國 立 中 央 大 學

資 訊 工 程 研 究 所

博 士 論 文

無線行動隨建即連網路之媒體存取問題

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研究生簽名: 吳 世 琳

論文名稱: 無線行動隨建即連網路上之媒體存取問題

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資訊工程研究所吳世琳君所提之論文

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（題　　目）

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資訊工程研究所吳世琳君所提之論文

無線行動隨建即連網路上之媒體存取問題

（題　　目）

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論文提要內容：

「無線行動隨建即連網路」(wireless mobile ad hoc network, MANET) 是由一群具有無線傳輸裝置的行動主機所組成的通訊網路。行動主機彼此之間的通訊不需依賴基地台，而是藉由其他行動主機合作，以多段通訊 (multihop communication) 的方式來達成在行動主機間傳遞訊息的目的。因此，這種網路可以不受時間、地點的限制，快速的由一群行動主機架構完成。無線傳輸媒體 (spectrum) 一般可分成單一頻道 (single-channel) 與多重頻道 (multi-channel) 兩種模式。網路的媒體存取層 (medium access control, MAC) 最主要的目的就是要增進媒體的使用效率。然而主要影響媒體使用效率的就是競爭與碰撞 (contention/collision)。在本篇論文中，我們將在這具有無線、行動且分散式的環境中，針對三種不同的環境，提出五種不同的協定來提昇媒體傳輸效率。這三種環境分別為「單一頻道」,「無座標式多重頻道」(multi-channel without location awareness) 及「有座標式多重頻道」(multi-channel with location awareness)。

我們知道在一定的區域內使用較小的發射功率可以讓同一時間更多行動主機使用相同的頻道。在單一頻道環境中，我們所設計的新協定 (protocol) 是藉由控制發射功率 (power control) 的大小，再結合傳統交換 RTS/CTS 及 busy-tone 的機制，更進一步的提升頻道的使用效率。另外我們也討論分析使用有限段式 (discrete) 取代連續無段式 (continuous) 的調整發射功率，並且修改協定使其達到最佳的成本效益比。最後我們經由分析及實驗證明這個協定確實優於傳統協定大約兩倍的效能。

多重頻道的技術是另一個減輕媒體競爭與碰撞的方法。多重頻道比單一頻道的好處主要有三點：(1)系統總頻寬可以立即增加數倍， (2) 降低傳輸封包的碰撞機率，(3) 較容易支援 QoS (quality of service)。雖然使用多重頻道有那麼多的好處，但是設計上除了要有良好的媒體存取機制外，還必須配合一套有彈性的頻道配置 (channel assignment) 機制，才能使多重頻道協定的效能發揮到極致。

在無座標式多重頻道環境中，我們設計一個具有動態頻道分配的協定，稱之為 DCA (dynamic channel assignment)。DCA 具有下列數個特性: (1)以 On-Demand 的方式分配頻道給需要通訊行動主機，(2) 系統提供給網路所需的頻道個數與網路的拓樸是無關的，(3) 此協定只需要交換少數的控制訊息(Control Messages)就可以同時完成媒體存取與頻道配置兩個功能，(4)行動主機不需要任何型式的時間同步(time synchronization)。經由分析與實驗得知 DCA 確實比其他協定較適合於無線行動隨建即連網路。另外，我們將控制發射功率的機制加入 DCA，讓頻道重複使用率更加提高。經由實驗得知，效能大約比 DCA 提昇四成左右。

無線行動隨建即連網路既然是在一個固定區域上運作，因此行動主機所在位置便成為很重要的資訊。在最後一個環境有座標式多重頻道中，我們設計一個新的協定稱為 GRID，它最大的特色就是利用位置資訊完成頻道的配置，行動主機完全不需負擔任何控制訊息的收送。在媒體存取方面，我們使用類似 RTS/CTS 的方式，保留媒體的使用權，這種方式的優點是行動主機間不需任何形式的時間同步，而且系統提供給網路頻道個數與網路的拓樸也是無關的。此外 GRID 所使用的頻道配置是靜態的。我們知道在現實狀況中，經常會有某些地區人口密集的狀況出現，如果只是使用簡單的靜態頻道配置，效率將會不好。因此我們提出借頻道的方式來達成動態是的頻道配置，經由實驗證明確實可以提昇不少效能。

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吳 世 琳

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第一章、 簡介

近年來無線傳輸技術之進步和普及，使得「communication anytime, anywhere」已然實現。這點可由眾多無線網路產品的發展看出：如 Lucent 的 WaveLan、Solectek 的 AIRLAN、BreezeCOM 的 BreezeNET、Proxim 的 RangeLINK 和 RangeLAN、Cylink 的 AirLink Bridge、CDPD 協定，以及個人通訊系統的發展：如 DECT、GSM 等。另一方面，由於各類體積小、重量輕的可攜式計算設備(如，個人數位助理 PDA、掌上型電腦、筆記型電腦) 技術的成熟更加促成產業另一次大革命，結合通訊與電腦兩大領域創造出「行動計算(mobile computing)」和「無所不在的計算(ubiquitous computing)」計算環境，提供人類更生活化的高科技享受。

有關無線通訊及計算方面的研究，無論是學術研究機構或工商業界，都是如火如荼的在進行。其中一種無基地台的無線網路架構稱之為「無線行動隨建即連網路」(wireless mobile ad hoc network, MANET)，更是目前大家所最觀注的研究課題之一。主要的原因是在許多無法設立固定基地台的環境下（例如高山地區沒有基地台的地方，如野外救援、戶外活動、考古與生態的探勘等），或網路基礎設施瞬間破壞而無法在短時間內重建的環境下（例如大地震後災區的緊急救難通訊），以及一些不易建置基地台之處（例如海洋上的艦隊、行軍中的縱隊、和天空中飛機的編隊等），MANET 仍然可以動態且迅速地建立網路通訊系統。

MANET 的是一種無基地台式的無線網路，所有通訊都靠行動主機 MH (Mobile Host)互相合作來完成。這和傳統細胞型系統不同的是，在無線行動隨建即連網路中沒有基地台來管理行動主機間的位址資訊、安排通訊頻道和轉播訊息，所以是屬於完全分散式的管理。因此在這種網路中，每個行動主機必須和其他主機互助合作，尋找主機間的資料傳遞路徑，並替其他主機轉播訊息。再加上無線傳輸及移動(mobility)等特性，使得網路拓樸呈現動態變化，所以在設計上有許多具挑戰性的問題值得探討。

一、研究動機與貢獻

本論文探討 MANET 上媒體存取層(Medium Access Control, MAC)之問題。無線傳輸主要是依靠有限的頻寬，因此如何有效管理此一珍貴的資源，便成為 MANET 網路中主要的研究重點。網路的媒體存取層最主要的目的就是要增進媒體的使用效率。然而主要影響媒體使用效率的就是競爭與碰撞 (contention/collision)。雖然國際組織 IEEE

已經提出 802.11 的標準，但應用在這個具有無線、行動且分散式的 MANET 環境時，仍然有許多問題和改善的空間。無線傳輸媒體 (spectrum) 一般可分成單一頻道 (single-channel) 與多重頻道 (multi-channel) 兩種模式。在本篇論文中，我們將針對三種不同的環境，提出五種 MAC 協定來提昇 MANET 上媒體傳輸的效率。這三種環境分別為 「單一頻道」，「無座標式多重頻道」 (multi-channel without location awareness) 及「有座標式多重頻道」 (multi-channel with location awareness)。以下我們針對這三個環境，說明五個 MAC 協定的功能與目的。

二、在單一頻道上設計具控制發射功率 (power control)之 MAC 協定

在 Ad Hoc 單一頻道網路架構下，為了要增加頻道（channel）的使用率，並避免 hidden-terminal 和 exposed-terminal 的問題，通常會利用 RTS/CTS-based (例如 MACA, MACAW, FAMA, CSMA/CA) 和 busy-tone-based (DBTMA) 等機制來減緩這些問題所造成的影響。除了這兩個機制之外，若是再引入 Power Control 觀念，更可以有效的增加 channel reuse 進而改善頻道的使用率。Power Control 就是控制傳送端傳送封包時的功率大小，以降低頻道之間彼此的破壞、干擾，如此可以增加頻道重覆使用的機率，降低對其他鄰居的干擾，亦可降低能量的消耗，達到省電的目地。我們所設計的這個協定，是藉由控制發射功率 (power control) 的大小，再結合傳統交換 RTS/CTS 及 busy-tone 的機制，目的就是更進一步的提升頻道的使用效率。另外我們也考慮到實做上的限制，分析使用有限段式 (discrete) 取代連續無段式 (continuous) 的調整發射功率，並且修改協定使其達到最佳的成本效益比。最後我們經由分析及實驗證明這個協定確實優於傳統協定大約兩倍的效能。

三、在多重頻道環境中設計具有動態頻道分配的 MAC 協定

現有 MANET 網路架構中，MAC 層通常假設單一共同的 channel (single common channel)。此種 channel model 最當的弱點就是當網路傳輸負載達到飽和時，若再增加傳輸負荷將會因為碰撞機率過高因而造成效能過低的結果。我們所提出的多重頻道 (multi-channel)就是要減緩這種結果的方法之一。由於硬體技術進步（如 CDMA, WCDMA 技術）使得 multi-channel 已具可行性。由於 multi-channel 可架構於 spread spectrum 的技術上，先天上就對 multiple path、signal fading 等干擾源較具免疫力；若能夠將 channel 分配妥善，更可進一步的降底 co-channel interference，提升 channel utilization，所以 multi-channel 的優點是毋庸置疑。除此之外，如果使用 multi-channel 將可在不修改硬體的架構下，馬上提昇頻寬數倍。另外，支援 QoS 也比 single channel 較有彈性。雖然使用多重頻道有那麼多的好處，但是設計上除了要有良好的媒體存取機制外，還必須配合一套有彈性的頻道配置 (channel assignment) 機制，才能使多重頻道協定的效能發揮到極致。然而如何將 channel 分配給行動主機，讓行動主機彼此不相干擾，卻是一個非常困難的問題（相關文獻已證明就算行動主機不會移動，它也是一個 NP-Completed 的問題）。另外，即使 channel 分配完成，又可能有新的行動主機移入或離開，將使問題更形複雜。

在多重頻道環境中，我們設計一個具有動態頻道分配的協定，稱之為 DCA (dynamic channel assignment)。DCA 具有下列數個特性: (1)以 On-Demand 的方式分配頻道給需要通訊行動主機，(2) 系統提供給網路所需的頻道個數與網路的拓樸是無關的，(3) 此協定只需要交換少數的控制訊息(Control Messages)就可以同時完成媒體存取與頻道配置兩個功能，(4)行動主機不需要任何型式的時間同步(time synchronization)。經由分析與實驗得知 DCA 確實比其他協定較適合於無線行動隨建即連網路。

為了減緩 packets 碰撞機率過高因而造成效能過低的另一種方法就是 power control。因此為了讓頻道重複使用率更加提高，我們整合 DCA 與 power control 兩種機制提出更有效率的新協定稱之為 DCA-PC。經由實驗得知，DCA-PC 效能大約比 DCA 提昇四成左右。

四、利用具有位置知覺的功能設計多重頻道 MAC 協定

無線行動隨建即連網路既然是在一個固定區域上運作，因此行動主機所在位置便成為很重要的資訊。其實地理位置的資訊與 channel assignment 是息息相關 (因為同一個 channel 必須在空間上加以區隔，才可以重複使用)，這點可由一般的 cellular phone system (例如 GSM, AMPS, …)。這類型系統基地台間如果要重複使用相同的 channel，必須相隔一定距離才可以。在最後一個環境有座標式多重頻道中，我們設計一個新的協定稱為 GRID。這個協定，會將地理區域分割成若干 grid，每個 grid 唯一個單位來分配 channel。它最大的特色就是利用位置資訊完成 channel 的配置，行動主機完全不需負擔任何控制訊息的收送。在媒體存取方面，我們使用類似 DCA 中交換 RTS/CTS 的方式，保留媒體的使用權，這種方式的優點是行動主機間不需任何形式的時間同步，而且系統提供給網路頻道個數與網路的拓樸也是無關的。經由實驗與分析得知

GRID 確實比 IEEE 802.11 好很多。

此外 GRID 所使用的頻道配置是靜態的，這種協定在現實環境中，效率將會受到影響。因為在現實狀況中，經常會有某些地區人口密集的狀況出現，如果只是使用簡單的靜態頻道配置，效率將會不好。因此我們提出借頻道的協定，稱之為 GRID-B，來達成動態是的頻道配置。它最主要的觀念是把鄰近不用的 channel 借過來使用。然而借 channel 的優先順序又可根據 sender 與 receiver 所在 grid 的位置及跟欲借 channel 的 grid 所在位置的關係(例如距離、順序)來排序。經由實驗證明確實可以提昇大約 15%左右的效能。

第二章、單一頻道上使用控制發射功率的機制

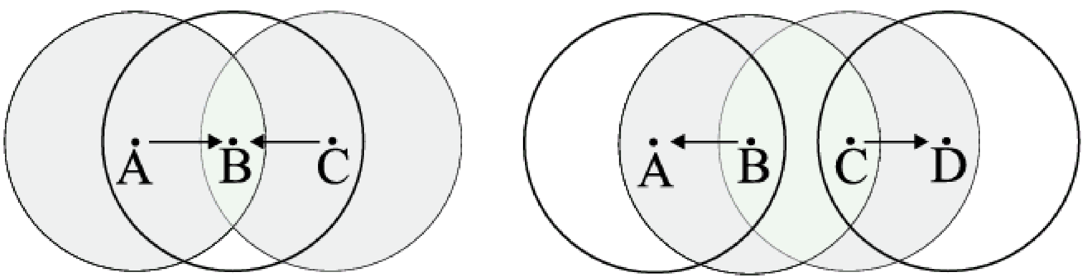
一、動機

在 Ad Hoc 單一頻道網路架構下，為了要增加頻道（channel）的使用率，並避免 hidden-terminal 和 exposed-terminal 的問題，通常會利用 RTS/CTS-based (例如 MACA, MACAW, FAMA, CSMA/CA) 和 busy-tone-based (DBTMA) 等機制來減緩這些問題所造成的影響。除了這兩個機制之外，若是再引入 Power Control 觀念，更可以有效的增加 channel reuse 進而改善頻道的使用率。我們知道在一定的區域內使用較小的發射功率可以讓同一時間更多行動主機使用相同的頻道。Power Control 就是控制傳送端傳送封包時的功率大小，以降低頻道之間彼此的破壞、干擾，如此可以增加頻道重覆使用的機率，降低對其他鄰居的干擾，亦可降低能量的消耗，達到省電的目地。

我們所設計的這個新的 MAC 協定，是藉由控制發射功率 (power control) 的大小，再結合傳統交換 RTS/CTS 及 busy-tone 的機制，目的就是更進一步的提升頻道的使用效率。另外我們也考慮到實做上的限制，分析使用有限段式 (discrete) 取代連續無段式 (continuous) 的調整發射功率，並且修改協定使其達到最佳的成本效益比。最後我們經由分析及實驗證明這個協定確實優於傳統協定大約兩倍的效能。

二、相關研究

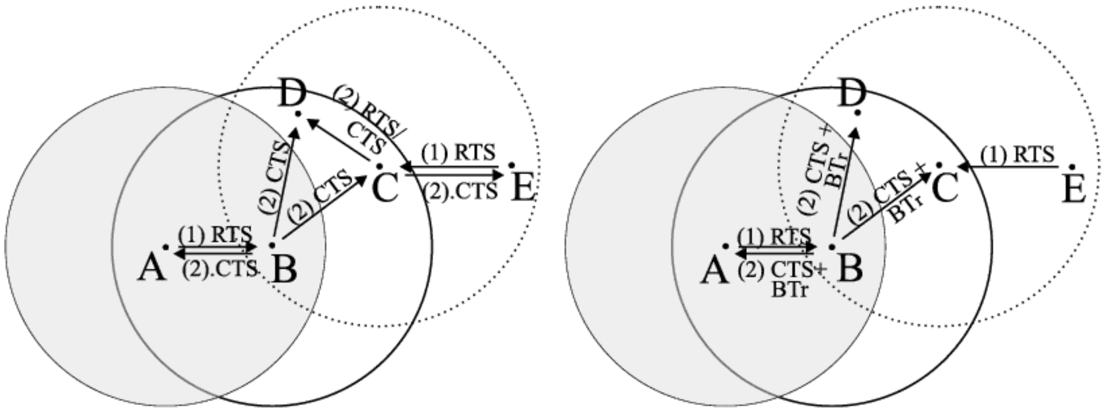
載波偵測多重存取(Carrier Sense Multiple Access, CSMA) 是一種廣泛使用於有限與無線區域網路的一種 MAC 協定。它主要的工作原理是當行動主機要傳送封包時，先做載波偵測，如果頻道上是 idle 的狀態就可傳送封包，否則就必須進入等待狀態。此種做法有兩種缺點: (1) hidden terminal problem, (2) exposed terminal problem。所謂 hidden terminal problem 與 exposed terminal problem 分別如下圖(a) (b)所示。



(a) (b)

Figure 2.1

為了減緩上述問題，有人便提出 RTS/CTS 的方法，借由交換長度非常小的 RTS/CTS control packets 警告鄰近的行動主機，以達到減少碰撞的機率。很不幸的，當網路負荷繼續增加時，這些小的 control packets 仍然可能產生碰撞，如 Figure 2.2(a)就是一個明顯的例子。



(a) (b)

Figure 2.2

因此有人提 DBTMA (dual busy tone multiple access) 的協定來解決這個問題。它利用 dual busy tones 的方式來防止因 control packets 碰撞而錯判媒體是 idle 的行動主機，所以可以保證 data packets 成功的傳送，如 Figure 2.2 (b)所示。DBTMA 的 channel model 如圖 Figure 2.3 所示。

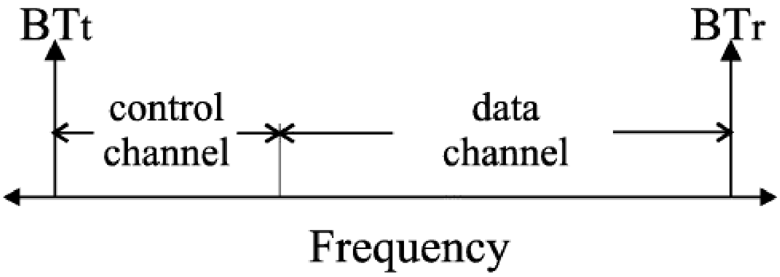


Figure 2.3: Frequency chart of the DBTMA protocol.

三、控制發射功率的 MAC 協定

我們所設計的這個協定，是藉由控制發射功率 (power control) 的大小，再結合傳統交換 RTS/CTS 及 busy-tone 的機制，目的就是更進一步的提升頻道的使用效率。這

個想法可從 Figure 2.4 做說明。

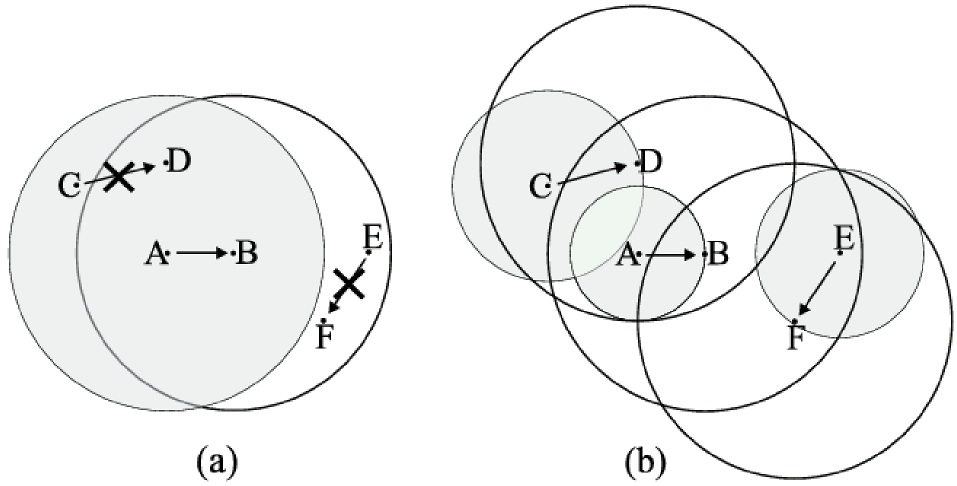


Figure 2.4

我們的協定如下:

1. sender 以一定的 power level 傳送 RTS， power level 的大小是以 sender 所收到最強的 BTr tones。
2. receiver 用最大 power level 的來傳送 CTS and BTr。
3. sender 送 data packet 和 BTt 是以 sender 與 revceiver 之間的距離來決定 power level 。

四、有限段式 (discrete) 控制發射功率

連續無段式 (continuous) 的調整發射功率在實做上是有困難，因此本節將考慮到實做上的限制，分析使用有限段式 (discrete) 取代連續無段式 (continuous) 的調整發射功率，並且修改協定使其達到最佳的成本效益比。

五、效能模擬

最後我們為了要評估新協定所能增加的效能，於是設計一個 simulator。它是由 CSIM 所開發完成，在 linux 環境下執行。實驗所用的參數如下:

- 區域大小: 8 km × 8 km
- 行動主機傳輸範圍: 0.5 或 1.0 km
- 600 個行動主機
- 傳輸速率: 1 Mbps

● control packet 長度為 100 bits

● 傳輸錯誤率 10^{-5} / bits

實驗數據結果如下:

