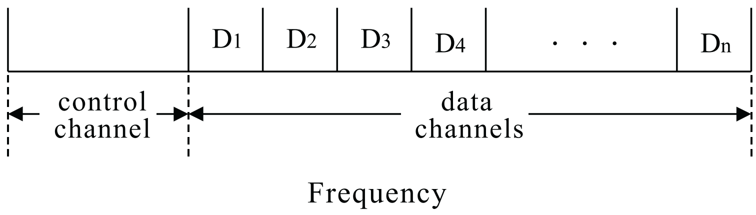

Figure 3.1: The channel model of our DCA protocol.

to transmit data packets and acknowledgements.

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

- $CUL[\,]$: This 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 three fields:
  - $CUL[i].host$: a neighbor host of X.
  - $CUL[i].ch$: a data channel used by $CUL[i].host$.
  - $CUL[i].rel\_time$: when channel $CUL[i].ch$ will be released by $CUL[i].host$.

  Note that this CUL is distributedly maintained by each mobile host and thus may not contain the precise information.

- FCL: This is called the *free channel list*, which is dynamically computed from CUL.

The main idea of our protocol is as follows. For a mobile host A to communicate with host B, A will send a RTS (request-to-send) to B carrying its FCL. Then B will match this FCL with its CUL to identify a data channel (if any) to be used in their subsequent communication and reply a CTS (clear-to-send) to A. On receiving B's CTS, A will send a RES (reservation) packet to inhibit its neighborhood from using the same channel. Similarly, the CTS will inhibit B's neighborhood from using that channel. All these will happen on the control channel. Finally, a data packet will be transmitted on that data channel.

The complete protocol is shown below. Table 3.1 lists the variables/constants used in our presentaiton.

Table 3.1: 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

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 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:

   $$(CUL[i].ch = D_j) \Longrightarrow (CUL[i].rel\_time \leq T_{curr} + (T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS})).$$

   Intuitively, this is to ensure that D_j is either not in the CUL or in CUL but will be free after a successful exchange of RTS and CTS packets. (Fig. 3.2 shows how the above timing is calculated.)

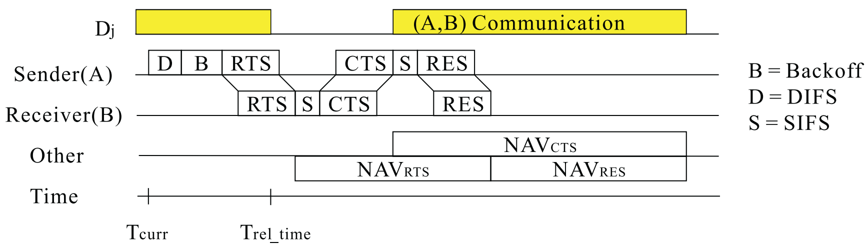

Figure 3.2: Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

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, 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:

$$(CUL[i].ch = D_j) \Longrightarrow (CUL[i].rel\_time \leq T_{curr} + (T_{SIFS} + T_{CTS})).$$

If so, D_j is a free channel that can be used. Then B picks any such D_j and replies a $CTS(D_j, NAV_{CTS})$ to A, where

$$NAV_{CTS} = L_d/B_d + T_{ACK} + 2\tau.$$

Then B tunes its data transceiver to D_j. Otherwise, B replies a $CTS(T_{est})$ 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 $\rightarrow$ CTS $\rightarrow$ 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 $CTS(D_j, NAV_{CTS})$, it performs the following steps:

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

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

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

$$NAV_{RES} = NAV_{CTS} - T_{SIFS} - T_{RES}$$

   c) Send its DATA packet to B on the data channel D_j. 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 $CTS(D_j, NAV_{CTS})$, C updates its CUL. This is the same as step 6a) except that

$$CUL[k].rel\_time = T_{curr} + NAV_{CTS} + \tau.$$

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

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

$$\begin{aligned} CUL[k].host &= A \\ CUL[k].ch &= D_j \\ CUL[k].rel\_time &= T_{curr} + NAV_{RES} \end{aligned}$$

9. On B completely receiving A's data packet, B replies an ACK on D_j.

To summarize, our protocol relies on the control channel to assign data channels. Because of the control channel, the deadlock problem can be avoided. For the same reason, the missing RTS/CTS and the hidden-terminal problems will be less serious.

Chapter 4

Analysis and Simulation Results

4.1 Arrangement of Control and Data Channels

One concern in our protocol is: Can the control channel efficiently distribute the communication job to data channels? For example, in Fig. 4.1, we show an example with 5 channels (1 for control and 4 for data). For simplicity, let's assume that the lengths of all control packets (RTS, CTS, and RES) are L_c, and those of all data packets $L_d = 9L_c$. Fig. 4.1 shows a scenario that the control channel can only utilize three data channels D_1, D_2, and D_3. Channel D_4 may never be used because the control channel is already fully loaded.

The above example indicates the importance of the relationship between control and data channels. In this thesis, we consider two bandwidth models.

- *fixed-channel-bandwidth:* Each channel has a fixed bandwidth. Thus, with more chan-

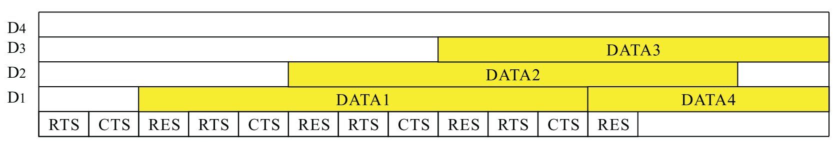

Figure 4.1: An example that the control channel is fully loaded and the data channel D_4 is not utilized.

nels, the network occupies more bandwidth.

- *fixed-total-bandwidth:* The total bandwidth offered to the network is fixed. Thus, with more channels, each channel shares less bandwidth.

Now, let's consider the relationship of the bandwidths of control and data channels. We investigate the fixed-channel-bandwidth model first. Since the control channel can schedule a data packet by sending at least 3 control packets, the maximum number of data channels should be limited by

$$n \leq \frac{L_d}{3 \times L_c}. \tag{4.1}$$

Also, consider the utilization U of the total given bandwidth. Since the control channel is actually not used for transmitting data packets, we have

$$U \leq \frac{n}{n+1}. \tag{4.2}$$

From Eq. (4.1) and Eq. (4.2), we derive that

$$\frac{U}{1-U} \leq n \leq \frac{L_d}{3 \times L_c} \Longrightarrow U \leq \frac{L_d}{3 \times L_c + L_d}. \tag{4.3}$$

The above inequality implies that the maximum utilization is a function of the lengths of control and data packets. Thus, decreasing the length of control packets or increasing the length of data packets will improve the utilization. Also, since the maximum utilization is only dependent of L_d and L_c, it will be unwise to unlimitedly increase the number of data channels.

Next, we investigate the fixed-total-bandwidth model. Suppose that we are given a fixed bandwidth. The problems are: (i) how to assign the bandwidth to the control and data channels, and (ii) how many data channels (n) are needed, to achieve the best utilization. Let the bandwidth of the control channel be B_c, and that of each data channel B_d. Again, the number of data channels should be limited by the scheduling capability of the control channel:

$$n \leq \frac{L_d/B_d}{3 \times L_c/B_c}. \tag{4.4}$$

Similarly, the utilization U must satisfy

$$U \leq \frac{n \times B_d}{n \times B_d + B_c}. \tag{4.5}$$

Combining Eq. (4.4) and Eq. (4.5) gives

$$\frac{UB_c}{B_d - UB_d} \leq n \leq \frac{L_d B_c}{3 \times L_c B_d} \Longrightarrow U \leq \frac{L_d}{3 \times L_c + L_d}. \tag{4.6}$$

Interestingly, this gives the same conclusion as that in the fixed-channel-bandwidth model. The bandwidths B_c and B_d have disappeared in the above inequality, and the maximum utilization is still only a function of the lengths of control and data packets. Thus, decreasing the length of control packets or increasing the length of data packets will improve the utilization. To understand how to divide the bandwidth, we replace the maximum utilization into Eq. (4.5), which gives

$$\frac{L_d}{3 \times L_c + L_d} = \frac{n \times B_d}{n \times B_d + B_c} \Longrightarrow \frac{B_c}{nB_d} = \frac{3L_c}{L_d}. \tag{4.7}$$

Thus, to achieve the best utilization, the ratio of the control bandwidth to the data bandwidth should be $3L_c/L_d$. Theoretically, since the maximum utilization is independent of the value of n, as long as the above ratio ($3L_c/L_d$) is used, it does not matter how many data channels are used.