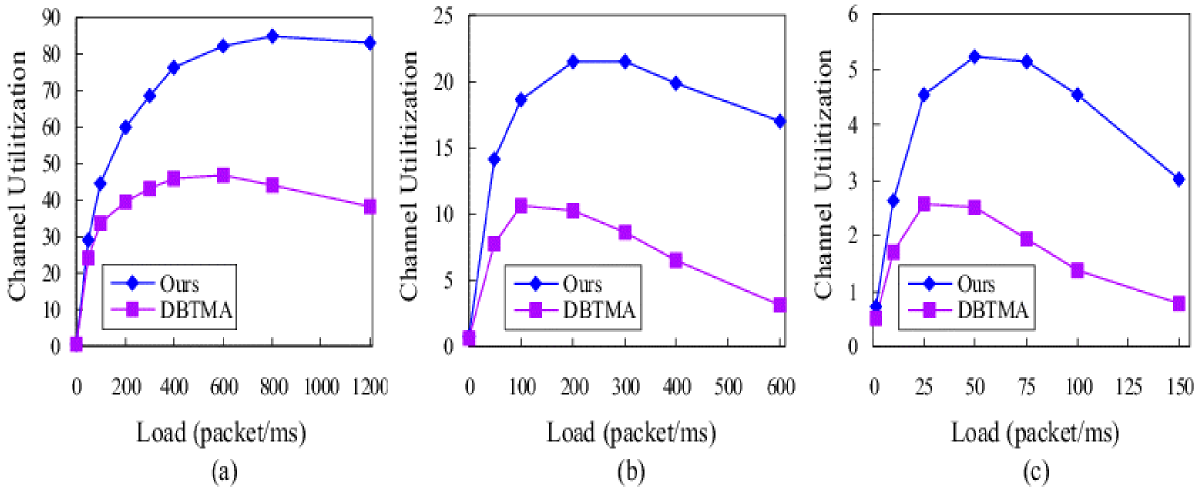


Figure 2.5

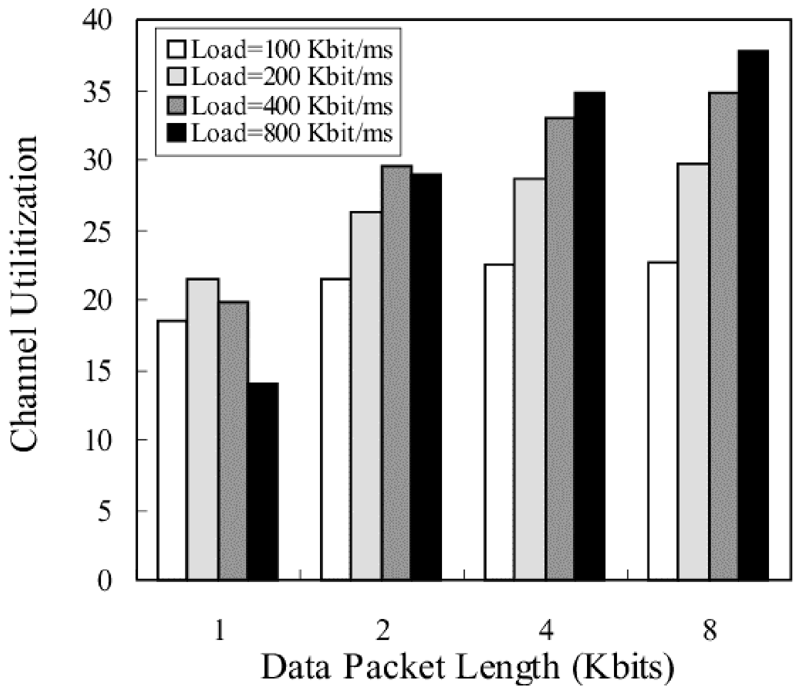


Figure 2.6

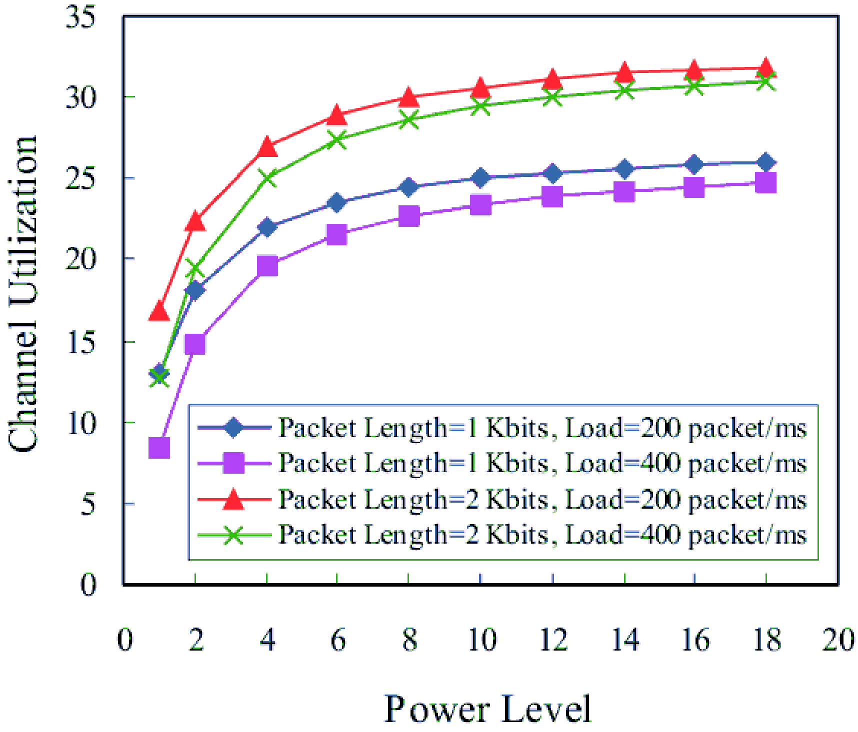


Figure 2.7

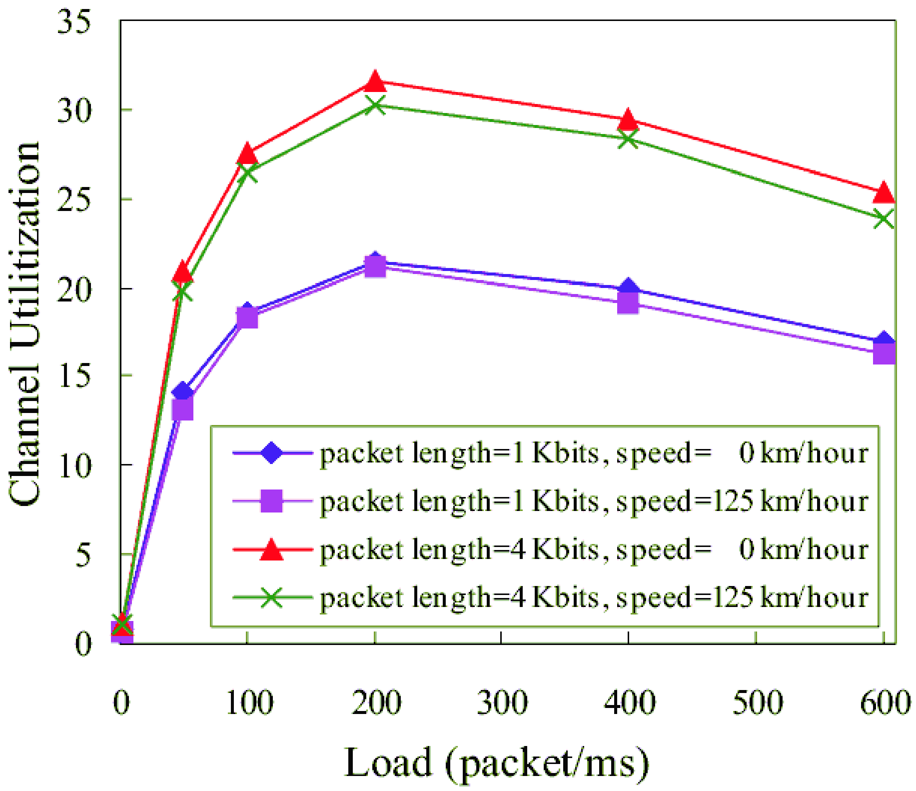


Figure 2.8

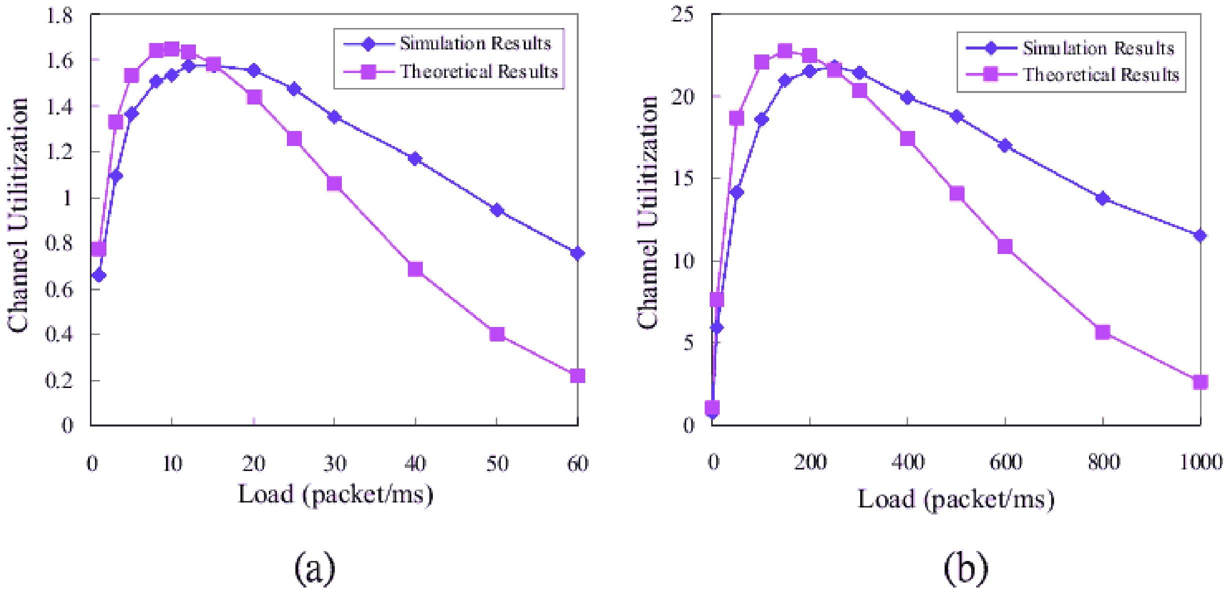

1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Channel Utilization
0
10
20
30
40
50
60
Load (packet/ms)
Simulation Results
Theoretical Results
(a)
25
20
15
10
5
0
Channel Utilization
0
200
400
600
800
1000
Load (packet/ms)
Simulation Results
Theoretical Results
(b)

Figure 2.9

第三章、在多重頻道中設計具有動態頻道分配的 MAC 協定

一、簡介

本章研究在一個無線行動隨建即連網路 (wireless mobile ad hoc network) MAC 層中有關的多重頻道(multi-channel)問題。現有 MANET 網路架構中，MAC 層通常假設單一共同的 channel (single common channel)。此種 channel model 最當的弱點就是當網路傳輸負載達到飽和時，若再增加傳輸負荷將會因為碰撞機率過高因而造成效能過低的結果。Multi-channel 的提出就是要減緩這種結果的方法之一。現今由於硬體技術進步（如 CDMA, WCDMA 技術）使得 multi-channel 已具可行性。由於 multi-channel 可架構於 spread spectrum 的技術上，先天上就對 multiple path、signal fading 等干擾源較具免疫力；若能夠將 channel 分配妥善，更可進一步的降底 co-channel interference，提升 channel utilization，所以 multi-channel 的優點是毋庸置疑。除此之外，如果使用 multi-channel 將可在不修改硬體的架構下，馬上提昇頻寬數倍。另外，支援 QoS 也比 single channel 較有彈性。

雖然使用多重頻道有那麼多的好處，但是設計上除了要有良好的媒體存取機制外，還必須配合一套有彈性的頻道配置 (channel assignment) 機制，才能使多重頻道協定的效能發揮到極致。然而如何將 channel 分配給行動主機，讓行動主機彼此不相干擾，卻是一個非常困難的問題（相關文獻已證明就算行動主機不會移動，它也是一個 NP-Completed 的問題）。另外，即使 channel 分配完成，又可能有新的行動主機移入或離開，將使問題更形複雜。

在多重頻道中，我們設計一個具有動態頻道分配的協定，稱之為 DCA (dynamic channel assignment)。DCA 具有下列數個特性: (1) 以 On-Demand 的方式分配頻道給需要通訊行動主機，(2) 系統提供給網路所需的頻道個數與網路的拓樸是無關的，(3) 此協定只需要交換少數的控制訊息就可以同時完成媒體存取與頻道配置兩個功能，(4) 行動主機不需要任何型式的時間同步。經由分析與實驗得知 DCA 確實比其他協定較適合於無線行動隨建即連網路。

二、相關研究

在傳統的 multi-hop packet radio networks 上已有相當多文獻被提出，但由於此種網路的主機不太會移動，因此這類文獻所提出的協定不具有 mobility，所以較不適用於

無線行動隨建即連網路。最近雖有許多協定被提，不是不具備 dynamic 的分配 channel 的策略，就是沒有 on-demand 的特性，要不就是與網路拓普結構有關。西元 1999 年有人提出 Multi-channel CSMA，他雖然不具有上述的缺點，但因為使用純 CSMA 的技術，因此仍然無法防止 hidden terminal problem 與 exposed terminal problem。除此之外，這個協定所需的硬體成本相當高，因為他的 transceiver 與 channel 的個數成正比。最近有人提出 HRMA (Hop Reservation Multiple Access)，他雖然沒有上面的缺點，但是卻需在行動主機間作時間同步，這在無線行動隨建即連網路上是非常困難的一見事。下表將把現存的協定與我們所提的 DCA 做一比較。

protocol	assignment	no_transceivers	no_channels	clock sync.
[4, 6, 8, 13, 15, 23]	static	1	deg.-dep.	no
Polling Scheme	N/A	2	N/A	no
CAM	dynamic	2	deg.-dep.	no
Multichannel CSMA	dynamic+on-demand	n	deg.-indep.	no
HRMA	dynamic+on-demand	1	deg.-indep.	yes
Ours	dynamic+on-demand	2	deg.-indep.	no

Table 2.1

三、**Multi-channel** 設計上的考量

我們在前面提過，multi-channel 協定需要完成頻道配置與媒體存取兩件事，才算是完整的 MAC 協定。本節所要探討的就是當頻道配置完成後，如果沒有良好的媒體存取機制(如果只是單純 IEEE802.11 的媒體存取機制)，multi-channel 協定所會面臨的問題。這些重要的觀察也是我們論文主要的動機之一。以下將以四張圖是察到的五種現象並做簡單說明。

- ***Missing RTS:***

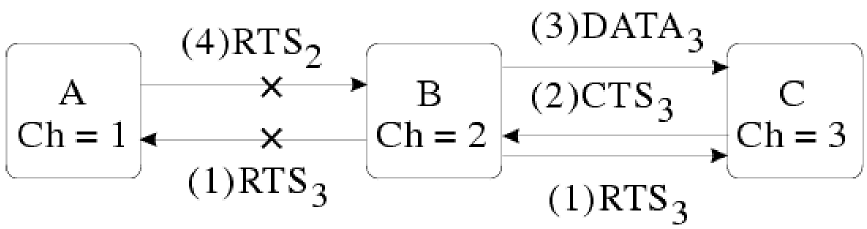


Figure 3.1: The problem of missing RTS in a multi-channel MAC. (The leading number on each message shows the message sequence; the subscript shows the channel on which the corresponding message is sent.)

- ***False Connectivity Detection:*** 由於 missing RTS 因此 sender 在幾次的嘗試後可能會做出錯誤判斷，因而造成系統不必要的資源浪費。

- ***Missing CTS***

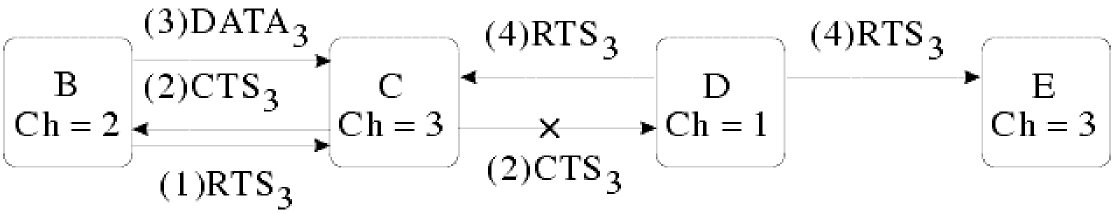


Figure 3.2: The problem of missing CTS in a multi-channel MAC.

- ***Exposed-Terminal Problem***

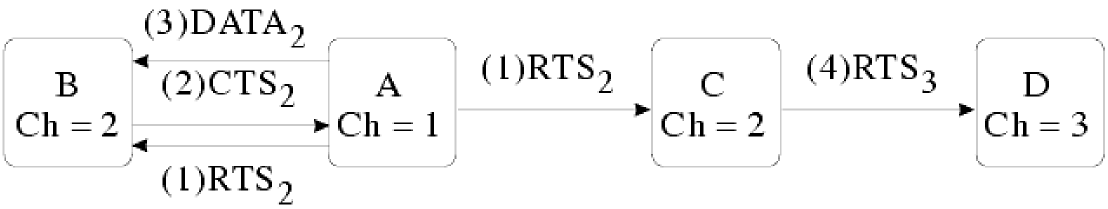


Figure 3.3: The exposed-terminal problem in a multi-channel MAC.

- ***Channel Deadlock problem***

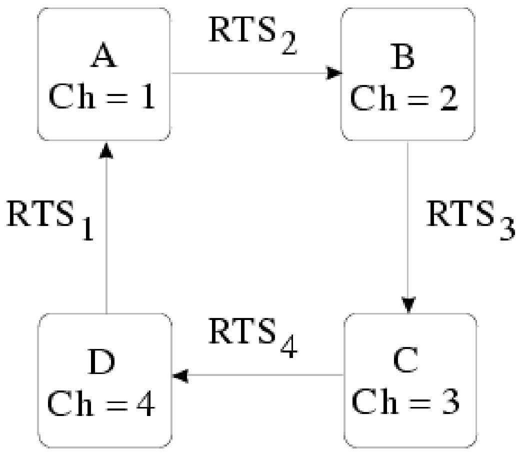


Figure 3.4: The channel deadlock problem in a multi-channel MAC.

四、DCA MAC 協定

本節將描述 DCA 協定。在前面提過，multi-channel 協定需要完成頻道配置與媒體存取兩件事，才算是完整的 MAC 協定。我們知道 DCA 以 On-Demand 的方式分配頻

道給需要通訊行動主機，因此系統提供給網路所需的頻道個數與網路的拓樸是無關的，而且只需要交換少數的控制訊息就可以同時完成媒體存取與頻道配置兩個功能，更重要的是行動主機不需要任何型式的時間同步。Figure 3.5 是我們的 channel model。整個頻寬被分成數個 channel。其中一個 channel 被指定成 control channel，其他再分成若干個 data channel。Control channel 是一個 common channel，所有的行動主機都必須用它來傳輸控制訊息或是竊聽別人的控制訊息。控制訊息主要是用來預約 data channel 及執行媒體存取的控制。

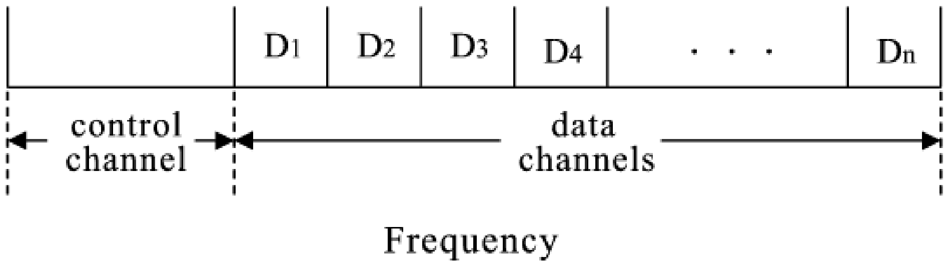


Figure 3.5: The channel model of our DCA protocol.

在我們的協定中每個行動主機都要維護它們自己的兩個資料結構 *Channel Usage Table (CUL)* 和 *Free Channel List (FCL)*。

- CUL
  - ✓ *CUL[i].host*: 紀錄鄰居 *X* 的識別碼，
  - ✓ *CUL[i].ch*: *X* 正在使用的 channel，
  - ✓ *CUL[i].rel_time*: 何時釋放 *CUL[i].ch*。
- FCL: 目前可用的 channel。

以下我們用一個例子來說明本協定的主要工作原理。當行動主機 A 想送 data packet 給行動主機 B 時，A 用 control channel 送出 RTS 給 B，並附帶 A 目前可用的 channel 於 FCL，當 B 收到 A 的 RTS 後，就從 A 的 FCL 之中挑出一個可用之 channel，然後以 CTS 回覆 A，這時所有 B 的鄰居也都會聽到並且記載於它們自己的 CUL 之中。當 A 收到 B 的 CTS 後，除依據 CTS 中所指定的 data channel 做傳輸，並且同時送出 RES 給它的鄰居保留這個 channel。

五、效能模擬

本實驗所使用的參數如 Table 3.3 所示。

Table 3.3: 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

我們一共做了六組實驗，分別針對 channel 個數，data packet 與 control packet 長度的比值，data channel 頻寬與 control channel 頻寬的比值，transmission range 做比較與觀察。由下列圖表得知，DCA 的確優於其他協定。

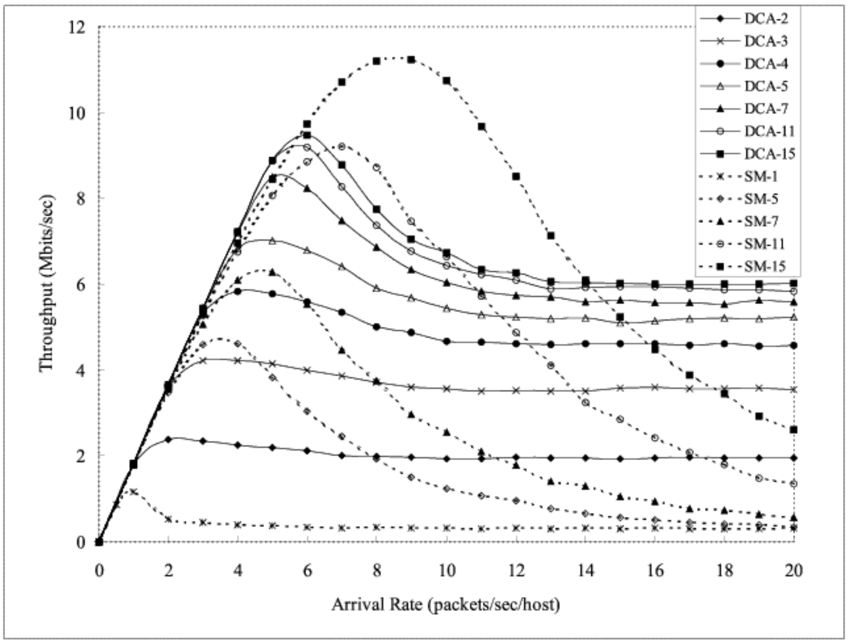


Figure 3.8: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

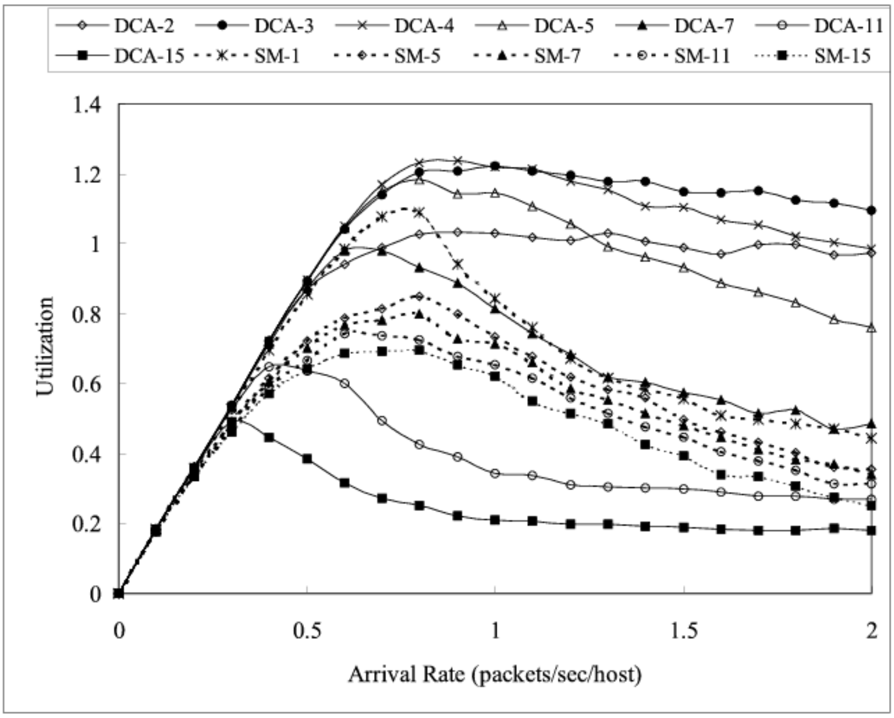


Figure 3.9: Arrival rate vs. utilization under the fixed-total-bandwidth model with different numbers of channels.

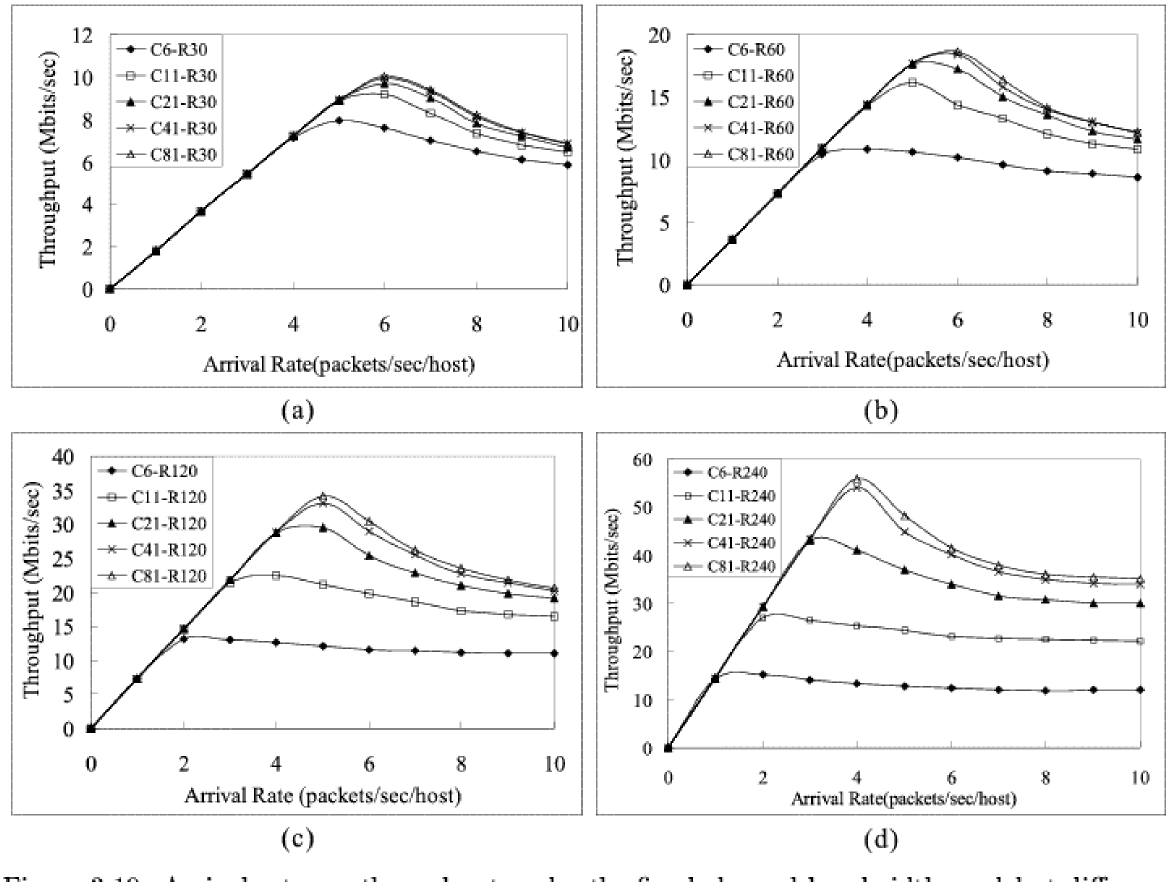


Figure 3.10: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different L_d/L_c ratios (Ci-Rj means using i channels, including control and data ones, with ratio $L_d/L_c = j$).

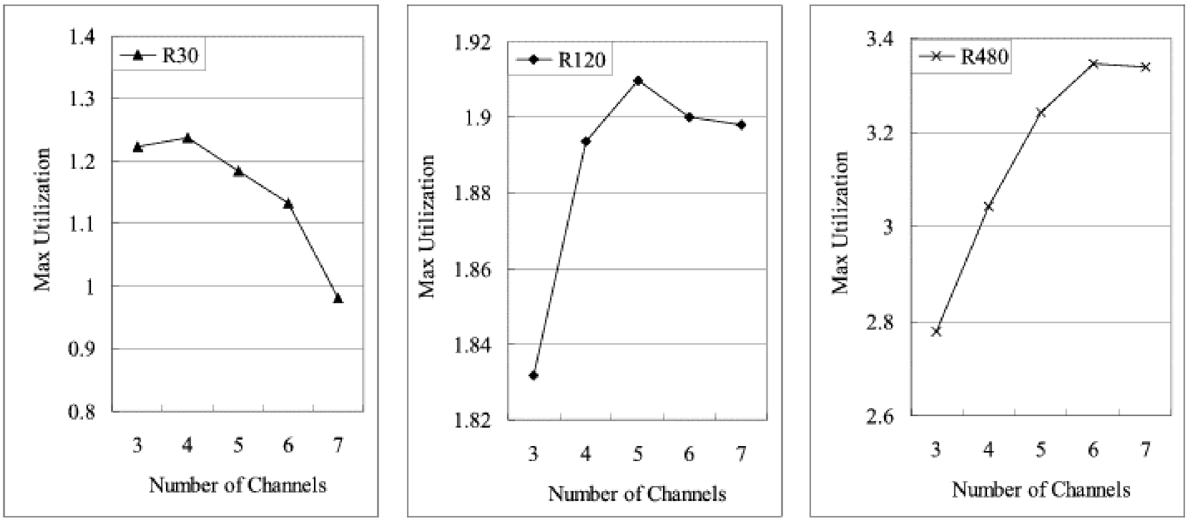


Figure 3.11: Number of channels vs. maximum utilization under the fixed-total-bandwidth model at different L_d/L_c ratios.

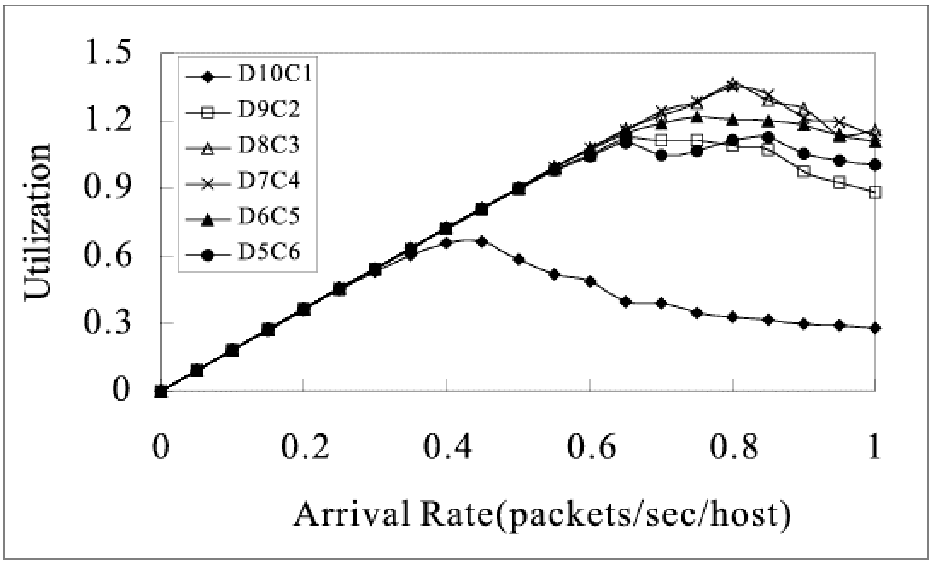


Figure 3.12: Arrival rate vs. throughput under the fixed-channel-bandwidth model given 11 channels (DiCj means using i data channels and j control channels).

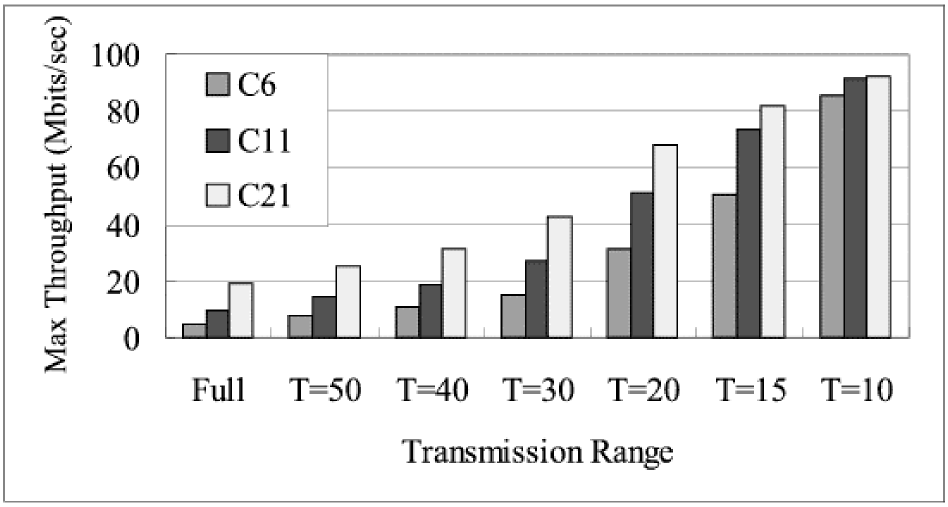


Figure 3.13: Transmission range vs. maximum throughput at different numbers of channels.

第四章、在 DCA 上使用控制發射功率的機制

在無座標式多重頻道環境中，我們設計一個具有動態頻道分配的協定，稱之為 DCA (dynamic channel assignment)。DCA 以 On-Demand 的方式分配頻道給需要通訊行動主機，因此系統提供給網路所需的頻道個數與網路的拓樸是無關的，而且只需要交換少數的控制訊息就可以同時完成媒體存取與頻道配置兩個功能，更重要的是行動主機不需要任何型式的時間同步。Power Control 可以讓同一時間更多行動主機使用相同的頻道，增加 channel reuse。此外還可以降低對其他鄰居的干擾，提高傳輸訊雜比 (Signal to Noise Ratio, SNR) 與可靠度 (Bit Error Rate, BER)，而且亦可達到省電的目地。因此，我們結合 DCA 與 power control 兩種機制提出更有效能的新協定稱之為 DCA-PC。

一、簡介

在上一章我們介紹無座標式 multi-channel 設計上所需考慮的問題，然後提出一個具有動態頻道分配的協定 DCA，並且證明他的效能的確優於 IEEE802.11 協定。在第二章我們也曾經提到減緩網路因為碰撞機率過高因而造成效能過低的另一種方法就是 power control。Power Control 就是控制傳送端傳送封包時的功率大小，我們知道在一定的區域內使用較小的發射功率可以讓同一時間更多行動主機使用相同的頻道，因此頻道重複使用率(channel reuse)就更加提高。另外他還可以降低頻道之間彼此的干擾、破壞，降低對其他鄰居的干擾，提高傳輸訊雜比 (Signal to Noise Ratio, SNR) 與可靠度 (Bit Error Rate, BER)，而且亦可降低能量的消耗，達到省電的目地。因此，我們結合 DCA 與 power control 兩種機制提出更有效能的新協定稱之為 DCA-PC。

DCA-PC 具有下列數個特性: (1)以 On-Demand 的方式分配頻道給需要通訊行動主機，(2) 系統提供給網路所需的頻道個數與網路的拓樸是無關的，(3) 此協定只需要交換少數的控制訊息就可以同時完成媒體存取與頻道配置兩個功能，(4)行動主機不需要任何型式的時間同步機制，(5) Power Control 可以增加頻道重複使用率，另外他還可以降低對其他鄰居的干擾，提高傳輸訊雜比與可靠度，降低能量的消耗，達到省電的目地。經由分析與實驗得知 DCA-PC 效能大約比 DCA 提昇四成左右，確實比其他協定較適合於無線行動隨建即連網路。

二、Our DCA-PC 協定

我們結合 DCA 與 power control 兩種機制提出更有效能的新協定稱之為 DCA-PC。我們知道 DCA 以 On-Demand 的方式分配頻道給需要通訊行動主機，因此系統提供給網路所需的頻道個數與網路的拓樸是無關的，而且只需要交換少數的控制訊息就可以同時完成媒體存取與頻道配置兩個功能，更重要的是行動主機不需要任何型式的時間同步。Power control 可由下圖了解到如何增加 channel reuse。

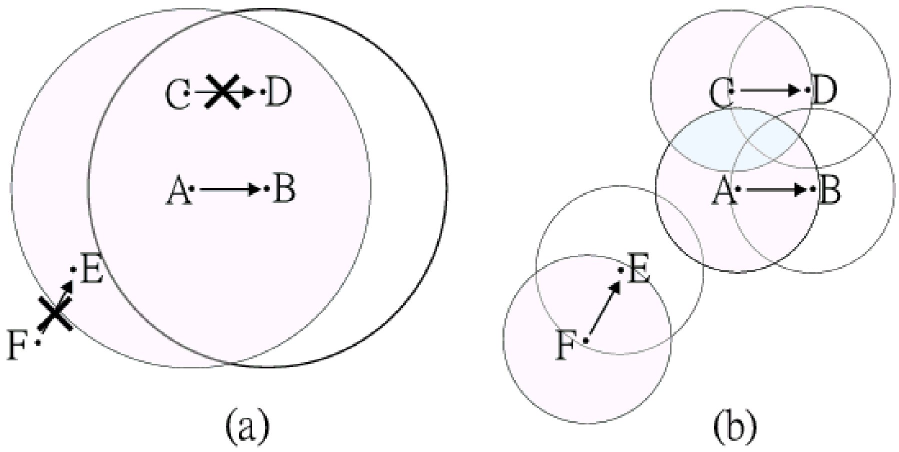


Figure 4.1: Transmission scenarios: (a) when there is no power control, and (b) when there is power control.

將詳細描述 DCA-PC 協定的運作原理。如同 DCA 一樣，在我們的協定中每個行動主機都要維護它們自己的兩個資料結構 *Channel Usage Table (CUL)* 和 *Free Channel List (FCL)*。其中在 *CUL* 中新增一欄位 *CUL[i].rel_time* 並增加一資料結構 *POWER[]*。

- *CUL*
  - ✓ *CUL[i].host*: 紀錄鄰居 *X* 的識別碼，
  - ✓ *CUL[i].ch*: *X* 正在使用的 channel，
  - ✓ *CUL[i].rel_time*: 何時釋放 *CUL[i].ch*，
  - ✓ *CUL[i].int*: 是否會影響本行動主機。
- *POWER[]*: 紀錄本行動主機到鄰居 *X* 所需最小 power 可使鄰居 *X* 正確收到 data packets。
- *FCL*: 目前可用的 channel。

DCA-PC 協定的運作原理如下:

- Data packets 使用是當的 power 來傳輸，也就是紀錄在自己 *POWER[]* 中的

power level，

- Control packets 使用最大的 power 通知所有鄰居。

以下我們用一個圖 figure 4.2 來說明本協定的主要工作原理。當行動主機 A 想送 data packet 給行動主機 B 時，A 用 control channel 送出 RTS 給 B，並附帶 A 目前可用的 channel 於 FCL，當 B 收到 A 的 RTS 後，就從 A 的 FCL 之中挑出一個可用之 channel，然後以最大 power level CTS 回覆 A，這時所有 B 的鄰居 D 也都會聽到並且記載於它們自己的 CUL 之中。當 C 以後想送 data packets 給 D 時，因 D 的 *CUL[B].int* 紀錄 B 會干擾，所以不能使用。若 C 想送 data packets 給 F 時，因 *POWER[F] > POWER[B]*，會影響本來 A 與 B 之間的傳輸，所以不能使用。所以只有當 C 想送 data packets 給 E 時，因 *POWER[E] < POWER[B]*，不會影響本來 A 與 B 之間的傳輸，所以可以安心使用。

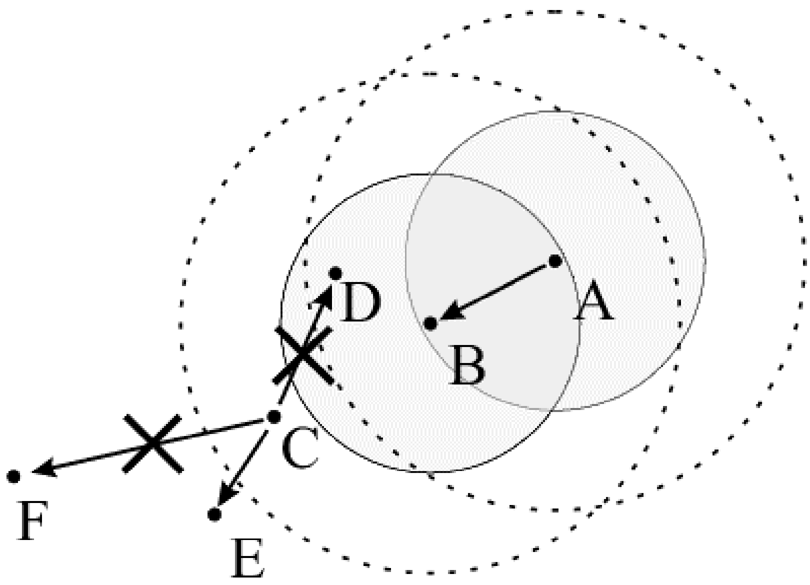


Figure 4.2 An example of our DCA-PC

三、效能模擬

最後我們為了要評估新協定所能增加的效能，設計一個 simulator，在 linux 環境下執行實驗。本實驗所使用的參數如 Table 4.1 所示。我們一共做了五組實驗，分別針對 channel 個數，data packet 與 control packet 長度的比值，行動主機分布的密度，硬體成本效益比即 power level 的個數，行動主機的移動速度即 host mobility 等做觀察。

Table 4.2: Simulation parameters.

number of mobile hosts (except for part C)	200
no. of power levels (except for part D)	5
max. speed of a mobile host (except for part E)	36 km/hr.
physical area	100×100
transmission range	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

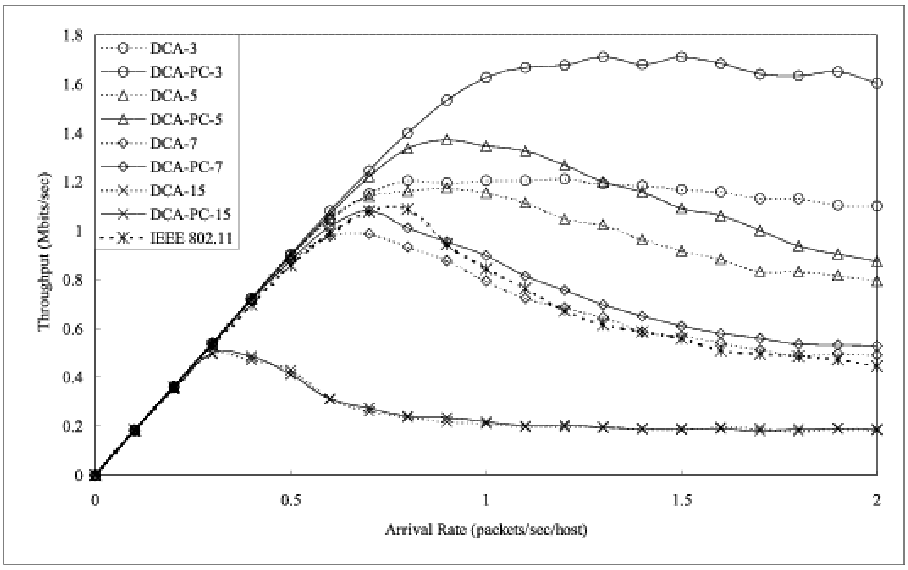


Figure 4.4: Arrival rate vs. throughput under the fixed-total-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

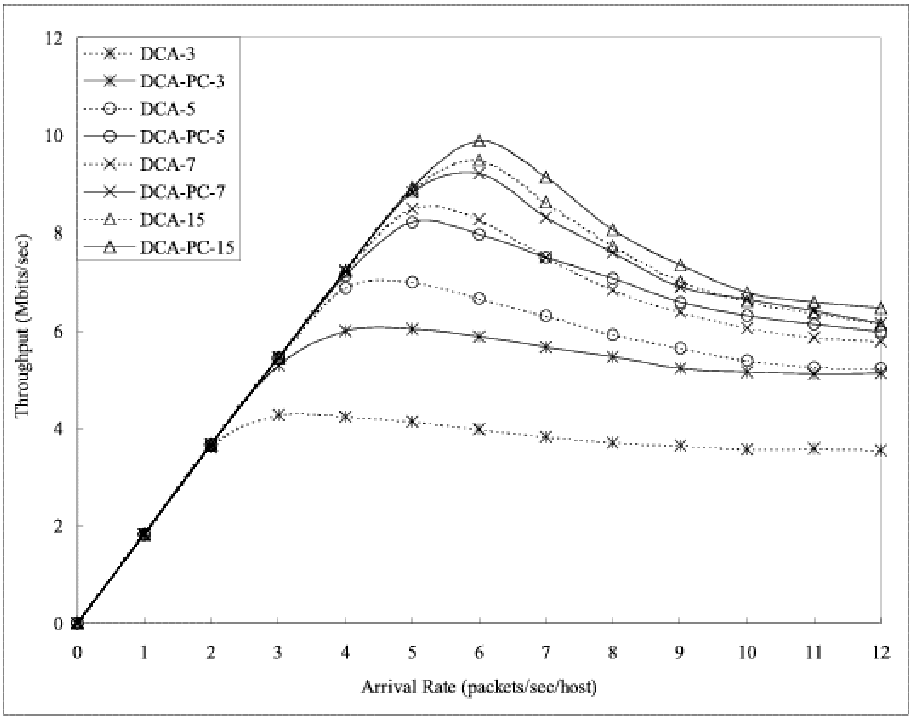


Figure 4.5: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels.

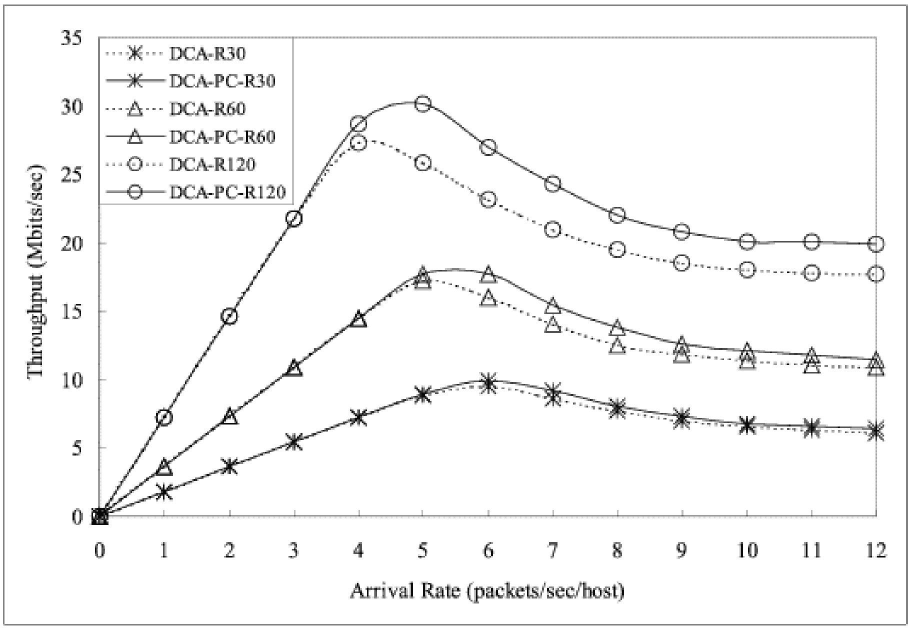


Figure 4.6: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different L_d/L_c ratios (Rj means the ratio $L_d/L_c = j$).

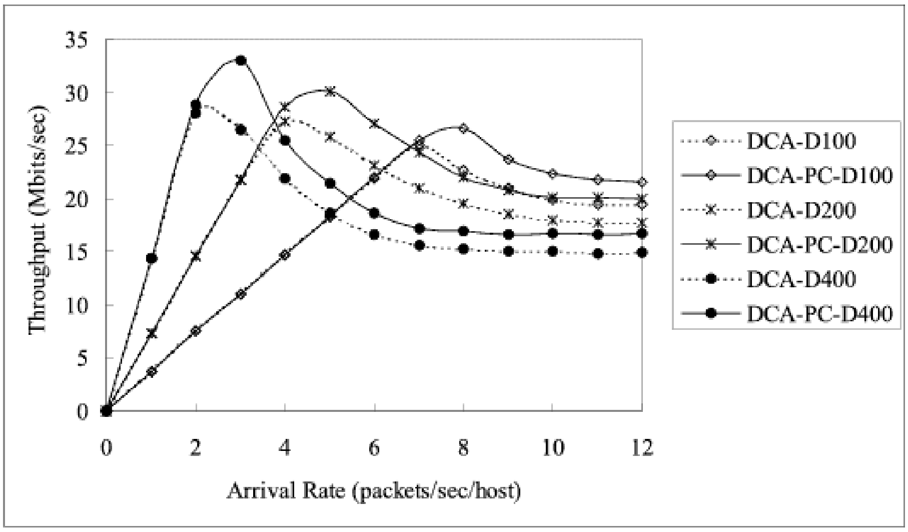


Figure 4.7: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different numbers of mobile hosts. (Di means i mobile hosts.)

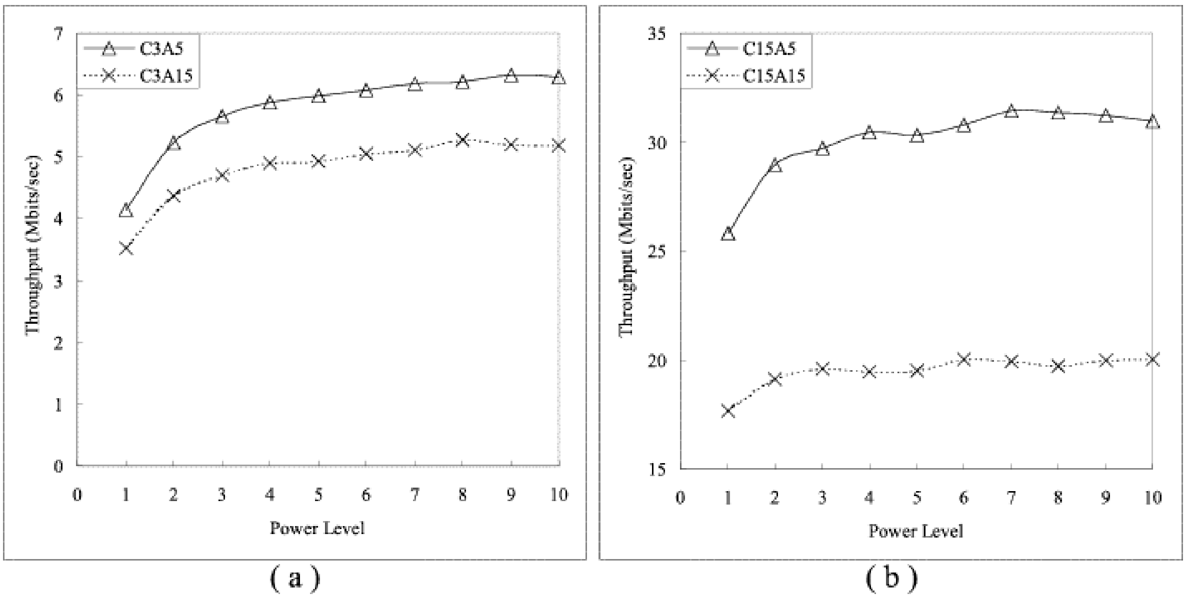


Figure 4.8: Number of power levels vs. throughput: (a) 3 channels with $L_d/L_c = 30$ and (b) 15 channels with $L_d/L_c = 120$. The number after "A" is the arrival rate (packets/sec/host). The peak throughput appears at around A5, while the saturated, but stable, throughput appears at around A15.