Finally, we comment on several minor things in the above analysis. First, if the control packets are of different lengths, the $3L_c$ can simply be replaced by the total length of RTS, CTS, and RES. Second, since the L_d has included the length of an ACK packet (say, k), the actual data packet length should be $L_d - k$. Third, we did not consider many protocol factors (such as propagation delay, SIFS, DIFS, collision, backoffs, etc.) in the analysis. In reality, the above utilization may be further lowered down. In the next section, we will investigate this through simulations.

4.2 Experimental Results

We have implemented a simulator to evaluate the performance of our DCA protocol. We mainly used SM as a reference for comparison. Also, note that when there is only one channel, SM is equal to IEEE 802.11. Two hundred mobile hosts were generated randomly in a physical area of size 100×100. 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.

In our simulation, both of the earlier bandwidth models are used. There are two performance metrics:

$$Throughput = \frac{\text{Packet\_Length} * \text{No\_Successful\_Packets}}{\text{Total\_Time}}$$

$$Utilization = \frac{\text{Packet\_Transmission\_Time} * \text{No\_Successful\_Packets}}{\text{Total\_Time} * \text{No\_Channels}}$$

The former will be more appropriate to evaluate the performance under the fixed-channel-bandwidth model, while the latter more appropriate under the fixed-total-bandwidth model. Note that the No_Channels includes both control and data channels.

The parameters used in our simulations are listed in Table 4.1. In the following, we present our simulation results from 4 aspects. Note that except in part C, each control and data channel is of the same bandwidth. 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.

A) Effect of the Number of Channels: In this experiment, we change the number of channels to observe its effect. Fig. 4.2 shows the result under the fixed-channel-bandwidth model. We observe that the throughput of SM will increase as more channels are used. Similar to SM, the throughput of our DCA increases as more channels are used, but will

Table 4.1: Simulation parameters.

number of mobile hosts	200
physical area	100×100
transmission range (for exp. A, B, C only)	30
max. no. of retrials to send a RTS	6
length of DIFS	50 μsec
length of SIFS	10 μsec
backoff slot time	20 μsec
signal propagation time	5 μsec
control packet length L_c	300 bits
data packet length L_d	a multiple of L_c

saturate at round 11 channels, after which points using more channels is of little help. This is because we used $L_d/L_c = 30$ in this simulation, so using more than $((Ld+Lc)/3Lc)+1 = 11.3$ channels is unnecessary (see Eq. (4.1)). As comparing these two protocols, we see that below the saturation point (11 channels), DCA can offer significantly more throughput than SM. However, with more than 11 channels, DCA will be less efficient than SM. This is because the control channel is already fully loaded and can not function well to distribute data channels to mobile hosts.

Another point to be made is that at high load, DCA will suffer less degradation than SM. There are two reasons. The first reason is that DCA separates control from data channels. In 802.11-like protocols, a RTS/CTS dialogue is not guaranteed to be heard by all neighboring hosts due to collision. Thus, any “innocent” host who later initiates a RTS/CTS will corrupt others’ on-going data packets (an analysis on this can be found in [8]). Separating control and data channels will relieve this problem. The second reason is that DCA uses multiple data channels. Using multiple data channels can further reduce the possibility of data packet collisions incurred by incorrect RTS/CTS/RES dialogues (by “incorrect”, we mean that some of the RTS/CTS/RES packets are collided/corrupted at some hosts, making them mistakenly choose the same data channel at the same time; a larger number of data channels will dilute

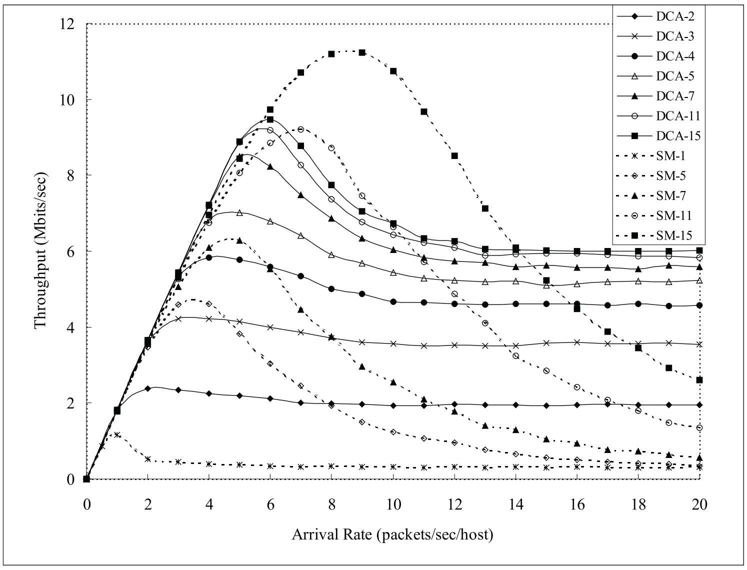

Figure 4.2: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

such probability).