第五章、具有位置知覺的多重頻道 MAC 協定

無線行動隨建即連網路既然是在一個固定區域上運作，因此行動主機所在位置便成為很重要的資訊。在最後一個環境有座標式多重頻道中，我們設計一個新的協定稱為 GRID，它最大的特色就是利用位置資訊完成頻道的配置，行動主機完全不需負擔任何控制訊息的收送。在媒體存取方面，我們使用類似 IEEE802.11 的 RTS/CTS 的方式，保留媒體的使用權，這種方式的優點是行動主機間不需任何形式的時間同步，而且系統提供給網路頻道個數與網路的拓樸也是無關的。經由實驗證明的確比其他不具位置知覺的協定提昇不少效能。

一、動機

無線行動隨建即連網路既然是在一個固定區域上運作，因此行動主機所在位置便成為很重要的資訊。其實地理位置的資訊與 channel assignment 是息息相關 (因為同一個 channel 必須在空間上加以區隔，才可以重複使用)，這點可由一般的 cellular phone system (例如 GSM, AMPS, …)。這類型系統基地台間如果要重複使用相同的 channel，必須相隔一定距離才可以。另一方面，隨著提供位置資訊硬體的進步，如室外的 GPS (global position system), differential GPS (DGPS)，室內的紅外線系統，要獲得目前所在位置的資訊已不在那麼昂貴遙不可及。

在最後一個環境有座標式多重頻道中，我們設計一個具有位置知覺的多重頻道 MAC 新協定稱為 GRID。這個協定，會將地理區域分割成若干 grid，每個 grid 唯一個單位來分配 channel。它最大的特色就是利用位置資訊完成 channel 的配置，行動主機完全不需負擔任何控制訊息的收送。另外，我們也探討 grid 邊長與傳輸半徑的關係。在媒體存取方面，我們使用類似 DCA 中交換 RTS/CTS 的方式，保留媒體的使用權，這種方式的優點有: (1) 以 On-Demand 的方式分配頻道給需要通訊行動主機，(2) 系統提供給網路頻道個數與網路的拓樸也是無關，(3) 行動主機間不需任何形式的時間同步。經由實驗與分析得知 GRID 確實比 IEEE 802.11 好很多。

二、頻道配置

我們在前面提過，multi-channel 協定需要完成頻道配置與媒體存取兩件事，才算是完整的 MAC 協定。這節我們將探討頻道配置的方法與步驟。頻道配置的方法可分

為 non-location-aware 與 location-aware 兩類。

在 non-location-aware channel assignment 包括有傳統的 multi-hop packet radio networks 上已有相當多文獻被提出，由於此種網路的主機不太會移動，因此這類文獻所提出的協定其 channel assignment 的策略多半是根據網路 topology，所以較不適用於天生擁有 mobility 的無線行動隨建即連網路。最近雖有許多協定被提，不是不具備 dynamic 的分配 channel 的策略，就是沒有 on-demand 的特性，要不就是與網路拓普結構有關。西元 1999 年有人提出 Multi-channel CSMA，他雖然不具有上述的缺點，但因為使用純 CSMA 的技術，因此仍然無法防止 hidden terminal problem 與 exposed terminal problem。除此之外，這個協定所需的硬體成本相當高，因為他的 transceiver 與 channel 的個數成正比。最近有人提出 HRMA (Hop Reservation Multiple Access)，他雖然沒有上面的缺點，但是卻需在行動主機間作時間同步，這在無線行動隨建即連網路上是非常困難的一見事。下表將把現存的協定與我們所提的 GRID 做一比較。

我們的 GRID 的 channel assignment 具有 location-aware 的特色。這個概念類似於 GSM cellular phone system，他們的基地台間如果要重複使用相同的 channel，必須相隔一定距離才可以。GRID 協定會預先將地理區域分割成若干 grid，以每個 grid 為一個單位來分配 channel，grid 間如果要重複使用相同的 channel，必須相隔一定距離才可以(如 Figure 5.1 所示)。它最大的特色就是利用位置資訊完成 channel 的配置，行動主機完全不需負擔任何控制訊息的收送。

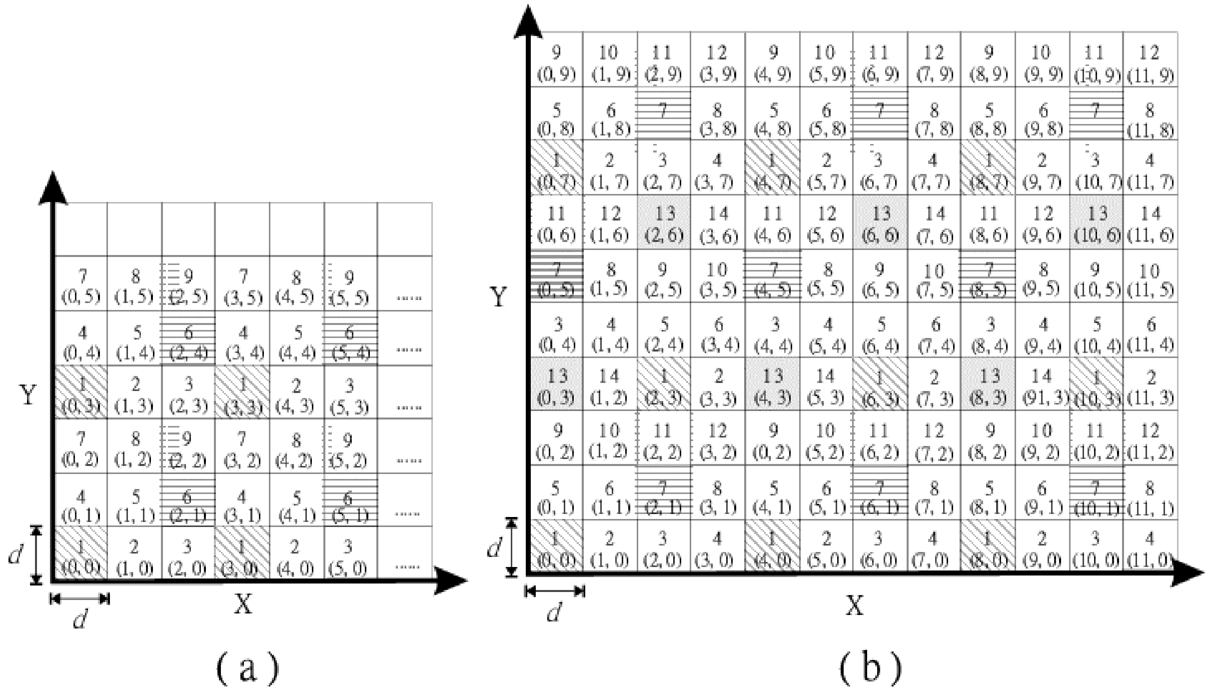


Figure 5.1: Assigning channels to grids in a band-by-band manner: (a) $n = 9$ and (b) $n = 14$. In each grid, the number on the top is the channel number, while those on the bottom are the grid coordinate. Here, we number channels from 1 to n.

另外，我們也探討 grid 邊長 *d* 與傳輸半徑 *r* 的關係。傳輸半徑與硬體發射功率及環境有關，無法在軟體方面控制。因此我們只能改變 grid 邊長，因為它是系統邏輯上的設定。下圖則是 *r/d* 的各種情況。

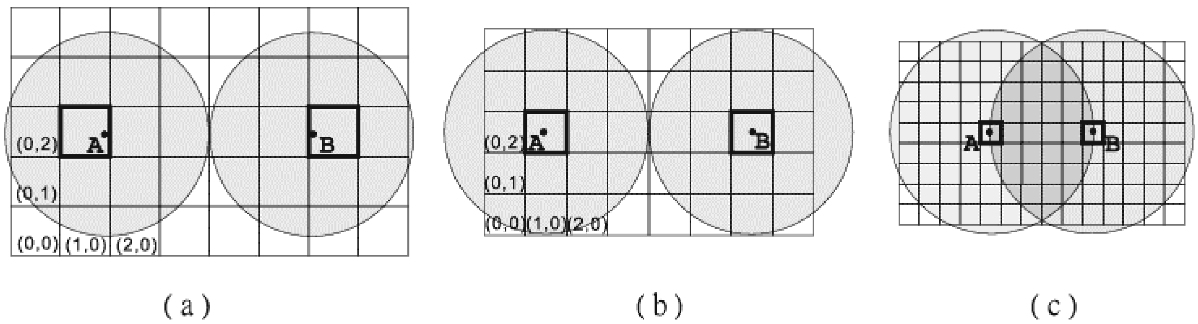
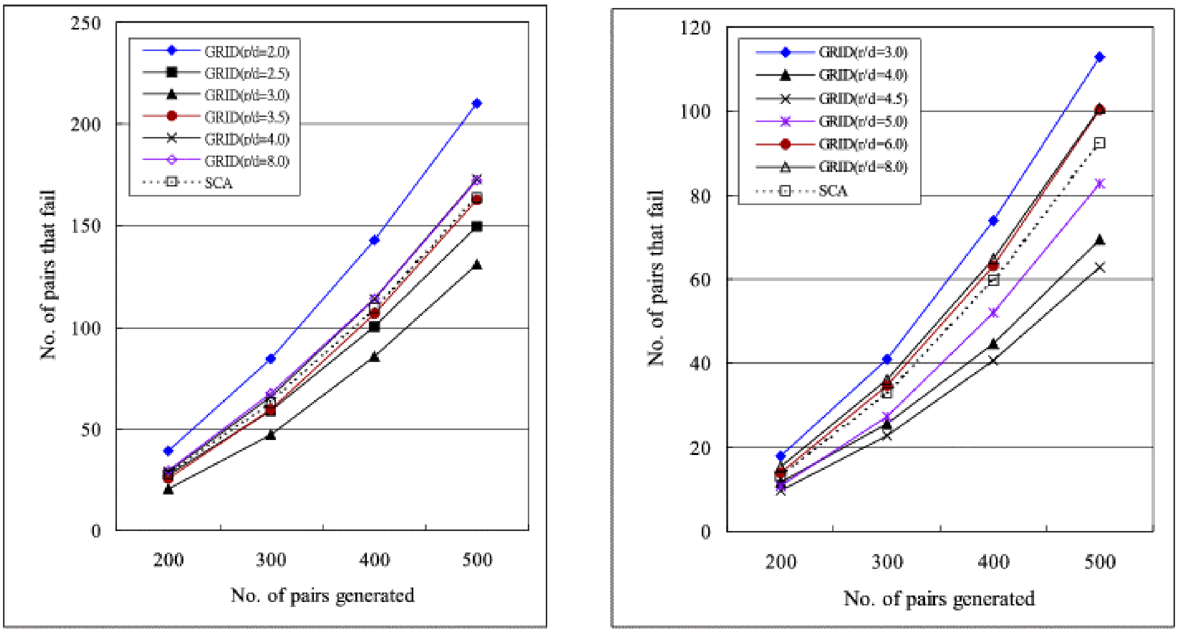


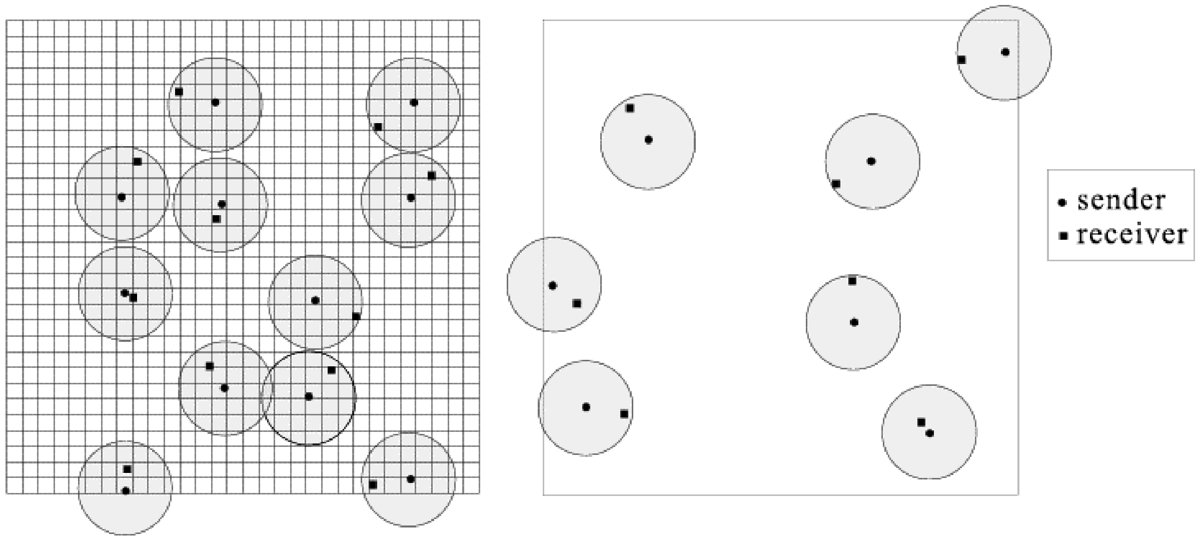
Figure 5.2: The effect of r/d ratio on channel co-interference when $n = 25$.

在了解有這麼多種 *r/d* 情況，但是何種接 *r/d* 才是最佳值呢? 於是接下來我們就做了一個簡單的實驗，其結果如圖表 Figure 5.3 所示。由實驗得知，最佳值大約出現在 $r/d = \sqrt{n/2}$ 。其中 *n* 是系統 channel 的個數。



(a) (b)

Figure 5.3: Tests of blocked sender-receiver pairs at different r/d ratios: (a) $n = 36$ and (b) $n = 81$.



(a) (b)

Figure 5.4: A snapshot of our experiment in Fig. 5.3 when $n = 36$ and $r/d = 3.0$: (a) GRID and (b) SCA. The snapshots are taken on a 1000 × 1000 area, and each circle means a sender-receiver pair.

三、MAC 協定

本節將描述我們所提出的 MAC 協定。在前面提過，multi-channel 協定需要完成頻

道配置與媒體存取兩件事，才算是完整的 MAC 協定。GRID 只有完成 channel assignment，因此必須有一套媒體存取的機制搭配使用。我們所提的新協定以 On-Demand 的方式分配頻道給需要通訊行動主機，因此系統提供給網路所需的頻道個數與網路的拓樸是無關的，而且依照 IEEE802.11 standard 的控制訊息就可以同時完成媒體存取與防止 hidden terminal 的功能，更重要的是行動主機不需要任何型式的時間同步。Figure 5.5 是我們的 channel model。整個頻寬被分成數個 channel。其中一個 channel 被指定成 control channel，其他再分成若干個 data channel。Control channel 是一個 common channel，所有的行動主機都必須用它來傳輸控制訊息或是竊聽別人的控制訊息。控制訊息主要是用來獲得媒體存取的控制。

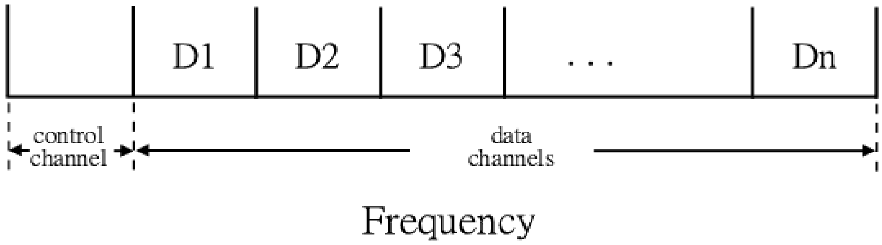


Figure 5.5

在我們的協定中每個行動主機都要維護它們自己的資料結構 *Channel Usage Table (CUL)*。

- CUL
  - ✓ *CUL[i].host*: 紀錄鄰居 *X* 的識別碼，
  - ✓ *CUL[i].ch*: *X* 正在使用的 channel，
  - ✓ *CUL[i].rel_time*: 何時釋放 *CUL[i].ch*。

以下我們用一個例子來說明本協定的主要工作原理。當行動主機 A 想送 data packet 給行動主機 B 時，首先檢查自己 *CUL* table，如果有人正在使用，就必須等待;否則 A 就可用 control channel 送出 RTS 給 B。這時除了 B 之外的所有鄰居都會將這訊息紀錄於自己的 *CUL* table 中。當 B 收到 A 的 RTS 後，如果確定自己 grid 的 channel 沒有人在使用，就以 CTS 回覆 A，這時所有 B 的鄰居也都會聽到並且記載於它們自己的 *CUL* 之中。當 A 收到 B 的 CTS 後，就可以用 B 所在 grid 的 channel 傳送 data packets。

四、效能模擬

本節將以實驗的方式來檢驗 GRID 的效能。本實驗所使用的參數如 Table 5.3 所

示。模擬是在 1000×1000 的地圖，傳輸半徑 200，傳輸速率 1M bits/sec，400 個行動主機。

Table 5.3: Experimental parameters.

physical area	1000×1000
no. of hosts	400
transmission range r	200
max. no. of retrials to send a RTS	6
length of DIFS	50 μsec
length of SIFS	10 μsec
backoff slot time	20 μsec
control packet length L_c	100 bits
data packet length L_d	a multiple of L_c

我們一共做了四組實驗，分別針對 channel 個數，data packet 與 control packet 長度的比值， 傳輸錯誤率 bit error ratio 做比較與觀察。由下列各圖表得知，GRID 的確優於其他協定。

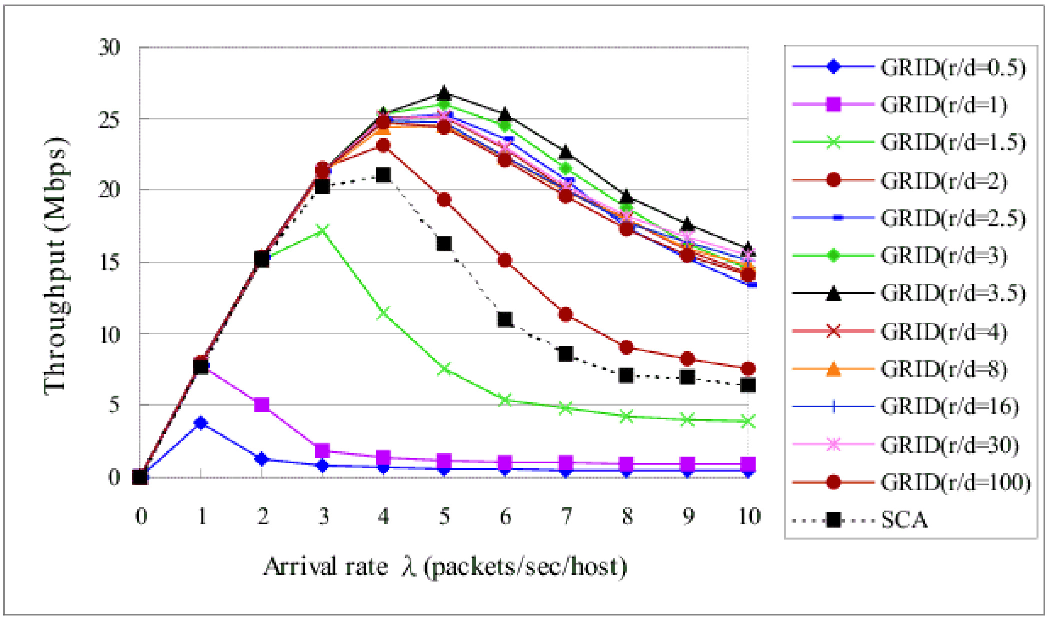


Figure 5.9: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different r/d ratios.

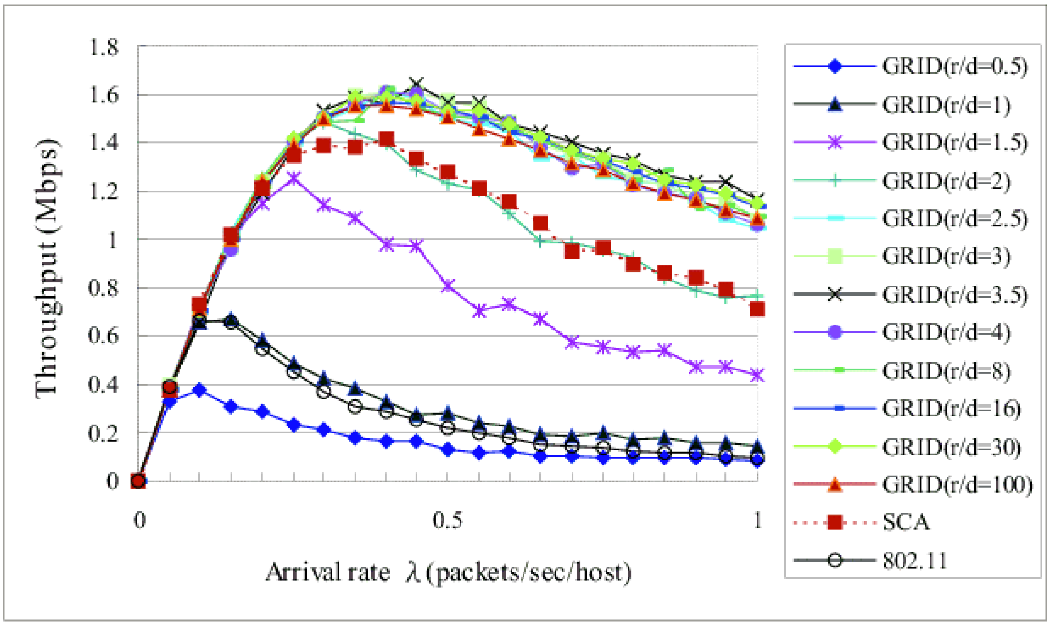


Figure 5.10: Arrival rate vs. throughput under the fixed-total-bandwidth model at different r/d ratios.

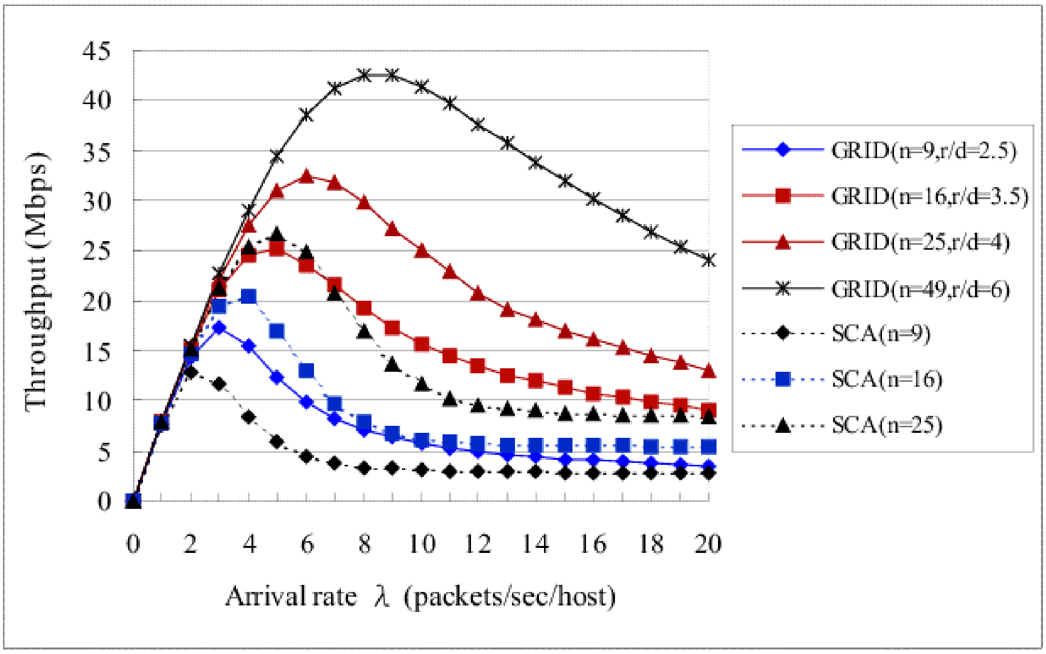


Figure 5.11: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of data channels.

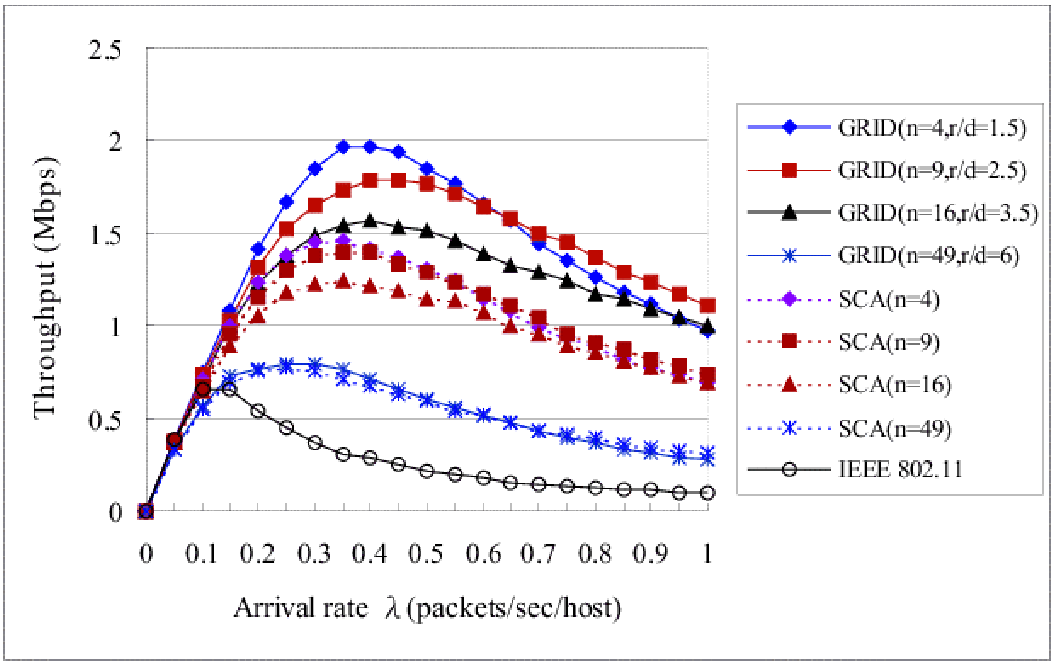
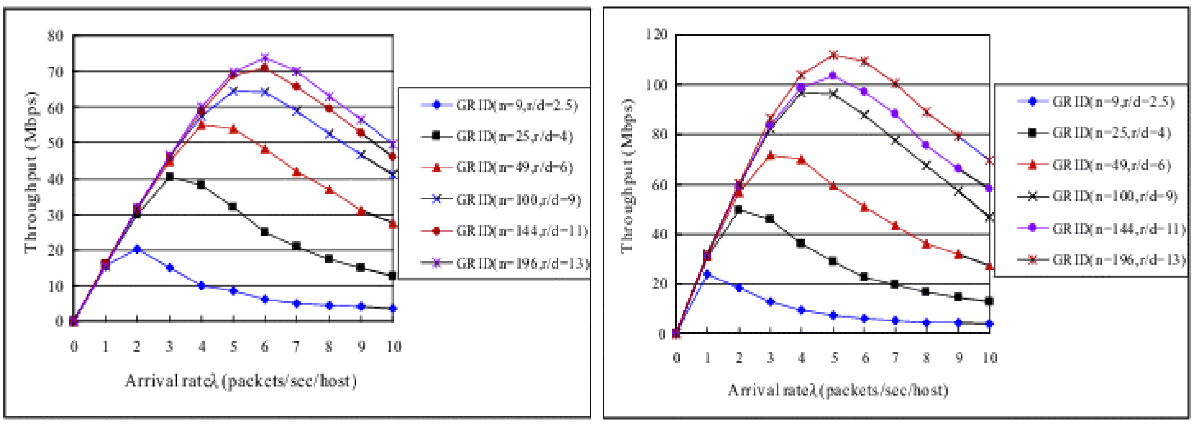
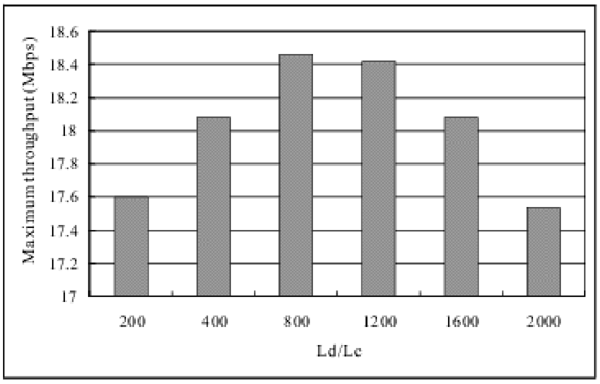


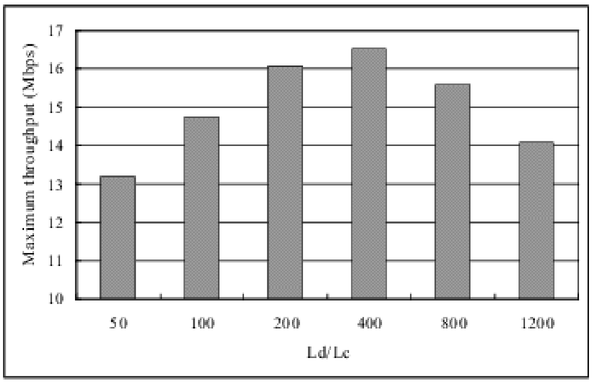
Figure 5.12: Arrival rate vs. throughput under the fixed-total-bandwidth model with different numbers of data channels.



(a) (b)

Figure 5.13: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different numbers of data channels: (a) $L_d/L_c = 50$ and (b) $L_d/L_c = 200$.





(a) (b)

Figure 5.14: Ratio L_d/L_c vs. maximum throughput under the fixed-channel-bandwidth model: (a) bit error rate $= 10^{-6}$ and (b) bit error rate $= 5 \times 10^{-6}$.

第六章、具有位置知覺的動態式多重頻道 MAC 協定

在有座標式多重頻道環境中，我們設計一個新的協定稱為 GRID，它最大的特色就是利用位置資訊完成頻道的配置，行動主機完全不需負擔任何控制訊息的收送。在媒體存取方面，我們使用類似 RTS/CTS 的方式，保留媒體的使用權，這種方式的優點是行動主機間不需任何形式的時間同步，而且系統提供給網路頻道個數與網路的拓樸也是無關的。雖然如此 GRID 所使用的頻道配置是靜態的。我們知道在現實狀況中，經常會有某些地區人口密集的狀況出現，如果只是使用簡單且固定的靜態頻道配置方式，效率將會不好。因此在最後一章我們提出借頻道的方式來達成動態是的頻道配置，經由實驗證明確實可以提昇不少效能。

一、動機

GRID 所使用的頻道配置是靜態的，這種協定在現實環境中，效率將會受到影響。因為在現實狀況中，經常會有某些地區人口密集的狀況出現，如果只是使用簡單的靜態頻道配置，將每個 grid 分配相同 channel 數，這會造成某個 grid 的 channel 不夠使用，某個 grid 的 channel 卻閒置沒用，這樣效率將會不好。如果我們把閒置的 channel 調借給 channel 不夠的 grid， channel 的使用率必然會增加，而我們並不會有額外的硬體負擔。因此我們提出借頻道的協定(稱之為 GRID-B, B 為 borrowing)來達成動態調借 channel 的目的。它最主要的觀念是把鄰近不用的 channel 借過來使用，以平衡網路負載，讓 channel 的使用更有彈性。然而借 channel 的優先順序又可根據 sender 與 receiver 所在 grid 的位置及跟欲借 channel 的 grid 所在位置的關係(例如距離、順序)來排序。經由實驗證明確實可以提昇大約 15%左右的效能。

二、GRID-B: 具有位置知覺的動態式多重頻道 MAC 協定

本協定是架構在 GRID MAC 協定上， GRID 的 channel assignment 具有 location-aware 的特色。GRID 協定會預先將地理區域分割成若干 grid，以每個 grid 為一個單位來分配 channel，grid 間如果要重複使用相同的 channel，必須相隔一定距離才可以(如 Figure 6.1 所示)。它最大的特色就是利用位置資訊完成 channel 的配置，行動主機完全不需負擔任何控制訊息的收送。本章提出借 GRID-B 來達成動態調借 channel 的目的。它最主要的觀念是把鄰近不用的 channel 借過來使用，讓 channel 的使用更有彈性。

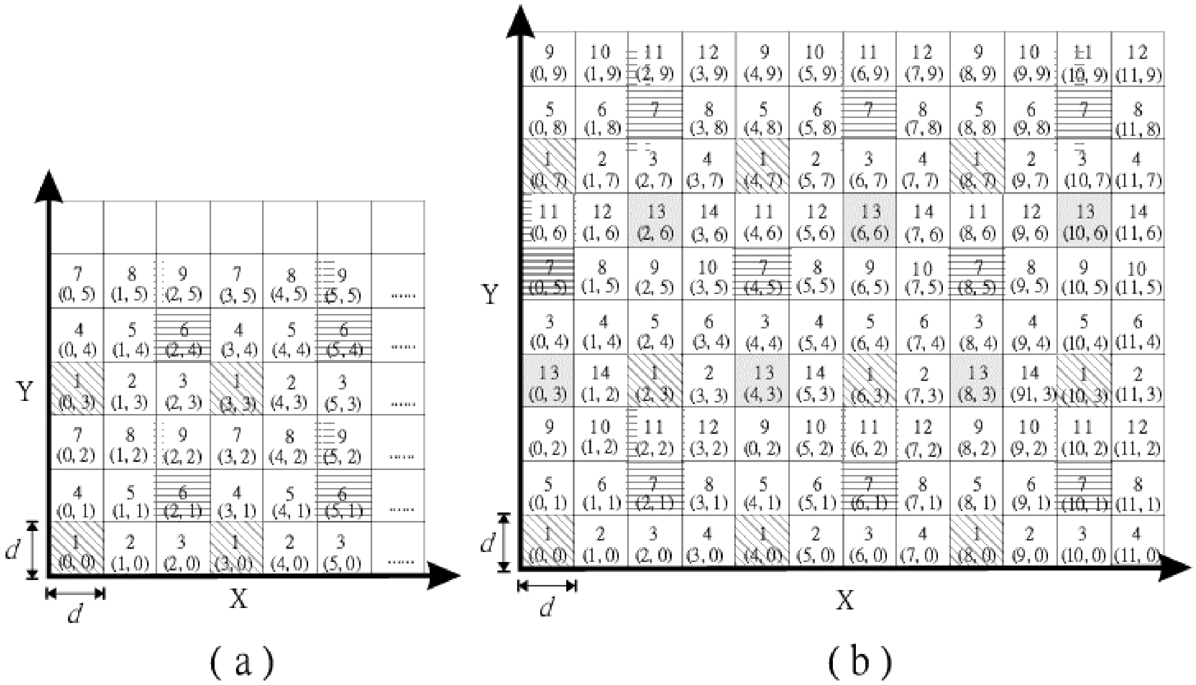


Figure 6.1: Assigning channels to grids in a band-by-band manner: (a) $n = 9$ and (b) $n = 14$. In each grid, the number on the top is the channel number, while those on the bottom are the grid coordinate. Here, we number channels from 1 to n.

然而借 channel 的優先順序又可根據 sender 與 receiver 所在 grid 的位置及跟欲借 channel 的 grid 所在位置的關係(例如距離、順序)來排序。我們利用一個範例說明協定主要精神所在。在 Figure 6.2 中，系統總共使用 16 個 channel，分別編號為 1,2,3,…,16。sender 所在的 grid 為 15，receiver 所在的 grid 是 12。四種演算法所代表的四個數列如下所示:

- GRID-B$_{ss}$: {15, 16, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14}
- GRID-B$_{sr}$: {12, 13, 14, 15, 16, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11}
- GRID-B$_{ds}$: {15, 5, 1, 6, 8, 9, 7, 13, 2, 4, 10, 12, 3, 11, 14, 16}
- GRID-B$_{dr}$: {12, 2, 1, 3, 6, 14, 4, 10, 5, 7, 13, 15, 8, 9, 11, 16}

其中，GRID-B 第一個註標 s 表示 sequence base，d 表示 distance base。第二個註標 s 表示 sender base，r 表示 receiver base。

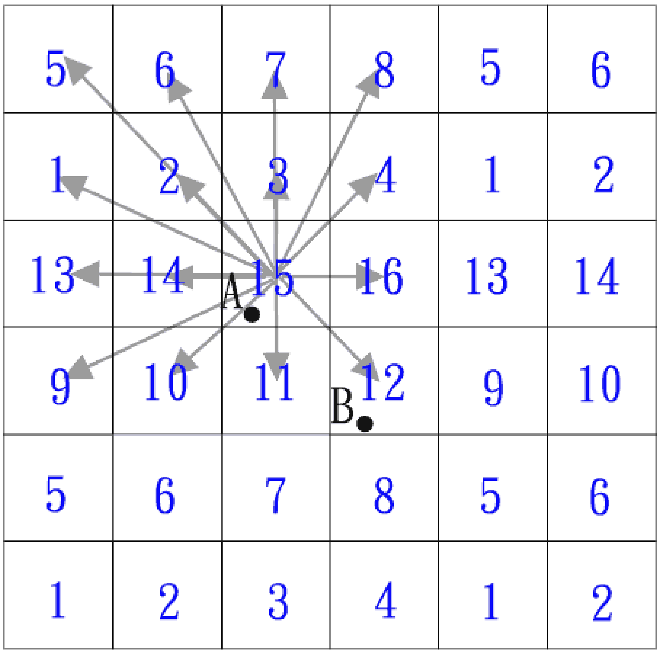


Figure 6.2: An example to determine the channel borrowing sequences in our strategies. The arrows radiated from A and B indicate the values of the distance functions $dist1$ and $dist2$, respectively.

三、效能分析

本節將以實驗的方式來檢驗 GRID-B 的效能。模擬是在 1000×1000 的地圖，傳輸半徑 200，傳輸速率 1M bits/sec，400 個行動主機。我們一共做了四組實驗，分別針對 grid size，GRID 與 GRID-B 比較，hot spot 影響，packet turnaround time 做觀察。由下列各圖表得知，GRID-B 的確優於其他協定。

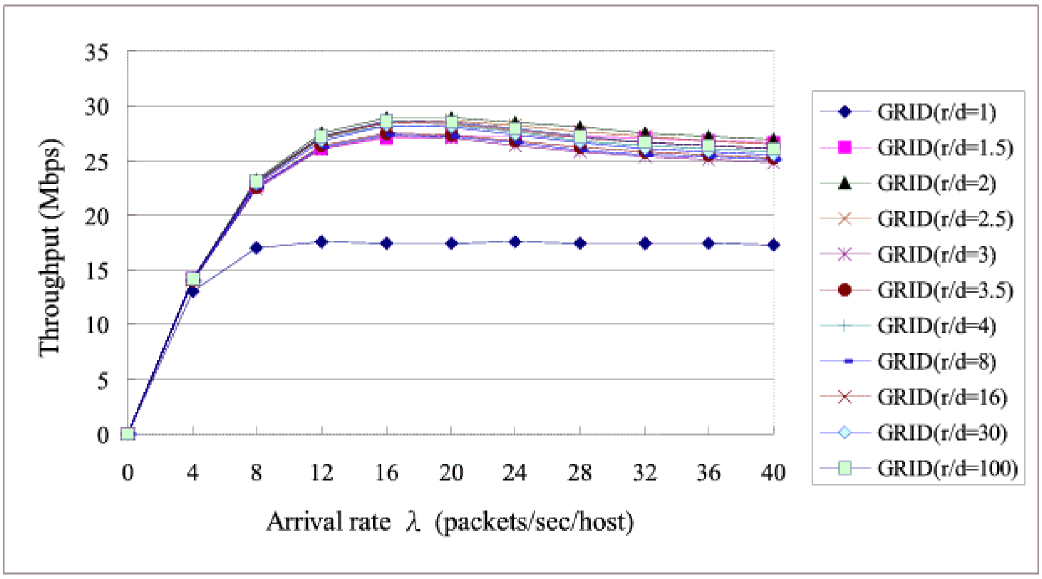


Figure 6.5: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different r/d ratios.

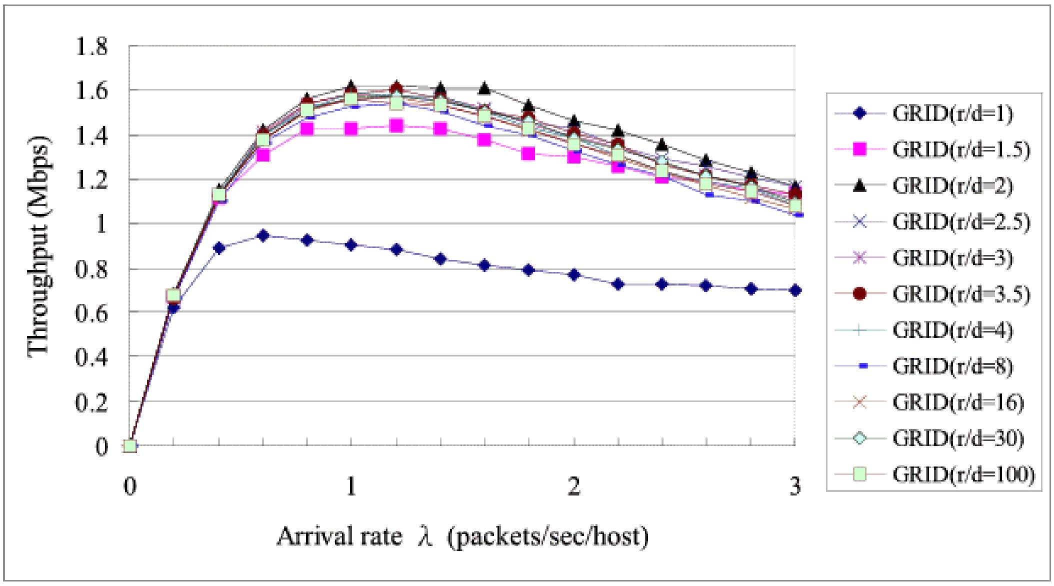
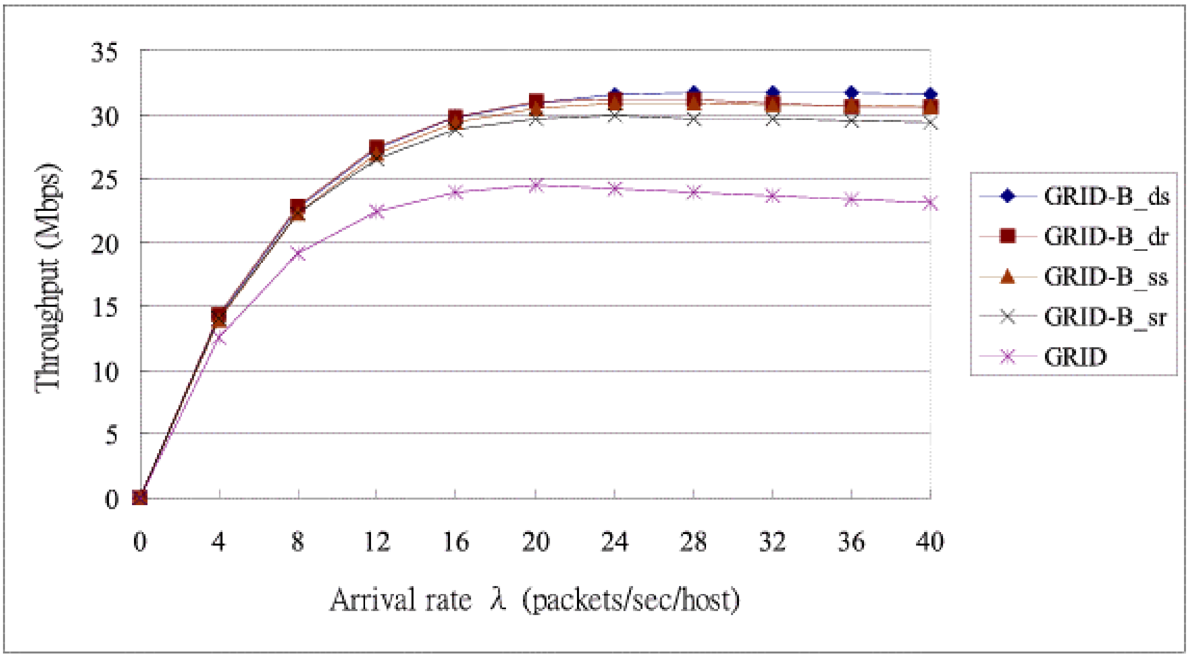
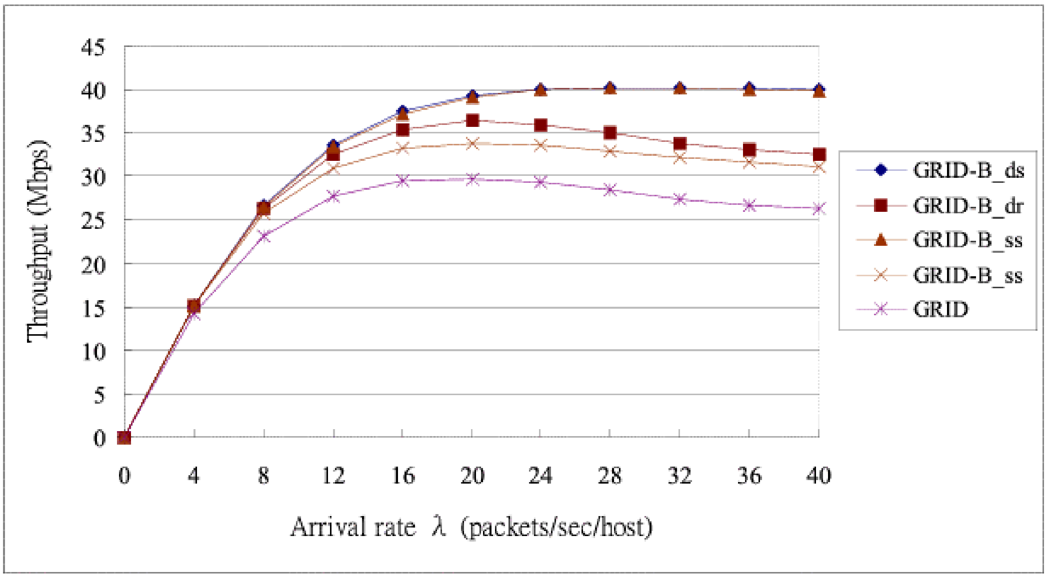


Figure 6.6: Arrival rate vs. throughput under the fixed-total-bandwidth model at different r/d ratios.

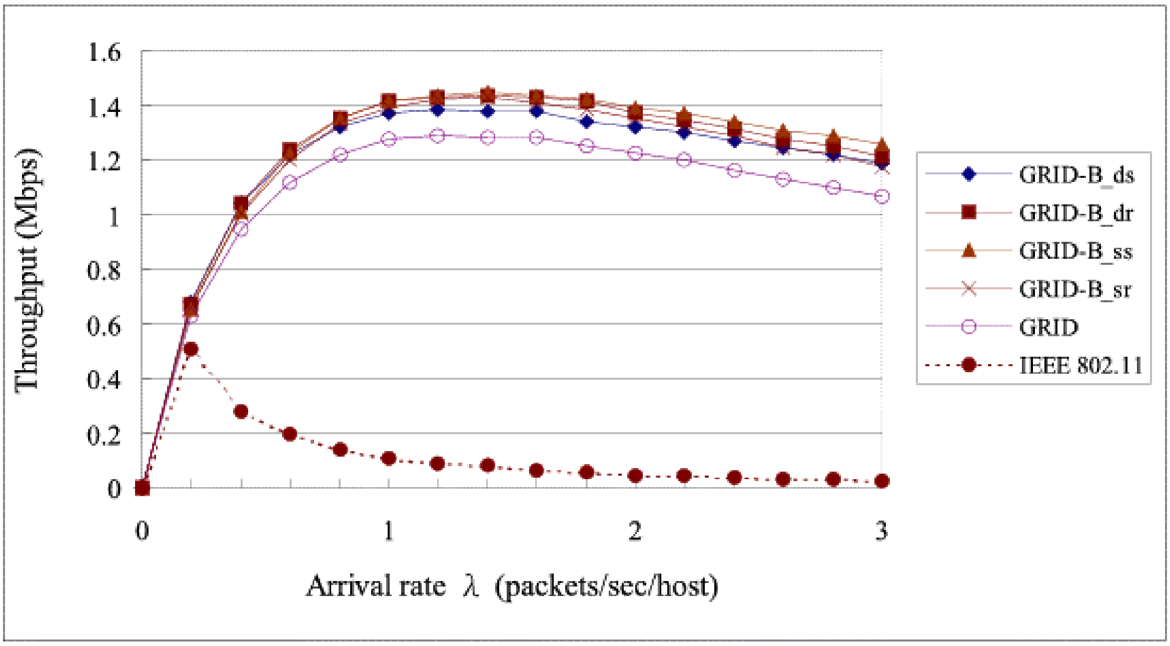


(a)

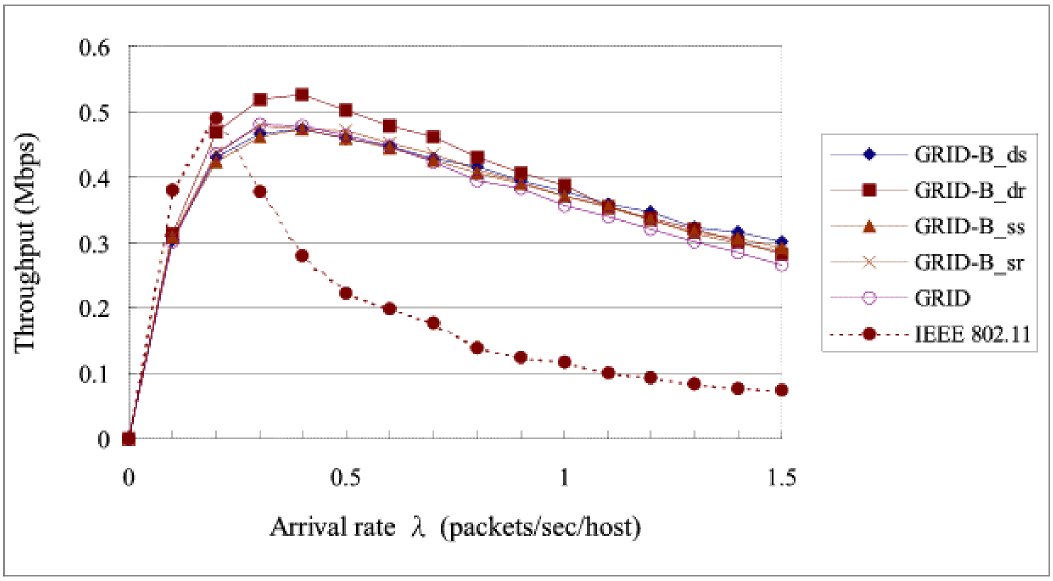


(b)

Figure 6.7: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different channel borrowing sequence: (a) $n = 16, r/d = 2$ and (b)$n = 49, r/d = 4$.



(a)



(b)

Figure 6.8: Arrival rate vs. throughput under the fixed-total-bandwidth model with different channel borrowing sequence: (a) $n = 16, r/d = 2$ and (b)$n = 49, r/d = 3$.

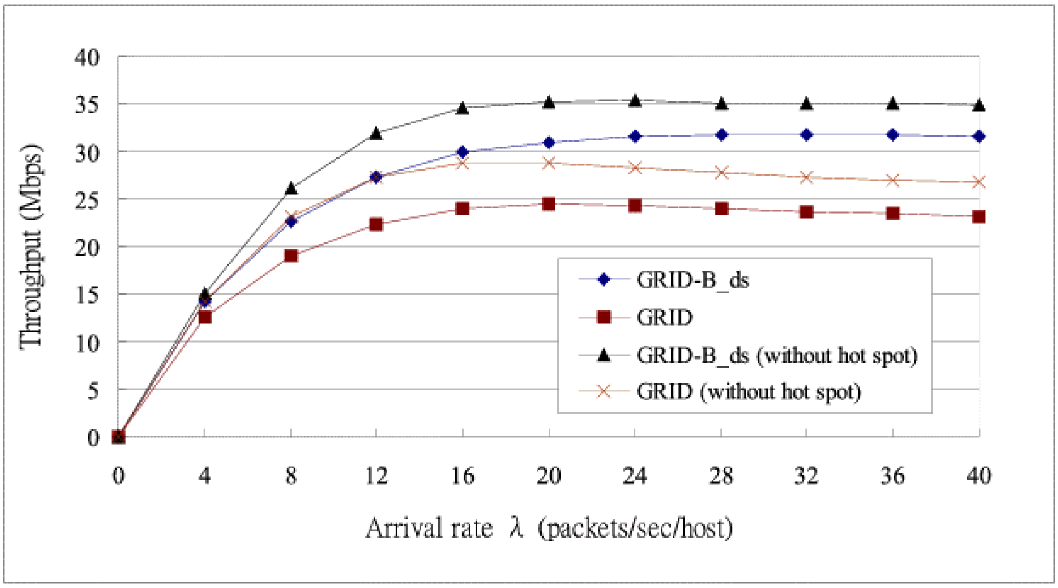


Figure 6.9: Arrival rate vs. throughput under the fixed-channel-bandwidth model with and without hot spots ($n = 16$).