Fig. 4.3 shows the same simulation under the fixed-total-bandwidth model. Note that we use utilization to compare the performance. We see that the utilization of SM decreases as more channels are used. This is perhaps because of the short of flexibility in static channel assignment. On the contrary, the best utilization of our DCA appears at around 4 channels. The peak performance is about 15% higher than SM-1 (i.e., IEEE 802.11). Also, at high load, our DCA will suffer less degradation than SM. With more channels, our DCA will degrade significantly. As analyzed in Section 4.1, the best utilization should happen at $\frac{B_c}{nB_d} = \frac{3L_c}{L_d} = \frac{1}{10}$. This implies that using $n = 10$ channels is the best choice. The reason for the deviation is that the duration of a successful RTS/CTS/RES dialogue will actually take longer than $3L_c$, due to many factors such as DIFS, SIFS, signal propagation time, unexpected contention, collision, and backoff time.

B) Effect of Data Packet Length: As observed in the previous experiment, the perfor-

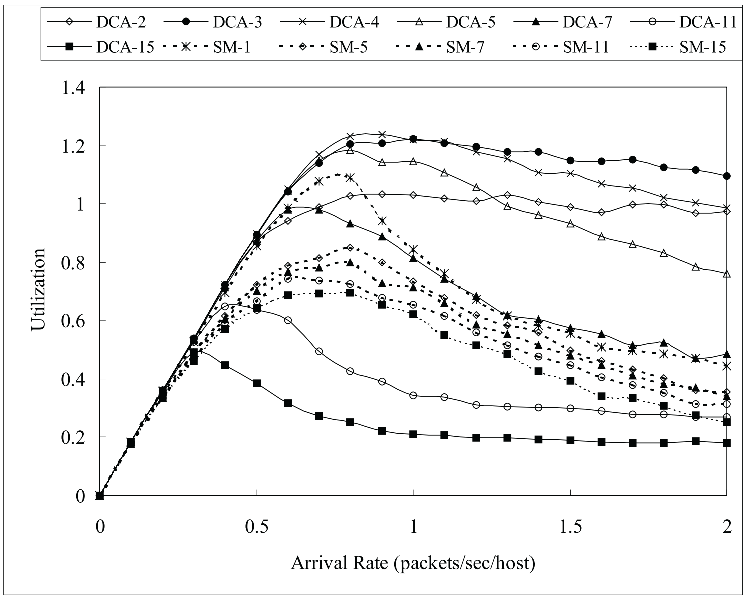

Figure 4.3: Arrival rate vs. utilization under the fixed-total-bandwidth model with different numbers of channels.

mance of our DCA protocol will be limited by the capability of the control channel. One possibility is to increase the length of data packets so as to reduce the load on the control channel. Here, we test 6, 11, 21, 41, and 81 channels, with $L_d/L_c = 30, 60, 120$, and 240. Fig. 4.4 shows the throughput under the fixed-channel-bandwidth model. According to Eq. (4.1), when $L_d/L_c = 30, 60, 120$, and 240, it is unnecessary to have more than 11, 21, 41, and 81 channels, respectively. This is why in Fig. 4.4(a) we see that when $L_d/L_c = 30$, increasing from 11 channels to 21 channels does not have much improvement on the throughput. If we further increase the ratio L_d/L_c, as shown in Fig. 4.4(b), (c), and (d), the throughput will saturate at larger numbers of channels. This implies that given more channels, we should appropriately adjust the data packet length so as to obtain a better performance.

Looking from another prospect, we may ask: given a fixed total bandwidth and a fixed packet length, how many data channels should be used. In Fig. 4.5, assuming $L_d/L_c = 30, 120$ and 480, we show the maximum utilization under different numbers of channels. The results suggest that 4, 5, and 6 channels should be used in these cases, respectively.

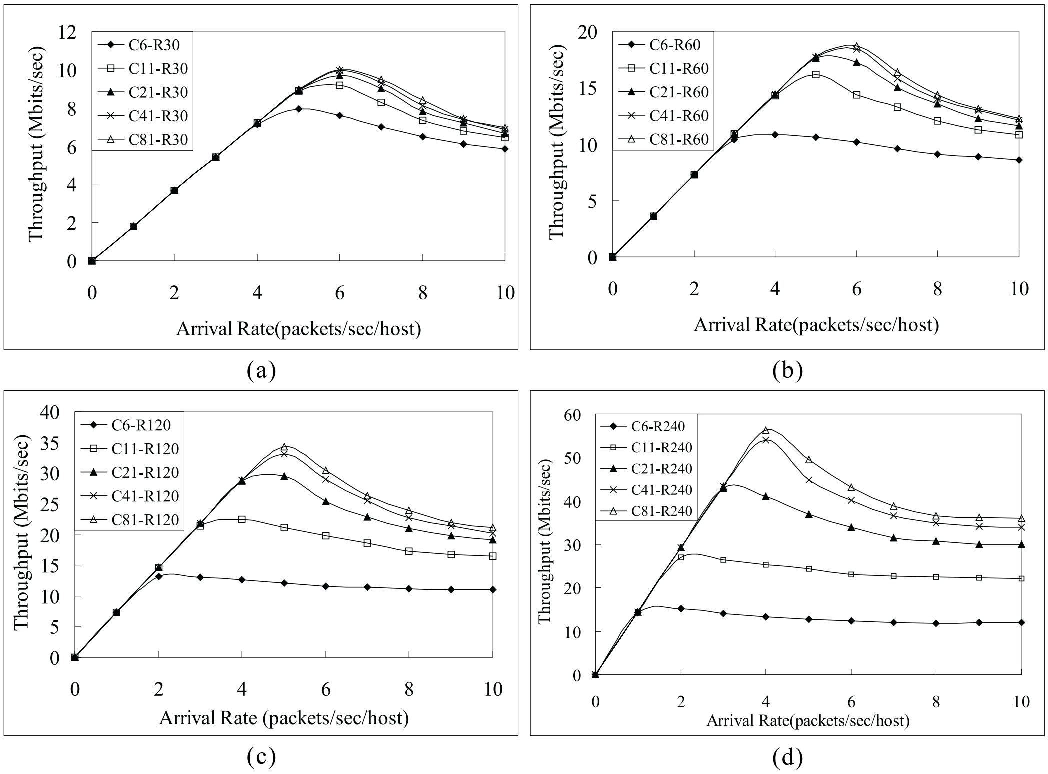

Figure 4.4: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different L_d/L_c ratios (Ci-Rj means using i channels, including control and data ones, with ratio $L_d/L_c = j$).

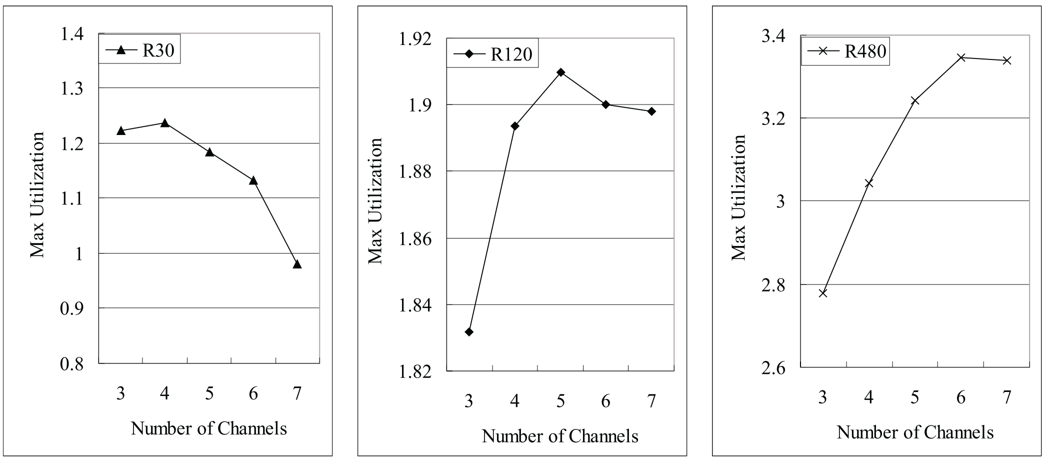

Figure 4.5: Number of channels vs. maximum utilization under the fixed-total-bandwidth model at different L_d/L_c ratios.