第七章、結論

在本篇論文中，我們在這具有無線、行動且分散式的環境中，針對三種不同的環境:單一頻道、無座標式多重頻道及有座標式多重頻道，提出五種不同的協定來提昇媒體傳輸效率。

一、貢獻

在單一頻道環境中，我們所設計的新協定 (protocol) 是藉由控制發射功率 (power control) 的大小，再結合傳統交換 RTS/CTS 及 busy-tone 的機制，更進一步的提升頻道的使用效率。另外我們也討論分析使用有限段式 (discrete) 取代連續無段式 (continuous) 的調整發射功率，並且修改協定使其達到最佳的成本效益比。最後我們經由分析及實驗證明這個協定確實優於傳統協定大約兩倍的效能。

在無座標式多重頻道環境中，我們設計一個具有動態頻道分配的協定，稱之為 DCA (dynamic channel assignment)。DCA 具有下列數個特性: (1)以 On-Demand 的方式分配頻道給需要通訊行動主機，(2) 系統提供給網路所需的頻道個數與網路的拓樸是無關的，(3) 此協定只需要交換少數的控制訊息(Control Messages)就可以同時完成媒體存取與頻道配置兩個功能，(4)行動主機不需要任何型式的時間同步(time synchronization)。經由分析與實驗得知 DCA 確實比其他協定較適合於無線行動隨建即連網路。

為了減緩 packets 碰撞機率過高因而造成效能過低的另一種方法就是 power control。因此為了讓頻道重複使用率更加提高，我們整合 DCA 與 power control 兩種機制提出更有效率的新協定稱之為 DCA-PC。經由實驗得知，DCA-PC 效能大約比 DCA 提昇四成左右。

在最後一個環境有座標式多重頻道中，我們設計一個新的協定稱為 GRID，它最大的特色就是利用位置資訊完成頻道的配置，行動主機完全不需負擔任何控制訊息的收送。在媒體存取方面，我們使用類似 RTS/CTS 的方式，保留媒體的使用權，這種方式的優點是行動主機間不需任何形式的時間同步，而且系統提供給網路頻道個數與網路的拓樸也是無關的。

此外 GRID 所使用的頻道配置是靜態的，這種協定在現實環境中，經常會有某些地區人口密集的狀況出現，效率將會受到影響。因此我們提出借頻道的協定，稱之為

GRID-B，來達成動態是的頻道配置。它最主要的觀念是把鄰近不用的 channel 借過來使用。經由實驗證明確實可以提昇大約 15%左右的效能。

二、未來研究方向

目前我們只有提出理論的部分，未來希望能利用現有 IEEE Std 802.11 無線網路卡與 GPS 的設備，實作出上述這五個協定，經由實際的測試讓我們的這些想法更趨成熟完美。

The Medium Access Control Problems in Mobile Ad Hoc Networks

by

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Advisors

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DISSERTATION

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Abstract

The architecture of a *wireless mobile ad hoc network* (MANET) is formed by a cluster of mobile hosts and can be rapidly deployed without any established infrastructure or centralized administration. The channel model of MAC layer can be categorized as the single-channel model or the multi-channel model. In single-channel model, all mobile hosts operate on the single common channel for communication. In multi-channel model, the overall bandwidth is divided into several channels and every mobile host can operate any one or some of these channels for communication. One essential issue of MAC layer is to how to increase channel utilization while avoiding the *hidden-terminal* and the *exposed-terminal* problems. Therefore, this dissertation proposes five protocols to increase MAC performance in three major topics, that is, single-channel with power control, multi-channel without location awareness, and multi-channel with location awareness.

It is well known that using smaller radio transmission power can increase channel reuse. In the first topic, we explore the possibility of combining the concept of *power control* with the RTS/CTS-based and busy-tone-based protocols to further increase channel utilization in the signle-channel. A sender will use an appropriate power level to transmit its packets so as to increase the possibility of channel reuse. The possibility of using discrete, instead of continuous, power levels is also discussed. Through analysis and simulations, we demonstrate the advantage of our new MAC protocol.

Another approach to relieving the contention/collision problem is to utilize multiple channels. This dissertation also considers the access of multiple channels in a MANET with

multi-hop communication behavior. Using multiple channels has several advantages. First, while the maximum throughput of a single-channel MAC protocol is 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, 54], using multiple channels experiences 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 [50].

In the second topic, we propose a new multi-channel MAC protocol DCA(Dynamic Channel Assignment), 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) [11, 34, 37], some require a number of channels which is a function of the maximum connectivity [11, 23, 34, 37], and some necessitate a clock synchronization among all hosts in the MANET [37, 67].

It is known that using smaller radio transmission power can increase channel reuse and thus channel utilization. It also saves the precious battery energy of portable devices and reduces co-channel interference with other neighbor hosts. Therefore, we combine the above DCA protocol with power control scheme for furthermore improving DCA performance.

Since a MANET should operate in a physical area, it is very natural to exploit location information in such an environment. Therefore, in the third topic, we propose another MAC protocol GRID in the multi-channel system with exploiting position information. Its channel assignment is characterized by two features: (i) it exploits location information by partitioning the physical area into a number of squares called *grids*, and (ii) it does not need to transmit any message to assign channels to mobile hosts. Several channel assignment schemes have been proposed earlier [23, 28, 37, 54, 67], but none of them explore in the location-aware direction. Based on a RTS/CTS-like reservation mechanism, this medium access protocol does not require any form of clock synchronization among mobile hosts and is also a degree-independent protocol.

In the above GRID protocol, channels are assigned to grids statically. In real world, however, some grids could be very crowded and thus "hot," while some could be "cold." Apparently, it will be more flexible if channels can be borrowed among grids to resolve the contention in hot spots. This has motivated us to investigate the possibility of dynamically assigning channels to grids. Based on the above protocol and this idea, we further proposed a new protocol, called *GRID-B* (read as GRID with channel borrowing). We propose four strategies for the sorting: *sequential-sender-based borrowing*, *sequential-receiver-based borrowing*, *distance-sender-based borrowing*, and *distance-receiver-based borrowing*. The basic idea is that we will assign to each grid a default channel, and a list of channels owned by its neighboring grids from which it may borrow. The purpose is twofold: (i) we dynamically assign channels to mobile hosts so as to take care of the load unbalance problem caused by differences among areas (such as hot and cold spots), and (ii) we sort channels based on mobile hosts' current locations so as to exploit larger channel reuse. In GRID, channels are assigned to grids statically, and we find that using a dynamic assignment in GRID-B can further improve the throughput of channels.

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Chapter 1

Introduction

Mobile computing (or *nomadic computing*) has received intensive attention recently [4, 7, 8, 10, 26, 45, 59, 86, 62, 64, 71, 75, 79, 82, 72, 87]. Users can move around, while at the same time still remaining connected with the rest of the world. Mobility has become a new issue on today's computing systems. The maturity of wireless transmissions and the popularity of portable computing devices have made the dream of "communication anytime and anywhere" possible. Many wireless communication products are available commercially, such as WaveLAN by Lucent, AIRLAN by Solectek, BreezeNET by BreezeCOM, RangeLAN and RangeLINK by Proxim, AirLink Bridge by Cylink, ARDIS, CDPD [13, 61], DECT [25], and GSM [24, 33]. Small, light-weight, economic hand-held *mobile hosts*, such laptop PCs, palmtop PCs, and PDAs, are also widespread.

There are two possibilities to form a wireless network: *infrastructure* and *ad-hoc*. In infrastructure networks, a number of base stations are used, through which all communications to or from the mobile hosts must go. The based stations can then be interconnected by wired networks, but generally speaking wide-area wireless networks can also be used for the interconnection. Through such infrastructure, larger-scale wireless networks can easily be formed.

On the other hand, a mobile ad-hoc network (MANET) is formed by a cluster of mobile hosts and can be rapidly deployed without any established infrastructure or centralized administration. Due to the transmission range constraint of transceivers, two mobile hosts can communicate with each other either directly, if they are close enough, or indirectly, by having other intermediate mobile hosts relay their packets. The applications of MANETs appear in places where pre-deployment of network infrastructure is difficult (e.g. fleets in oceans, armies in march, natural disasters, and battle fields) or unavailable (e.g., convention centers, 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 [14, 36, 23, 42, 47, 46, 57, 54, 35, 55, 56, 66, 67, 70, 84, 81, 80, 73].

1.1 Research Overview and Contributions

The channel model of MAC can be categorized as a single-channel or multi-channel. In single-channel model, all mobile hosts operate on the single common channel for communication. In multi-channel model, the overall bandwidth is divided into several channels and every mobile host can operate any one or some of this channels for communication. One essential issue of MAC layer is to how to increase channel utilization while avoiding the *hidden-terminal* and the *exposed-terminal* problems. Therefore, this dissertation proposes five protocols to increase MAC performance in three major topics ,that is, single-channel with power control, multi-channel without location awareness, and multi-channel with location awareness.

1.2 Single-Channel with Power Control

In single share-channel, Several mechanisms, such as *ALOHA* [5], *CSMA* [40], *RTS/CTS-based* [39, 12, 48, 65], *CSMA/CA* [21, 3] and *busy-tone-based* schemes [68, 17, 29], have been proposed to alleviate these problems. It is well known that using smaller radio transmission power can increase channel reuse. In this dissertation, we have proposed a new MAC protocol [84, 85] for MANETs that utilizes the intelligence of power control on top of the RTS/CTS dialogues and busy tones. Channel utilization can be significantly increased because the severity of signal overlapping is reduced.

Through analyses and simulations, We show how power control can help to increase channel utilization in a MANET. Significant gains are shown to be obtainable using power control over the *Dual Busy Tone Multiple Access (DBTMA)* protocol [17]. So the outlook of using power control is promising to enhance the performance of a MANET. For practical and implementation concerns, we also consider the possibility of using *discrete*, instead of *continuous*, power levels for transmission. Specifically, given a constant k, we show how to determine k levels of power that can exploit the best channel utilization.

1.3 Multi-Channel Protocol without Position Device

One common problem with single-channel protocols is that the network performance will degrade quickly 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. 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, 54], 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 [50].

In this dissertation, we design a new multi-channel MAC protocol, called DCA [80], 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 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.

Both the channel assignment and medium access problems are solved in an integrated manner with light control traffic overhead. 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.

It is known that using smaller radio transmission power can increase channel reuse and thus channel utilization. It also saves the precious battery energy of portable devices and reduces co-channel interference with other neighbor hosts. Therefore, we combine the above DCA protocol with power control scheme for furthermore improving DCA performance [73].

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 to improve the performance of a MANET.

1.4 Multi-Channel Protocol with Position Device

Since a MANET should operate in a physical area, it is very natural to exploit location information in such an environment. Indeed, location information has been exploited in several issues in MANET (such as location-aware routing [42, 43, 44, 47] and location-aware broadcast [55]), but not on channel assignment. GSM (Global System for Mobile Communications) is an instance which uses location information to exploit channel reuse, but MANET has quite different features (e.g., host has mobility and there is no base station). The availability of the physical location of a mobile host may be obtained from a positioning device such as GPS (global positioning systems) receiver attached to the host through an RS-232 port. GPS receivers are appropriate for outdoor use, and the positioning accuracy ranges in about a few tens of meters. To improve the accuracy, assistance from ground stations can be applied. Such systems, called *differential GPS (DGPS)*, can reduce the error to less than a few meters [44]. Recently, the US government ordered to discontinue the SA (Selective

Availability), which intentionally degrades the civilian GPS signals [78]. This is expected to increase the accuracy of GPS significantly, which further motivates the work in this field. The price of a GPS module is less than US $100.

In this dissertation, we propose a new multi-channel MAC protocol [83] for MANET. A multi-channel MAC typically needs to address two issues: *channel 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. These two issues are sometimes addressed separately, but eventually one has to integrate them to provide a total solution.

The channel assignment, called *GRID*, is characterized by two features: (i) it exploits location information by partitioning the physical area into a number of squares called *grids*, and (ii) it does not need to transmit any message to assign channels to mobile hosts. Several channel assignment schemes have been proposed earlier [23, 28, 37, 54, 67], but none of them explore in the location-aware direction. Based on a RTS/CTS-like reservation mechanism, our medium access 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.

Our simulation results have also indicated that it is worthwhile to consider using multiple channels under both the fixed-channel-bandwidth model and the fixed-total-bandwidth model.

In the above GRID protocol, channels are assigned to grids statically. In real world, however, some grids could be very crowded and thus "hot," while some could be "cold." Apparently, it will be more flexible if channels can be borrowed among grids to resolve the contention in hot spots. This issue has been studied quite a lot in the area of cellular systems [18, 9, 53]. This has motivated us to investigate the possibility of dynamically assigning channels to grids. Based on the above protocol and this idea, we further proposed a new protocol, called *GRID-B* (read as GRID with channel borrowing).

A mobile host, on needing a channel to communicate, will dynamically compute a list of channels based on the grid where it is currently located. The list of channels is in fact sorted based on location information. We propose four strategies for the sorting: *sequential-sender-based borrowing*, *sequential-receiver-based borrowing*, *distance-sender-based borrowing*, and *distance-receiver-based borrowing*. The basic idea is that we will assign to each grid a default channel, and a list of channels owned by its neighboring grids from which it may borrow. The purpose is twofold: (i) we dynamically assign channels to mobile hosts so as to take care of the load unbalance problem caused by differences among areas (such as hot and cold spots), and (ii) we sort channels based on mobile hosts' current locations so as to exploit larger channel reuse. In GRID, channels are assigned to grids statically, and we find that using a dynamic assignment in GRID-B can further improve the throughput of channels.

Extensive Simulation results show the new GRID-B protocol significant improvements, in both throughput and delay, over the GRID protocol.

1.5 Organization of the Dissertion

The rest of this dissertation is organized as follows. In Chapter 2, we describe the problem of single-channel MAC protocol, review some of exist protocols and then present our research results. Chapter 3 identifies the multi-channel assignment problem, introduces related works and shows our protocol. Based on the proposed protocol, Chapter 4 develops adaptive schemes that further improve the efficiency of MANET broadcasting without sacrificing its reliability. Chapter 5 gives the multi-channel assignment problem without position devices and then proposes our protocol. Based on this protocol, we further improve the performance of GRID with the idea of channel borrowing in Chapter 6. Finally, we conclude our research results and propose some future works in Chapter 7.

Chapter 2

Single-Channel MAC Protocol with Busy Tones and Power Control

In a *mobile ad-hoc networks (MANET)*, one essential issue is how to increase channel utilization while avoiding the *hidden-terminal* and the *exposed-terminal* problems. Several MAC protocols, such as *RTS/CTS-based* and *busy-tone-based* schemes, have been proposed to alleviate these problems. In this chapter, we explore the possibility of combining the concept of *power control* with the RTS/CTS-based and busy-tone-based protocols to further increase channel utilization. A sender will use an appropriate power level to transmit its packets so as to increase the possibility of channel reuse. The possibility of using discrete, instead of continuous, power levels is also discussed. Through analyses and simulations, we demonstrate the advantage of our new MAC protocol. This, together with the extra benefits such as saving battery energy and reducing co-channel interference, does show a promising direction to enhance the performance of MANETs.

2.1 Introduction

A *mobile ad-hoc network (MANET)* is formed by a cluster of mobile hosts and can be rapidly deployed without any established infrastructure or centralized administration. Due to the transmission range constraint of transceivers, two mobile hosts can communicate with each other either directly, if they are close enough, or indirectly, by having other intermediate mobile hosts relay their packets. The applications of MANETs appear in places where infrastructure networks are difficult to build or unavailable (e.g. fleets in oceans, armies in march, natural disasters, battle fields, festival field grounds, and historic sites). A working group called MANET has been formed by the Internet Engineering Task Force (IETF) to stimulate research in this direction [51].

In a MANET, it is well-known that the hidden-terminal problem and exposed-terminal problem can severely reduce channel utilization [68]. To relieve these problems, many protocols based on RTS/CTS dia logues have been proposed [12, 21, 39, 48, 65]. However, as shown in [17], when the traffic load is heavy, a data packet may still experience collision with probability as high as 60% due to loss of RTS or CTS packets. This is especially serious if the propagation and the transmission delays are long. To alleviate this problem, a scheme using special signals similar to carrier sense, called *busy tones*, is proposed to prevent other mobile hosts unaware of the earlier RTS/CTS dialogues from destroying the on-going transmission [17]. It is shown that the channel utilization can be increased by about twice [17].

In this topic, we try to bring the concept of *power control* into the medium access problem in a MANET. A new MAC protocol that combines the mechanisms of power control, RTS/CTS dialogue, and busy tones is proposed. The main idea is to use the exchange RTS and CTS packets between two intending communicators to determine their relative distance. This information is then utilized to constrain the power level on which a mobile host transmits its data packets. Using lower power can increase channel reuse, and thus channel utilization. It also saves the precious battery energy of portable devices and reduces co-channel interference with other neighbor hosts. There are two ways a mobile host can predict another host's relative location. The simplest way is to use GPS (global positioning system) [38], which is very economical nowadays but is more appropriate for outdoor use. The other, which our dissertation is based on, is to use the signal strengths on which RTS/CTS packets are received to estimate the distance.

In this dissertation, we show through analyses and simulations how power control can help to increase channel utilization in a MANET. Significant gains are shown to be obtainable using power control over the *Dual Busy Tone Multiple Access (DBTMA)* protocol [17]. So the outlook of using power control is promising to enhance the performance of a MANET. For practical and implementation concerns, we also consider the possibility of using *discrete*, instead of *continuous*, power levels for transmission. Specifically, given a constant k, we show how to determine k levels of power that can exploit the best channel utilization.

The rest of this chapter is organized as follows. In Section 2.2, we briefly review two existing MAC protocols. Our newly proposed protocol is presented in Section 2.3. Section 2.4 demonstrates the advantage of our protocol through analysis. How to use discrete power levels is discussed in Section 2.5. Simulation results are in Section 2.6 and summaries are in Section 2.7.

2.2 Review of Some MAC Protocols

In this section, we review CSMA [40] protocol, the RTS/CTS-based protocols, and then the DBTMA [17].

2.2.1 Carrier Sense

Carrier Sense Multiple Access (CSMA) has been widely used in wired/wireless LAN [40]. Nodes with packets to send should sense the channel first. Transmission is allowed only if no carrier is sensed. This mechanism can reduce the probability of collision. Unfortunately, the assumption made in CSMA that every node can hear all other nodes' transmission is not necessarily true in a MANET.

2.2.2 RTS/CTS-Based Protocols

In a MANET, a MAC protocol has to contend with the *hidden-terminal* and the *exposed-terminal* problems. To see the first problem, consider the scenario of three mobile hosts in Fig. 2.1(a). Hosts A and B are within each other's transmission range, and so do hosts B and C. However, A and C can not hear each other. When A is transmitting to B, since host C can not sense A's transmission, it may falsely conclude that the medium is free and transmit, thus destroying A's ongoing packets. The problem that a station can not detect a potential competitor because the competitor is too far away is called the *hidden-terminal* problem.

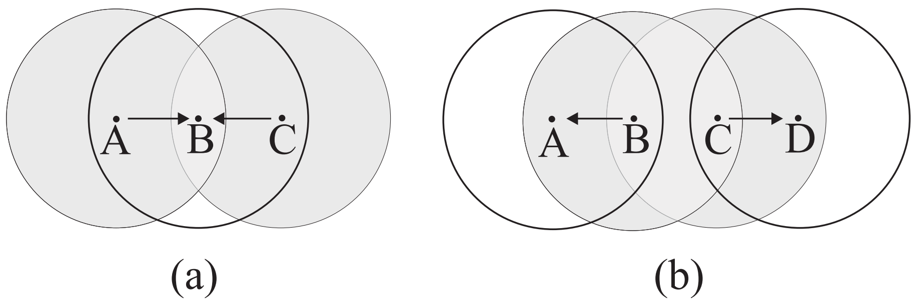


Figure 2.1: Scenarios to show (a) the hidden-terminal problem, and (b) the exposed-terminal problem.

In Fig. 2.1(b), when B is transmitting to A, host C can sense the medium and thus will conclude that it can not transmit. However, if C's intended recipient is D, then such transmission can actually be granted. Such inefficiency in channel use is called the *exposed-terminal* problem.

To alleviate these problems, a number of protocols have been proposed based on sending RTS (request to send) and CTS (clear to send) packets before the data transmission is actually taken place [12, 21, 39, 48]. When a node wishes to transmit a packet to a neighbor, it first transmits a RTS packet. The receiver then consents to the communication by replying a CTS packet. On hearing the CTS, the sender can go on transmitting its data packet. The hidden-terminal problem in Fig. 2.1(a) will be eliminated when C hears the CTS packet, and the exposed-terminal problem in Fig. 2.1(b) will be eliminated if we grant C to transmit if it can hear B's RTS but not A's CTS. Such an approach has been accepted by the IEEE 802.11 standard [3]. In IEEE 802.11, a field called NAV (Network Allocation Vector) is added in the RTS/CTS packets to indicate the expected transmit/receive time of the data packet.

2.2.3 RTS/CTS Dialogue Enhanced with Busy Tones

Although the RTS/CTS dialogue can alleviate some hidden- and exposed-terminal problems, as observed in [17], when propagation and transmission delays are long, the CTS packets can easily be destroyed. This will result in destroy of data packets when traffic load is heavy. Consider the scenario in Fig. 2.2(a). Node A sends a RTS to B, which in turn replies a CTS to A. In the meanwhile, as host C can not hear A's RTS, it may send a RTS (to start a

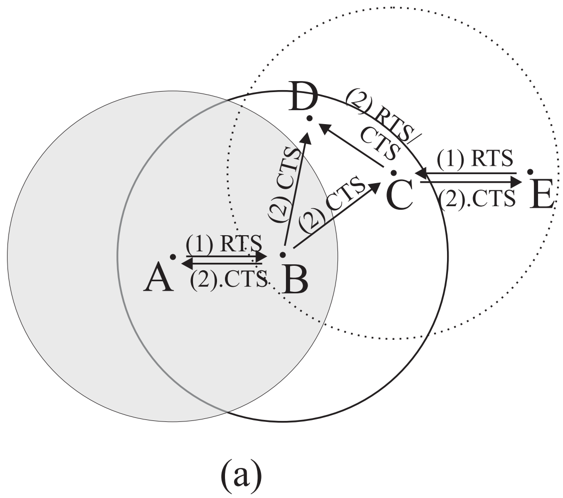


Figure 2.2: (a) A scenario that B's CTS is destroyed at D by C's RTS/CTS. (b) Using busy tones to resolve the CTS destroyed problem.

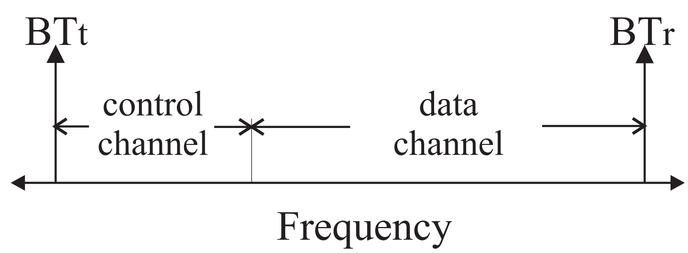


Figure 2.3: Frequency chart of the DBTMA protocol.

transmission with D) or a CTS (to respond to E's RTS). In either case, D can hear neither C's nor B's RTS/CTS, but the transmission from A and B will continue as normal. If later D decides to send any packet while A is transmitting to B, the packet will be destroyed at B. As analyzed in [17], the probability of data packets experiencing collision will be as high as 60% when traffic load is high.

To resolve the above problem, a protocol called *DBTMA (dual busy tone multiple access* is proposed [17, 29]. The single common channel is split into two sub-channels: a data channel and a control channel. The control channel is to transmit RTS/CTS dialogues. Also, two narrow-band busy tones, called *transmit busy tone* (BT_t) and *receive busy tone* (BT_r), are placed on the spectrum at different frequencies with enough separation. Fig. 2.3 shows a possible spectrum allocation.

The purpose of busy tones is to add a capability similar to carrier sense to transceivers — BT_t is to indicate that a host is transmitting, while BT_r does that a host is receiving. A sending host must turn its BT_t on when transmitting a data packet and a receiving host must turn its BT_r on when it replies the sender a CTS. When a host wants to send a RTS, it has to make sure that there is no BT_r around it. Conversely, to reply a CTS, a host must make sure that there is no BT_t around. So in the scenario of Fig. 2.2(a), host D will be aware of, through B's BT_r, B's receiving activity. Fig. 2.2(b) illustrates this scenario — B's BT_r will prohibit C's RTS/CTS.

In summary, a simple rule is used in DBTMA: a host should not send if it hears any BT_r, and should not consent to send if it hears any BT_t. As a final comment, it is also possible to use busy tones to save power [63], but this is out of the scope of this dissertation.

2.3 A New MAC Protocol with Power Control

In this section, we show how to enhance the DBTMA protocol [17, 29] with power control. Using smaller transmission power may increase channel reuse in a physical area. To motivate our work, consider Fig. 2.4(a), where a communication from A to B is ongoing. The communication from C to D can not be granted because D can hear A's BT_t, and similarly that from E to F can not be granted because E can hear B's BT_r. However, as shown in Fig. 2.4(b), if we can properly tune each transmitter's power level, all communication pairs can coexist without any interference.

The following discussion gives a basic idea how to incorporate power control into the original protocol. First, we should enforce A to transmit its data packet and BT_t at a minimal power level, but keep B's BT_r at the normal (largest) power level. When C wants to communicate with D, C senses no BT_r, so it can send a RTS to D. At this moment, D hears no BT_t, so D can reply a CTS to C. Now if C appropriately adjusts its transmission power, the communication from C to D will not corrupt the transmission from A to B. The communication from E to F deserves more attention. At this time, E can sense B's BT_r. Ideally, E should send a RTS to invite F with a power level that is sufficiently large to reach

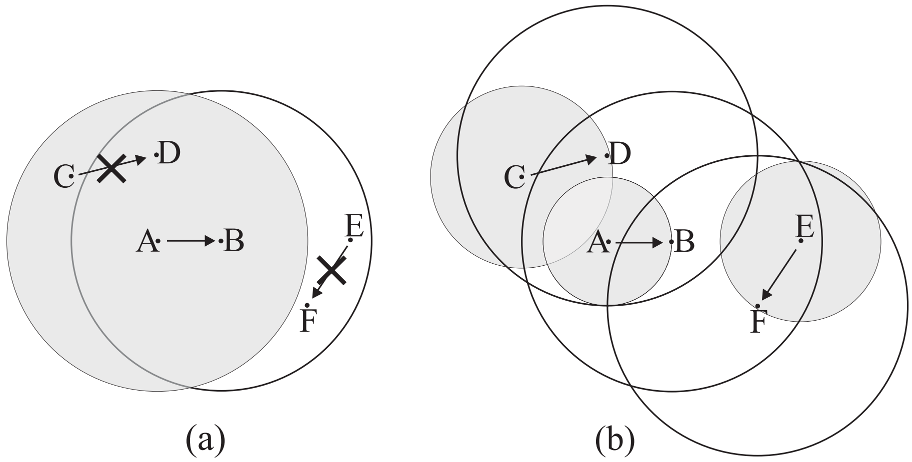


Figure 2.4: Transmission scenarios (a) when there is no power control, and (b) when there is power control. Transmit busy tones are shown in gray and receive busy tones are shown in white.

F but not B. The basic idea is that E's yet-to-be-transmitted data packet should not corrupt B's reception. Host F, which must be closer to E than B is, will reply with a CTS. This causes no problem as F hears no BT_t. Then the communication from E to F can be started.

To summarize, the rules in our protocol are: (i) data packet and BT_t are transmitted with power control based on the power level of the received CTS, (ii) CTS and BT_r are transmitted at the normal (largest) power level, and (iii) RTS is transmitted at a power level to be determined based on how strong the BT_r tones are around the requesting host.

In the following, we first demonstrate how power control can increase channel utilization under an ideal situation. Then we discuss the fundamentals to tune transmission power, followed by a formal description of our protocol.

2.3.1 Benefits of Power Control

At this point, it deserves to predict, under ideal situations, how much benefit power control can offer. We have developed a simple simulation without caring how MAC protocols are designed. We simulated an area of size 500×500. On the area, we randomly generated a sender A and then randomly generated a receiver B within the circle of radius r_{max} centered at A, where $r_{max} = 50$ is the maximum transmission distance of a host. Two models were

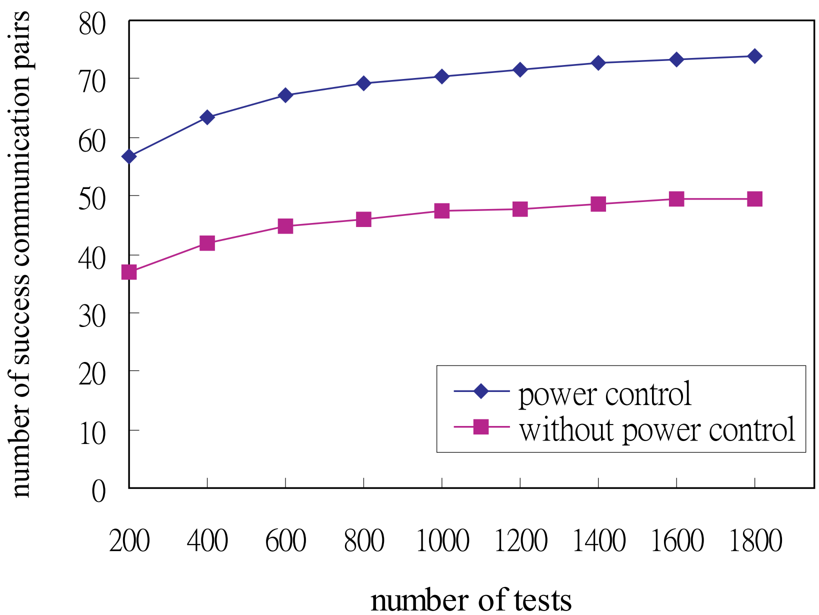


Figure 2.5: The potential numbers of communication pairs in a 500×500 area with and without power control. The maximum transmission distance is 50 units.

assumed: (i) A sends to B with the maximum power, and (ii) A sends to B with a smallest power such that B can receive correctly. Based on the surroundings, we then tested whether the transmission from A to B will interfere any ongoing communication pair or not. If not, the transmission from A to B was granted; otherwise, it was dropped. We then repeated the above tests for a number of times (ranging from 200 to 1800), trying to add more communication pairs to the area.

We observed the numbers of communication pairs that were granted in the area based on the two models. The result is shown in Fig. 2.5, where each point is from the average of 1000 simulations. The x-axis shows the number of tests we have performed. As can be seen, power control can offer about 1.5 times more communication pairs than that without power control.

2.3.2 Tuning Power Levels

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

- *Transmission Power:* A mobile host can choose on what power level to transmit a packet. This function should be offered by the physical layer.
- *Signal Strength:* On receiving a packet, the physical layer can offer the MAC layer the power level on which the packet was received.

Now, suppose a source host transmits a packet to a destination host. Let P_t and P_r be the power levels on which the packet is transmitted and received on the sender and receiver sides, respectively. Then the following equation holds (refer to the Chapter 2 of [77]):

$$P_r = P_t(\frac{\lambda}{4\pi d})^n g_t g_r, \tag{2.1}$$

where λ is the carrier wavelength, d is the distance between the sender and the receiver, n is the path loss coefficient, and g_t and g_r are the antenna gains at the sender and the receiver, respectively. Note that λ, g_t, and g_r are constants in normal situations. The value of n is typically 2, but may vary between 2 and 6 depending on the physical environment, such as existence of walls, cabinets, or obstacles.

One important factor that our protocol relies on is that during a very short period, the values of d and n can be treated as constants. This makes possible choosing appropriate power levels to transmit packets, even if the values of d and n are *unknown*. For instance, suppose host X transmits a RTS with power P_t to host Y, who receives the packet with power P_r. If Y wants to reply a CTS to X at a certain power level P_{CTS} such that X's receiving power is the smallest possible, say P_{min}, then we have

$$P_{min} = P_{CTS}(\frac{\lambda}{4\pi d})^n g_t g_r. \tag{2.2}$$

Dividing Eq. (2.2) by Eq. (2.1), we have

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

Thus, Y can determine the power level $P_{CTS} = P_t P_{min}/P_r$ even if d and n are unknown.

In practice, the level of power to transmit packets does not have to be infinitely tunable. Offering only certain discrete values may simplify hardware design. This possibility will be explored in Section 2.5. Also, to take transmission reliability into account, the real transmission power in the above example should be larger than P_{CTS} by a certain level.

2.3.3 The MAC Protocol

Below, we show how to incorporate power control into the DBTMA protocol [17, 29]. The main idea is to use the exchange of RTS/CTS packets to determine which power level to transmit. The following notations regarding power levels will be used.

- P_{max}: the maximum transmission power
- P_{min}: the minimum power level for a host to distinguish a signal from a noise
- P_{noise}: a power level under which an antenna will regard a signal as a noise (P_{noise} should be less than P_{min} by some constant; ideally, we assume that $P_{min} - P_{noise}$ is a very small value.)

The complete protocol is formally described below.

1. On a host X intending to send a RTS to host Y, host X should sense any receive busy tone BT_r around it and send a RTS on the control channel at power level P_x as determined below:
   - If there is no receive busy tone, then $x = P_{max}$.
   - Otherwise, let P_r be the power level of the BT_r that has the highest power among all BT_r's that X receives. We let

$$P_x = \frac{P_{max} P_{noise}}{P_r}. \tag{2.3}$$

     That is, the RTS signal should not go beyond the nearest host that is currently receiving a data packet. Note that P_{max} is used in Eq. (2.3) because a receive busy tone BT_r is always transmitted at the maximum power level (see rule 2 below).

2. On host Y receiving X's RTS packet, it should sense any transmit busy tone BT_t around it. There are two cases:

   - If there is any such busy tone, then Y ignores the RTS (because collision would occur if X does send a data packet to Y).
   - Otherwise, Y replies with a CTS at the maximum power P_{max} and turns on its receive busy tone BT_r at the maximum power P_{max}.

3. On host X receiving Y's CTS, it turns on its transmit busy tone BT_t and starts transmitting its data packet, both at the power level

$$P_x = \frac{P_{min} P_{max}}{P_r},$$

   where P_r is the level of the power at which X receives the CTS. This power level P_x is the minimum possible to ensure that Y can decode the data packet correctly.

For instances, the reader can verify that our protocol will grant the transmissions from C to D and from E to F in Fig. 2.4(b).

2.4 Performance Analysis

This subsection presents some performance analysis of our MAC protocol. Section 2.4.1 compares the DBTMA and our protocols on the success possibility that two nearby communication pairs can coexist in a MANET. Section 2.4.2 analyzes the channel utilization offered by our protocol.

2.4.1 Analysis of Probability of Two Nearby Communication Pairs

We are interested in how much benefit our protocol can offer over the DBTMA by allowing more communication pairs to exist in a small physical area. Specifically, the following scenario is considered: There is a MANET of four hosts A, B, C, and D. Suppose that A is currently sending a packet to B. We want to find out the probability under such constraint that C can successfully initiate a transmission (through RTS/CTS dialogue) with D. Formally, denote

Table 2.1: Comparison on the probability $Prob(C \rightarrow D)$ given the condition that another communication $A \rightarrow B$ is ongoing.

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

the probability by $Prob(C \rightarrow D)$. We want to determine

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

where $\overline{XY}$ denotes the distance between two hosts X and Y, and r_{max} the maximum transmission distance of an antenna (when power P_{max} is used). Note that the constraint $\overline{BC} \leq 3r_{max}$ is imposed because beyond this distance the two transmissions ($A \rightarrow B$ and $C \rightarrow D$) are free from interference.

To simplify the analysis, we assume that the area that a packet can reach is bounded by a circle and that a host can tune its transmission power to a level with arbitrary accuracy. Also, we assume an ideal model that the difference $P_{min} - P_{noise} = \epsilon$ is an arbitrarily small value (i.e., the gap to distinguish a signal and a noise is negligible).

The discussion is separated into two cases depending on the value of $\overline{BC}$. Table 2.1 gives a preview of our analysis result. As can be seen, when $\overline{BC} \leq r_{max}$, the $Prob(C \rightarrow D)$ of our protocol is about 40%, whereas it is impossible for DBTMA to grant $C \rightarrow D$. When $r_{max} < \overline{BC} \leq 3r_{max}$, both protocols have a high success probability (ours is about 0.06 higher than DBTMA). This implies that our protocol is more useful when the density of mobile hosts is high.

Definition 1 Consider two points A and B on an xy-plane which are the centers of two circles of radii R_A and R_B, respectively. Define $INTC(R_A, R_B, \overline{AB})$ to be the area of the intersection of these two circles.

Definition 2 Consider three points A, B, and C on an xy-plane which are the centers of three circles of radii R_A, R_B, and R_C, respectively. Define $INTC3(R_A, R_B, R_C, \overline{AB}, \overline{AC}, \overline{BC})$

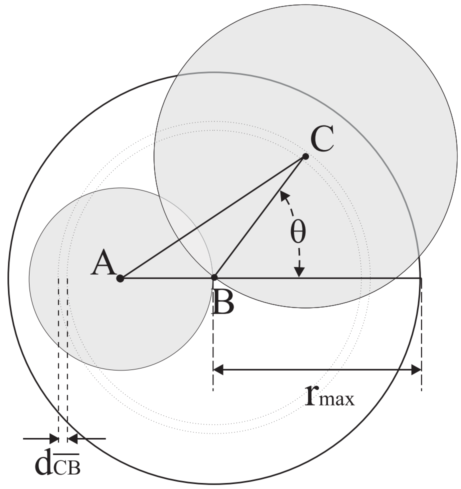


Figure 2.6: Analysis of the success probability of two nearby coexisting communication pairs (case $\overline{BC} \leq r_{max}$).

to be the area of the intersection of these three circles.

Case 1: $\overline{BC} \leq r_{max}$

In this case, host C can hear B's receive busy tone BT_r. Our protocol may grant the transmission $C \rightarrow D$ if the following events happen: (i) host C sends a RTS with a power level which reaches B with a power level P_{noise}, (ii) D hears C's RTS and returns a CTS. Note that (ii) can succeed only if D is within the range of C's RTS, but is out of range of A's BT_t. In Fig. 2.6, we draw a possible relationship among hosts A, B, and C, where the circles centered at A, B, and C indicate the transmission ranges of A's BT_t, B's BT_r, and C's RTS, resepctively.

Without loss of generality, let B be a reference point, A be on B's left-hand side, and the angle between $\overrightarrow{BC}$ and the x-axis be θ (refer to Fig. 2.6). Note that D could be located in any place at a distance of r_{max} from C. If D is within the circle centered at C, but not in the circle centered at A, the transmission $C \rightarrow D$ will be granted. Let's denote by $p_1(\overline{AB}, \overline{CB}, \theta)$ the value of $Prob(C \rightarrow D)$ under this instance. The success probability is

$$p_1(\overline{AB}, \overline{CB}, \theta) = \frac{\pi \overline{CB}^2 - INTC(\overline{AB}, \overline{CB}, \overline{AC})}{\pi r_{max}^2}, \qquad (2.4)$$

where $\overline{AC} = \sqrt{(\overline{CB}\sin\theta)^2 + (\overline{AB} + \overline{CB}\cos\theta)^2}$. The numerator is the area of the circle centered at C with radius $\overline{CB}$ excluding the intersection of the gray circles centered at A and C. The demoninator is the area that D may be located.

For a fixed $\overline{AB}$, the average success probability can be obtained by integrating the value in Eq. (2.4) for $\theta = 0..2\pi$ and then integrating the result for $\overline{CB} = 0..r_{max}$:

$$\int_0^{r_{max}} \left(\frac{2\pi\overline{CB}}{\pi r_{max}^2} \int_0^{2\pi} \left(\frac{p_1(\overline{AB}, \overline{CB}, \theta)}{2\pi} \right) d\theta \right) d\overline{CB}. \tag{2.5}$$

Finally, integrating the value in Eq. (2.5) for $\overline{AB} = 0..r_{max}$, we obtain

$$Prob(C \to D) = \int_0^{r_{max}} \left(\frac{2\pi\overline{AB}}{\pi r_{max}^2} \int_0^{r_{max}} \left(\frac{2\pi\overline{CB}}{\pi r_{max}^2} \int_0^{2\pi} \frac{p_1(\overline{AB}, \overline{CB}, \theta)}{2\pi} d\theta \right) d\overline{CB} \right) d\overline{AB}.$$

On the contrary, in the DBTMA protocol, as C can hear B's receive busy tone BT_r, the RTS/CTS dialogue will fail. So the probability $Prob(C \to D) = 0$ for the DBTMA.

Case 2: $r_{max} < \overline{BC} \leq 3r_{max}$

In this case, host C can not hear B's receive busy tone BT_r. So C's RTS will be sent with power level P_{max}. Let's follow the model in the previous section. There is no change on the radii of the circles centered at A and B, but radius of the circle centered at C becomes r_{max}. Still, the transmission $C \to D$ will be granted if D is inside C's transmission range, but outside A's transmission range. The main difference is that the circles centered at A and C may or may not intersect. Fig. 2.7 illustrates this difference: when C is located at C_1, there is not intersection, but when C is at C_2, there is some intersection.

First, given fixed $\overline{AB}$, $\overline{CB}$, and θ, we recalculate the success probability

$$p_2(\overline{AB}, \overline{CB}, \theta) = \frac{\pi r_{max}^2 - INTC(\overline{AB}, r_{max}, \overline{AC})}{\pi r_{max}^2}. \tag{2.6}$$

For a fixed $\overline{AB}$, the average success probability can be obtained by integrating the value in Eq. (2.6) for $\theta = 0..2\pi$ and then integrating the result for $\overline{CB} = r_{max}..3r_{max}$:

$$\int_{r_{max}}^{3r_{max}} \left(\frac{2\pi\overline{CB}}{3^2\pi r_{max}^2 - \pi r_{max}^2} \int_0^{2\pi} \left(\frac{p_2(\overline{AB}, \overline{CB}, \theta)}{2\pi} \right) d\theta \right) d\overline{CB}. \tag{2.7}$$

Finally, integrating the value in Eq. (2.7) for $\overline{AB} = 0..r_{max}$, we obtain

$$Prob(C \to D) = \int_0^{r_{max}} \left(\frac{2\pi\overline{AB}}{\pi r_{max}^2} \int_{r_{max}}^{3r_{max}} \left(\frac{2\pi\overline{CB}}{3^2\pi r_{max}^2 - \pi r_{max}^2} \int_0^{2\pi} \left(\frac{p_2(\overline{AB}, \overline{CB}, \theta)}{2\pi} \right) d\theta \right) d\overline{CB} \right) d\overline{AB}.$$

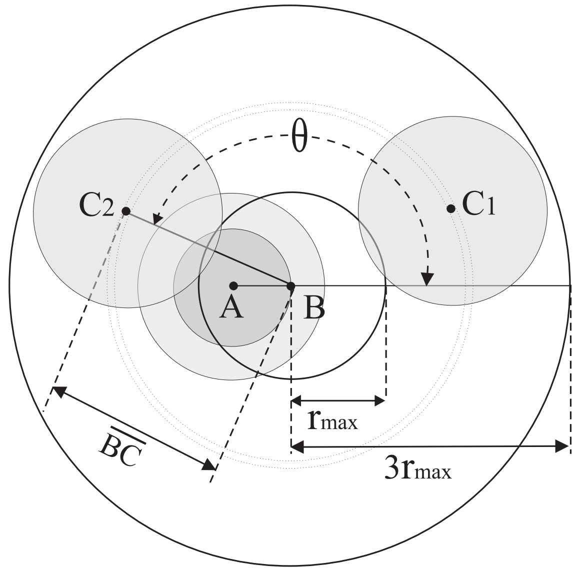


Figure 2.7: Analysis of the success probability of two nearby coexisting communication pairs (case $r_{max} < \overline{BC} \leq 3r_{max}$).

The main difference in the DBTMA protocol as opposed to ours is that host A will use power P_{max} to transmit its BT_t. This will reduce the probability for D to reply C's RTS. So the success probability needs to be recalculated:

$$p_3(\overline{AB}, \overline{CB}, \theta) = \frac{\pi r_{max}^2 - INTC(r_{max}, r_{max}, \overline{AC})}{\pi r_{max}^2}. \tag{2.8}$$

Clearly, $p_3 \leq p_2$. Substituting p_3 for the p_2 in Eq. (2.4.1), we will have the $Prob(C \rightarrow D)$ of DBTMA.

2.4.2 Analysis of Channel Utilization

This subsection derives the *channel utilization* of our protocol, where channel utilization is the average aggregrate time used for successful data transmission in a physical area at every instant. Our analysis follows the model in [29, 40]. Each host is a Poisson source with a packet arrival rate of λ. Hosts are randomly distributed in an area S_{area} with density ρ. With power control, the average distance of all sender-receiver pairs can be written as $R = r_{max}/\sqrt{2}$. To simplify the analysis, every unsuccessful data packet is destroyed by the transmitter.

Consider a pair of hosts A and B intending to communicate. The probability $Prob(A \rightarrow$

B) can be formulated as:

$$\begin{aligned} Prob(A \rightarrow B) = \; & Prob(\text{RTS successful}) \cdot Prob(\text{CTS successful} \mid \text{RTS successful}) \cdot \\ & Prob(\text{data successful} \mid \text{CTS successful}). \end{aligned}$$

Host A's RTS will succeed if there is no other transmissions that can corrupt B's reception during its vulnerable period, so

$$Prob(\text{RTS successful}) = e^{-(2\gamma+\tau)\lambda(\rho\pi R^2-1)} \tag{2.9}$$

where γ is the transmission time of a control packet and τ is the propagation delay.

After receiving A's RTS, B will set its BT_r on and reply a CTS. All nodes that are in B's BT_r range but not in A's RTS range are hidden terminals to A. The number of such hosts is:

$$N_{ht} = \rho\pi r_{max}^2 - INTC(\overline{AB}, r_{max}, \overline{AB}).$$

So the probability that the CTS is successful depends on whether any of these hidden terminals starts any transmission during the propagation period τ which can potentially corrupt the transmission $A \rightarrow B$, i.e.,

$$\begin{aligned} & Prob(\text{CTS successful} \mid \text{RTS successful}) = \\ & \quad e^{-\tau\lambda N_{ht}} + (1 - e^{-\tau\lambda N_{ht}}) Prob(\text{harmless hidden terminal}), \end{aligned}$$

where the first part is the probability that no hidden terminals start any transmission during a τ period, and the second part that some hidden terminal starts a transmission but is harmless to $A \rightarrow B$.

To find $Prob$(harmless hidden terminal), suppose C is a hidden terminal to A. Also, let D be C's intended communication party (refer to Fig. 2.8, where D_1, D_2, D_3, D_4 are four possible locations of D.). We analyze the effect of the hidden terminal C depending on the location of D:

1. D in A's RTS range: The transmission $C \rightarrow D$ will be prohibited by A's RTS (e.g., D_1 in Fig. 2.8).

2. D in B's CTS range: The transmission $C \rightarrow D$ will fail because C's RTS and B's CTS will collide in D (e.g., D_2 in Fig. 2.8).

3. D in the circle centered at C with radius $\overline{BC}$: The transmission $C \to D$, no matter being granted or not, will not corrupt the transmission $A \to B$ (e.g., D_3 in Fig. 2.8).

4. D in C's RTS range, but not falling in the above three cases: The transmission will corrupt the transmission $A \to B$ (e.g., $D4$ in Fig. 2.8).

So the only harmful area is what identified in item 4, and the harmless area is the circle centered at C with radius r_{max} excluding this area,

$$\begin{aligned} H_{area}(A,B,C) =& \pi\overline{CB}^2 + \\ & INTC(r_{max}, r_{max}, \overline{CB}) - INTC(\overline{CB}, r_{max}, \overline{BC}) + \\ & INTC(r_{max}, \overline{AB}, \overline{AC}) - INTC(\overline{CB}, \overline{AB}, \overline{AC}) + \\ & INTC3(\overline{CB}, r_{max}, \overline{AB}, \overline{BC}, \overline{AC}, \overline{AB}) - \\ & INTC3(r_{max}, r_{max}, \overline{AB}, \overline{AB}, \overline{BC}, \overline{AC}) \end{aligned} \tag{2.10}$$

Thus, C is a harmless hidden terminal with probability $\frac{H_{area}(A,B,C)}{\pi r_{max}^2}$. Integrating this probability over all possible locations of C, we have

$$Prob(\text{harmless hidden terminal}) = \frac{1}{\pi r_{max}^2 - INTC(r_{max}, \overline{AB}, \overline{AB})} \int_0^{r_{max}} \left(\int_0^{\cos^{-1}\frac{\overline{BC}^2}{2\overline{AB}\cdot\overline{BC}}} \left(\frac{H_{area}(A,B,C)}{\pi r_{max}^2} \right) d\theta_C \right) d\overline{BC}$$

where θ_C is the angle shown in Fig. 2.8.

Once both busy tones BT_t and BT_r are set up correctly, A's data packet will be sent correctly. So $Prob(\text{data successful} \mid \text{CTS successful}) = 1$. This leads to

$$Prob(A \to B) = e^{-\lambda(2\gamma+\tau)\lambda(\rho\pi R^2-1)} \left(e^{\tau\rho R(\pi R + \overline{AB}\sin\theta - 2R\theta)} + (1 - e^{\tau\rho R(\pi R + \overline{AB}\sin\theta - 2R\theta)}) Prob(\text{harmless hidden terminal}) \right).$$

Let's define a busy period as the period between two consecutive idle periods. There are two types of busy periods: successful transmission period and unsuccessful transmission period. The expected time of a busy period is then:

$$\overline{B} = T_s Prob(A \to B) + T_f(1 - Prob(A \to B)),$$

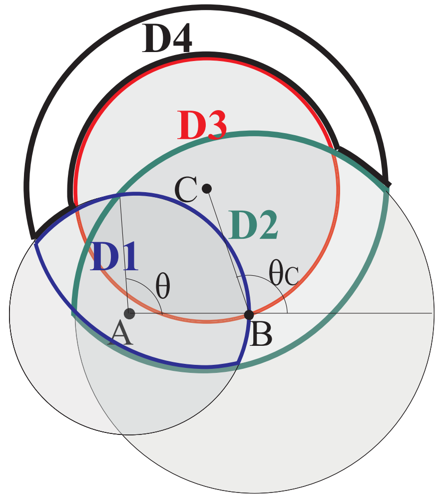


Figure 2.8: Analysis of harmful/harmless hidden terminals.

where T_s is the expected time of a successful transmission period, and T_f is the expected time of an unsuccessful transmission period. A successful transmission time consists of an RTS packet transmission time, a CTS packet transmission time, and a data packet transmission time (δ), each followed by propagation time τ:

$$T_s = 2\gamma + 3\tau + \delta.$$

An unsuccessful transmission period consists of an RTS packet transmission time followed by τ and a collision time before the channel becomes idle again [40]:

$$T_f = \gamma + 2\tau - \frac{1 - e^{-\tau\lambda\rho\pi R^2}}{\lambda\rho\pi R^2}.$$

An idle period is the time between two consecutive busy periods. According to the property of a Poisson process, the expected time of an idle period is:

$$\overline{I} = \frac{1}{\lambda\rho\pi R^2}.$$

So the average utilization period can be expressed as:

$$\overline{U} = \delta Prob(A \rightarrow B),$$

which gives the effective channel utilization ratio:

$$T(A \rightarrow B) = \frac{\overline{U}}{\overline{B} + \overline{I}}.$$

As the above analysis is only for a particular value of $\overline{AB}$ (which may range from 0 to R), taking this into consideration through integration, we have the average channel utilization

$$\overline{T} = \frac{1}{\lambda \rho \pi R^2} \int_0^R \left(\rho 2\pi \overline{AB} \cdot T(A \to B) \right) d\overline{AB}. \tag{2.11}$$

In the area S_{area}, the *maximum number of concurrent transmission pairs* can be conservatively approximated by $m = S_{area}/(3\sqrt{3}R^2/2)$, where the denominator is the area of a hexagon of side length R. So the aggregated channel utilization in the area S_{area} is $m\overline{T}$.