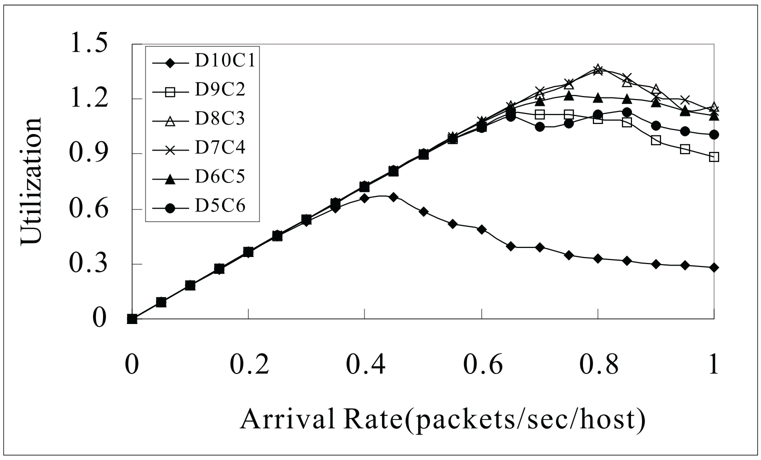

Figure 4.6: Arrival rate vs. throughput under the fixed-channel-bandwidth model given 11 channels (DiCj means using i data channels and j control channels).

C) Effect of the Bandwidth of the Control Channel: Another way to relieve the load on the control channel is to increase its bandwidth. In this simulation, we use the fixed-total-bandwidth model with $L_d/L_c = 30$. We assume a total bandwidth of 1 Mbits/sec and divide it into 11 channels. Then we assign i channels as data channels, and j channels as control ones, where $i + j = 11$. These j control channels are collectively used as *one* channel (thus, the transmission speed is j times faster). The result is in Fig. 4.6. Thus, given a CDMA system with 11 codes, using 3 or 4 codes for control will be most beneficial.

D) Effect of Host Density: In all the earlier experiments, we have used a transmission range $T = 30$ for each mobile host. In this experiment, we vary T to observe the effect. Intuitively, a larger T means a more crowded environment. Note that when $T = 100\sqrt{2}$, the network is fully connected. Fig. 4.7 shows the result under the fixed-channel-bandwidth model with $L_d/L_c = 240$ and a total of 6, 11, and 21 channels (note that control always occupies one channel). We see that the maximum throughput will increase as T decreases. This is reasonable because a smaller T means higher channel reuse. As comparing different numbers of channels, we see that in a more crowded environment, using more channels is more beneficial. Thus, our DCA protocol is more useful in a more crowded environment.

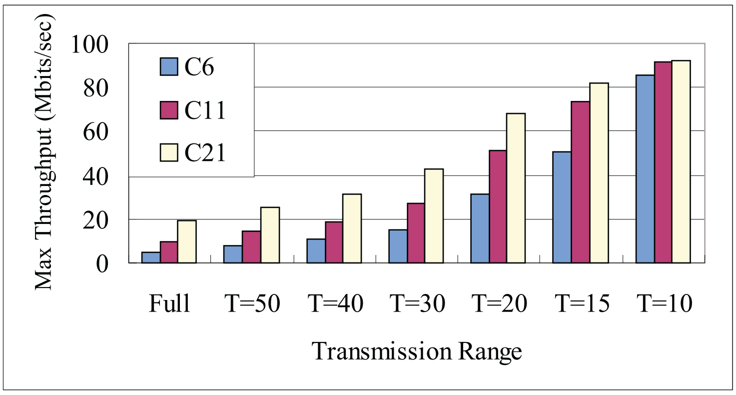

Figure 4.7: Transmission range vs. maximum throughput at different numbers of channels.

This shows the practical value of our result.

Chapter 5

Conclusions

We have proposed a new multi-channel MAC protocol based on an on-demand channel assignment concept. The number of channels required is independent of the network size, degree, and topology. There is no form of clock synchronization used. These features make our protocol more appropriate for MANETs than existing protocols. We solve the channel assignment and medium access problems in an integrated manner in one protocol. The hardware requirement is two transceivers per mobile host. Simulation results have justified the merit of our protocol under both fixed-channel-bandwidth and fixed-total-bandwidth models. The result for the fixed-channel-bandwidth model is particularly interesting for the currently favorable CDMA technology. Another noticeable discussion in this thesis is the missing-RTS, missing-CTS, hidden-terminal, exposed-terminal, and channel deadlock problems, which may behave differently in a multi-channel environment as opposed to a single-channel environment. We are currently working on extending our access mechanism to a reservation one (such as reserving a train of data packets, so as to relieve the load on the control channel).

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