2.5 Discrete Power Control

In practice, the levels of power provided by the physical layer may not be infinitely tunable. A more reasonable assumption is that only a certain number of (discrete) power levels are offered. In this section, we try to answer the question: given a fixed integer k, how to determine k power levels to maximize channel utilization.

Throughout this section, our development is based on Eq. (2.1) and we will assume that $n = 2$. Observe that channel utilization is proportional to the number of concurrent transmitting hosts in the MANET, which is in turn proportional to number of non-overlapping circles of radius r_{avg} that can coexist in a physical area, where r_{avg} is the average transmission distance in our protocol. Since the average of power levels, P_{avg}, used for transmission is proportional to r_{avg}^n, to maximize channel utilization we should minimize the expected value $E(P_{avg})$.

In the following, when $n = 2$ we show that evenly spreading the k power levels is the best choice.

Lemma 1 *When $n = 2$ in Eq. (2.1), given an integer k, the k power levels, $\frac{1}{k}P_{max}$, $\frac{2}{k}P_{max}$, ... , and $\frac{k}{k}P_{max}$, will give the minimum $E(P_{avg}) = \frac{k+1}{2k}P_{max}$.*

Proof.

Induction Basis: When $k = 2$, assume that a power P_x is offered other than the maximum power P_{max}. Let r_x and r_{max} be the radii of the circles that can be covered by these two power levels, respectively. By Eq. (2.1), we have $P_x/P_{max} = r_x^2/r_{max}^2$. As a receiver is randomly distributed around a sender within a distance r_{max}, the sender has a probability $\frac{\pi r_x^2}{\pi r_{max}^2}$ to use power P_x, and $\frac{\pi r_{max}^2 - \pi r_x^2}{\pi r_{max}^2}$ to use P_{max}. So the expected power level being used is:

$$\begin{aligned} E(P_{avg}) &= P_x \frac{\pi r_x^2}{\pi r_{max}^2} + P_{max} \frac{\pi r_{max}^2 - \pi r_x^2}{\pi r_{max}^2} \\ &= P_x \frac{P_x}{P_{max}} + P_{max}(1 - \frac{P_x}{P_{max}}). \end{aligned}$$

Letting the differentiation $E'(P_{avg}) = 0$, we have $E'(P_{avg}) = \frac{2P_x}{P_{max}} - 1 = 0$. So $P_x = \frac{P_{max}}{2}$, which gives $E(P_{avg}) = \frac{3}{4}P_{max}$.

Induction Hypothesis: Assume that with the $k-1$ power levels, $\frac{1}{k-1}P_{max}, \frac{2}{k-1}P_{max}, \dots, \frac{k-1}{k-1}P_{max}$, the $E(P_{avg}) = \frac{k}{2(k-1)}P_{max}$ is the minimum.

Induction Step: Now assume that the second largest power level is P_x. By the induction hypothesis, the power levels should be arranged as $\frac{1}{k-1}P_x, \frac{2}{k-1}P_x, \dots, \frac{k-1}{k-1}P_x, P_{max}$. Again, let r_x be the radius of the circle that can be covered by power P_x. A sender has a probability $\frac{\pi r_x^2}{\pi r_{max}^2}$ to use power levels $\leq P_x$, and $\frac{\pi r_{max}^2 - \pi r_x^2}{\pi r_{max}^2}$ to use P_{max}. So the expected power level being used is:

$$\begin{aligned} E(P_{avg}) &= \frac{kP_x}{2(k-1)} \cdot \frac{\pi r_x^2}{\pi r_{max}^2} + P_{max} \frac{\pi r_{max}^2 - \pi r_x^2}{\pi r_{max}^2} \\ &= \frac{kP_x}{2(k-1)} \cdot \frac{P_x}{P_{max}} + P_{max}(1 - \frac{P_x}{P_{max}}). \end{aligned}$$

Letting the differentiation $E'(P_{avg}) = 0$, we have $E'(P_{avg}) = \frac{P_x k}{(k-1)P_{max}} - 1 = 0$. So we have $P_x = \frac{k-1}{k}P_{max}$, which gives $E(P_{avg}) = \frac{k+1}{2k}P_{max}$. As $E(P_{avg}) \to \frac{P_{max}}{2}$ as $k \to \infty$, this also tells us that the theoretical upper bound for channel utilization improvement is at most two times that without power control. □

We comment that when n is of other values, the derivation will be similar.

2.6 Simulation Results

We have developed a simulator to verify the performance of our scheme and compare our result to the DBTMA protocol. A MANET with a certain number of mobile hosts which may roam around in a physical area was simulated. The simulation parameters are listed below.

- physical area = $8km \times 8km$
- maximum transmission distance (r_{max}) = 0.5 or 1.0 km
- number of mobile hosts = 600
- speed of mobile host = 0 or 125 Km/hr.
- length of control packet = 100 bits
- link speed = 1 Mbps
- transmission bit error rate = 10^{-5}/bit

Data packets were generated to the MANET by a Poisson distribution. For each packet, we randomly chose one of the mobile host as the source node and a neighbor host within distance r_{max} as the receiver. We varied the number of data packets injected into the MANET and observed the channel utilization in the area.

Fig. 2.9 shows the channel utilization of the DBTMA and our protocols at different traffic loads when $r_{max} = 0.5$ km. Data packets length is fixed at 1000 bits. From Fig. 2.9(a), we see that the DBTMA protocol will saturate at around load = 600 packets/ms, while our protocol at around load = 800 packets/ms. Also, our protocol can deliver a channel utilization about 2 times that of the DBTMA. Moving to Fig. 2.9(b) and (c), where $r_{max} = 1.0$ km and 2.0 km, respectively, we observe that both protocols will saturate at lower loads. This is reasonable because a larger transmission distance means a more crowded environment (signals are more likely to overlap with each). As comparing these three figures, we further see that a larger transmission distance r_{max} will slightly favor our protocol (the gap between DBTMA and our protocols enlarges slightly). Hence power control is of more importance in more crowded environments.

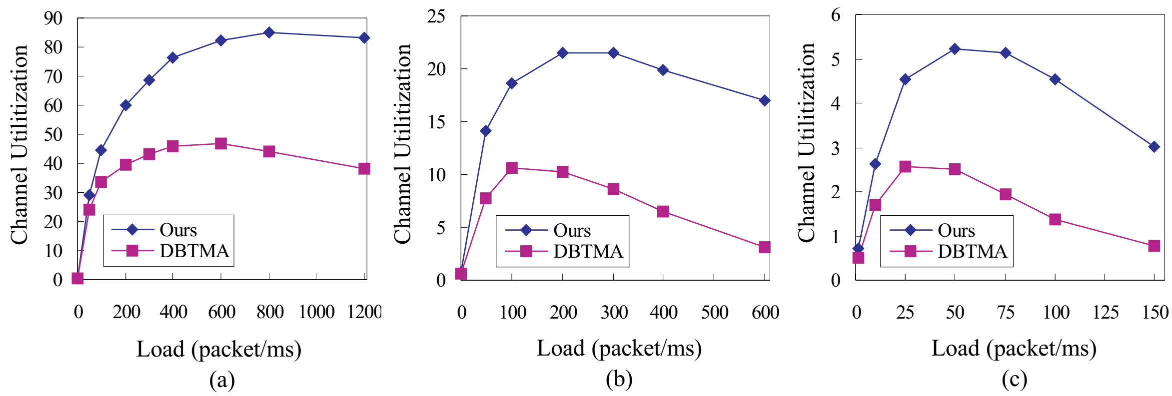


Figure 2.9: Channel utilization vs. traffic load when (a) $r_{max} = 0.5$ km, (b) $r_{max} = 1.0$ km, and (c) $r_{max} = 2.0$ km.

Next, we observe the effect of packet length. Fig. 2.10 shows our simulation results when $r_{max} = 1.0$ km. As can be seen, longer data packets can deliver higher channel utilization. This shows an interesting result that longer packets are less vulnerable with busy tones and power control. This is perhaps because the hidden-terminal problem is less serious (less interruption/interference from hidden terminals).

The above simulations have used infinite power levels. We also simulated discrete power levels and observed its effect on channel utilization. Setting $r_{max} = 1$ km, arrival rate = 200 or 400 packets/ms, and packet length = 1 or 2 Kbits, Fig. 2.11 shows the channel utilization using different numbers of power levels. Apparently, more power levels enable a host to transmit with less interference to its surroundings, thus giving higher channel utilization. However, using 4 to 6 power levels can already deliver a channel utilization close to that of using infinite power levels. So it makes not much sense to have too many power levels. This shows the practical value of our result.

The previous simulations are based on no host mobility. Fig. 2.12 demonstrates the effect of host mobility. We compare the channel utilization when hosts have no mobility and when hosts move at 125 km/hr with random direction. (A speed of 125 km/hr means a very fast vehicle, such as cars on highways.) The results show that the effect of host mobility to channel utilization is very limited and thus negligible at the MAC layer, which is the same as the

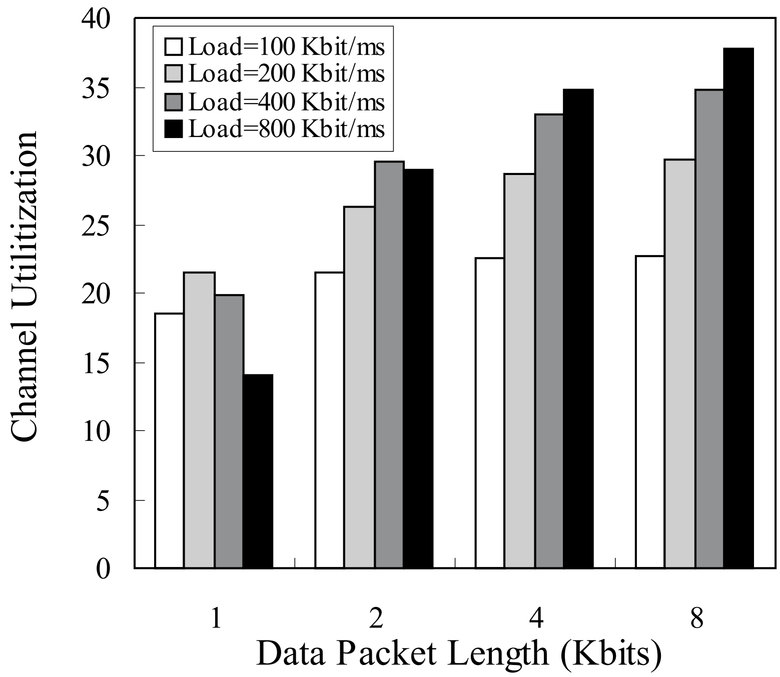


Figure 2.10: Channel utilization vs. data packet length at various traffic loads.

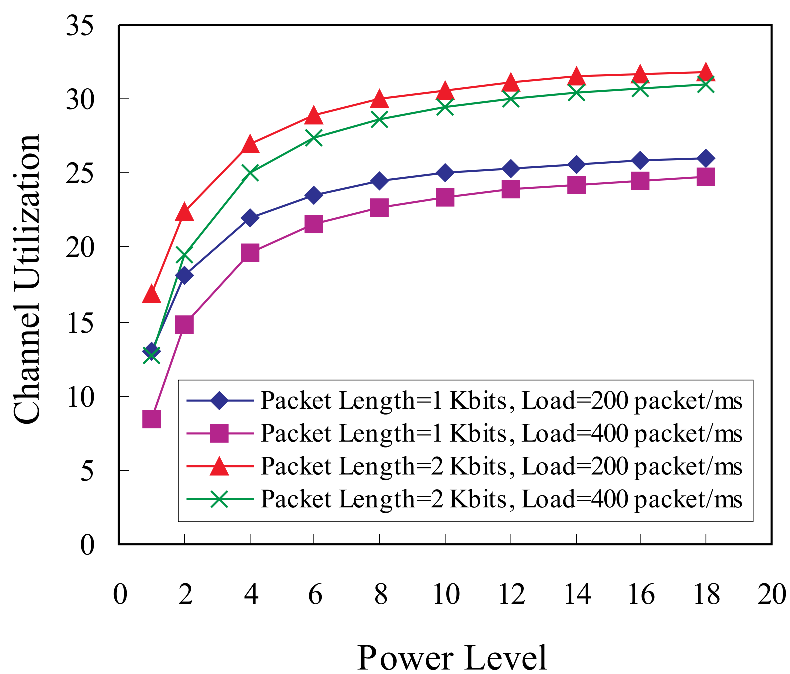


Figure 2.11: Channel utilization vs. number of power levels at $r_{max} = 1$ km, arrival rate = 200 or 400 packets/ms, and packet length = 1 or 2 Kbits.

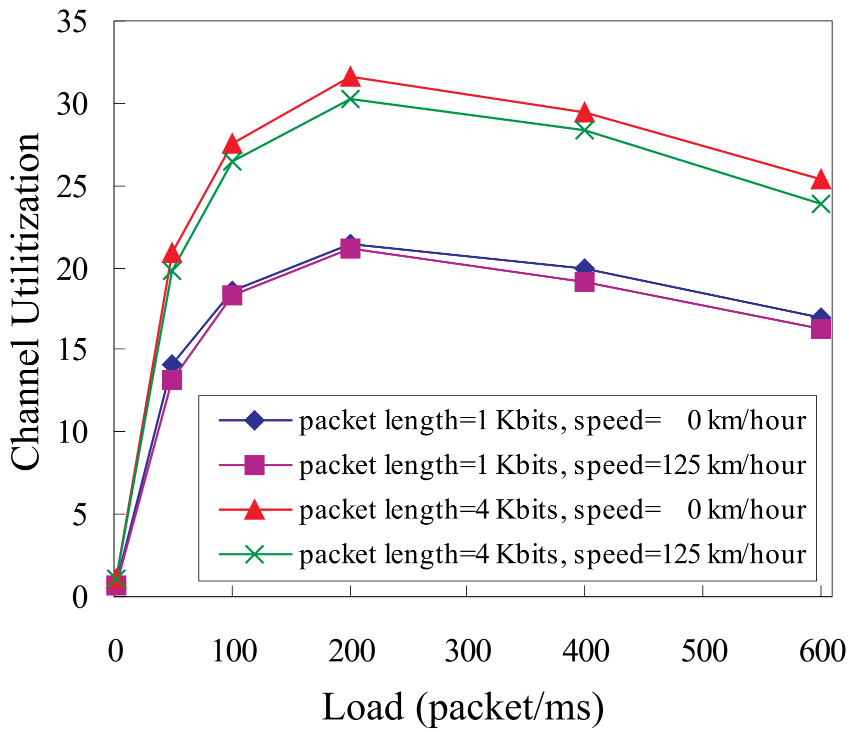


Figure 2.12: Channel utilization vs. traffic load when hosts have no mobility and when hosts move at 125 km/hr. The transmission distance $r_{max} = 1$ km.

observation in [17].

Finally, Fig. 2.13 compares the channel utilization obtained from our simulation against that from our analysis in Section 2.4.2 (i.e., $m\overline{T}$). The results in Fig. 2.13(a) are obtained from a physical area of size 1 km $\times$ 1 km with 50 mobile hosts each with a transmission distance of $r_{max} = 0.5$ km. This case represents a small value of $m = 3.07$ (recall that this is an estimation on the number of concurrent transmission pairs). The purpose here is to reduce the effect of error induced by m on the overall channel utilization. We can see that the peak theoretical utilization is slightly higher than the peak simulated utilization. We believe that this is because the theoretical analysis does not consider some timing factors (such as backoff, transmission delays, message preambles, etc.) which are considered in our simulations. However, as the load exceeds the throughput of the network, we see that the simulated utilization will outperform the theoretical utilization. We believe that this

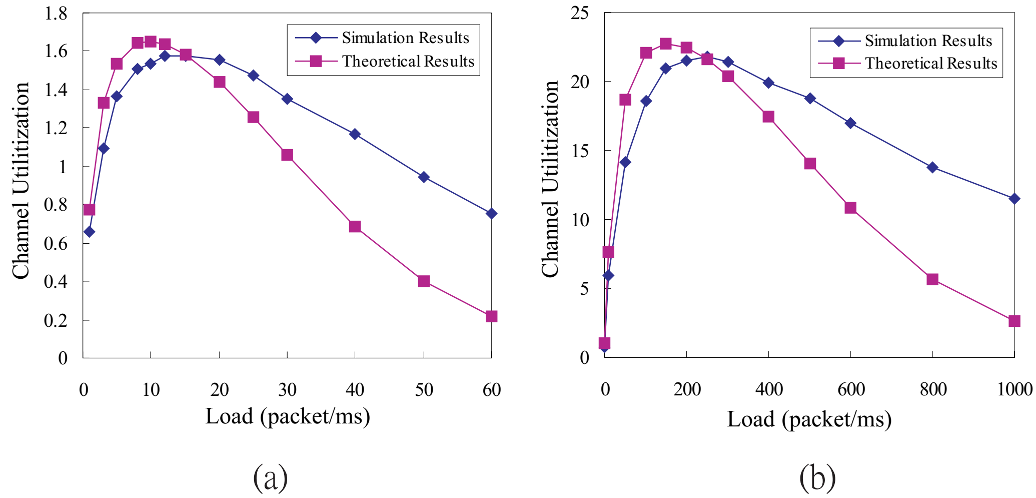


Figure 2.13: Simulated channel utilization vs. theoretical channel utilization: (a) in a 1 km × 1 km area with 50 mobile hosts, and (b) in a 8 km × 8 km area with 600 mobile hosts.

is because the probability $Prob$(RTS successful) in Eq. (2.9) is too conservative when the traffic load is high. This probability is to estimate the number of potential attackers on a RTS packet. The estimation has considered all potential attackers at a certain distance (R) from the receiver of this RTS. However, as the traffic load is high, many attackers will be prohibited by the earlier RTS/CTS dialogues in the surroundings. Similarly, the $Prob$(CTS successful | RTS successful) might be conservative, too, when the traffic load is high. This explains why after the peak utilization our simulated result will outperform the theoretical analysis in Fig. 2.13(a). The results in Fig. 2.13(b) are obtained from a physical area of size 8 km × 8 km with 600 mobile hosts each with a transmission distance of $r_{max} = 1.0$ km. This represents a larger value of $m = 49.27$. The trend is very similar to that in Fig. 2.13(a).

2.7 Summary

The main objective of MAC protocols is to arbitrate the accesses of communication medium among multiple mobile hosts. This is of more challenge in a MANET environment since radio signals from different antennas are likely to overlap with each other in many areas, thus serious wasting the medium. In this section, we have proposed a new MAC protocol for MANETs that utilizes the intelligence of power control on top of the RTS/CTS dialogues and busy tones. Channel utilization can be significantly increased because the severity of signal overlapping is reduced. Analyses and simulation results have all shown the advantages of using our protocol. As to future work, RTS/CTS is only one of the many possibilities to access wireless medium. Future research could be directed to applying the power-control concept to other domains. Recently, some works have addressed the possibility of using an intermediate relay node to transmit a packet in an indirect manner [32, 60], instead of transmitting a packet directly. It will be interesting to investigate further applying power control on this issue.

Chapter 3

Multi-Channel MAC Protocol with On-Demand Channel Assignment

This chapter 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) [11, 34, 37], some require a number of channels which is a function of the maximum connectivity [11, 23, 34, 37], and some necessitate a clock synchronization among all hosts in the MANET [37, 67]. Extensive simulations are conducted to evaluate the proposed protocol.

3.1 Introduction

A *mobile ad-hoc network (MANET)* is formed by a cluster of mobile hosts without the infrastructure of 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 station is required, one of its main advantages 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. Issues related to MANET have been studied intensively [23, 36, 42, 47, 54, 55, 67, 70, 81].

A *MAC (medium access control)* protocol is to address how to resolve potential contention and collision on using the communication medium. Many MAC protocols have been proposed for wireless networks [12, 21, 39, 41, 49, 48], which assume a common channel shared by mobile hosts. We call such protocols *single-channel MAC protocols*. 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 quickly 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. 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, 54], 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 [50].

Here, we use “channel” upon a logical level. Physically, a channel can be a frequency band (under FDMA), or an orthogonal code (under CDMA). How to access multiple channels is thus technology-dependent. Disregarding the transmission technology (FDMA or CDMA), we can categorize a mobile host based on its capability to access multiple channels as follows:

- *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 transceiver is still capable of switching from one channel to another channel.

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

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 [11, 16, 17, 19, 23, 34, 37, 52, 54, 67, 28, 84]. References [11, 16, 19, 34, 52] 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 [17, 84], 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 [37], 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 [28] 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 [23] 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 [54]. 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 [67]. 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 chapter, 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 3.1, 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 chaper is organized as follows. In Section 3.2, 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. Section 3.3 presents our multi-channel MAC protocol. Some analysis and simulation results are given in Section 3.4. Conclusions are drawn in Section 3.5.

Table 3.1: Comparison of multi-channel MAC protocols.

protocol	assignment	no_transceivers	no_channels	clock sync.	info. collected
[17, 84]	no need	2	2	no	none
[11, 16, 19, 34, 52]	static	1	deg.-dep.	no	global
[37]	static	n	deg.-indep.	yes	none
[28]	N/A	2	N/A	no	N/A
[23]	dynamic	2	deg.-dep.	no	2-hop
[54]	dynamic	n	deg.-indep.	no	none
[67]	dynamic	1	deg.-indep.	yes	none
ours	dynamic	2	deg.-indep.	no	1-hop

3.2 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.

3.2.1 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, ..., $n-1$, 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.

3.2.2 Some Observations

Below, we make some observations associated with the above SM protocol. 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. 3.1, 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.

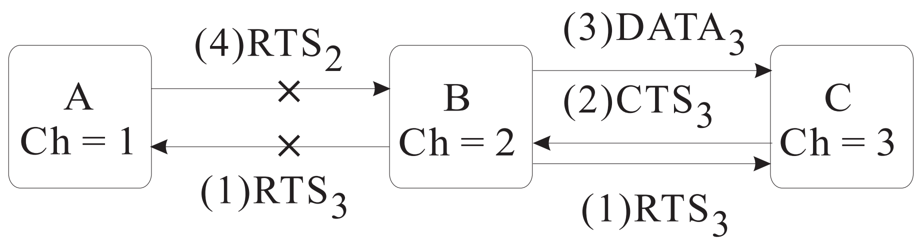


Figure 3.1: The problem of missing RTS in a multi-channel MAC. (The leading number on each message shows the message sequence; the subscript shows the channel on which the corresponding message is sent.)

- *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 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 [30, 36, 56, 58]. 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 [55], 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. 3.2, 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. 3.2, 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

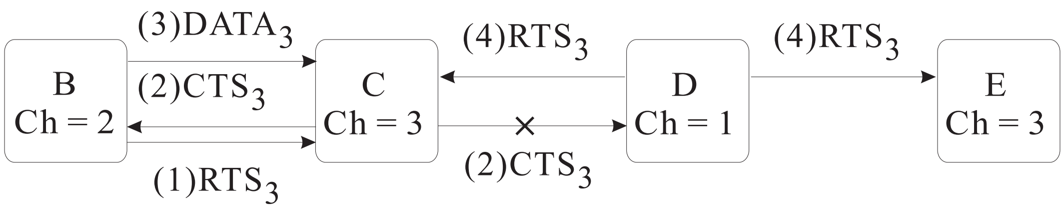


Figure 3.2: The problem of missing CTS in a multi-channel MAC.

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 [11, 23]), this problem can be eliminated.

- *Exposed-Terminal Problem:* Consider the exposed-terminal problem in Fig. 3.3, 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. 3.4, 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.

3.3 Our 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

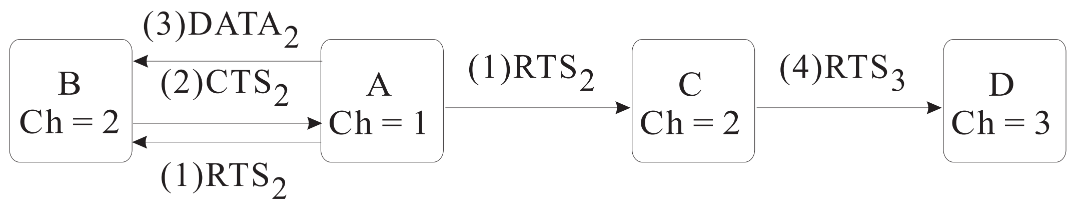


Figure 3.3: The exposed-terminal problem in a multi-channel MAC.

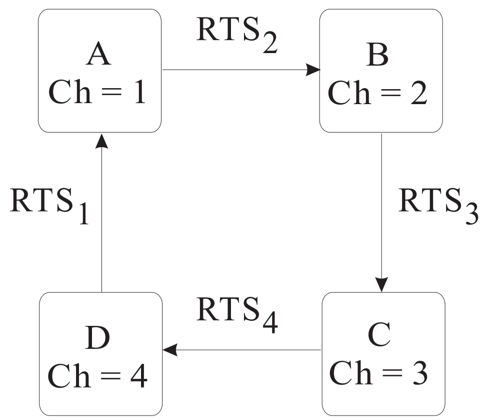


Figure 3.4: The channel deadlock problem in a multi-channel MAC.

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. 3.5, 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.

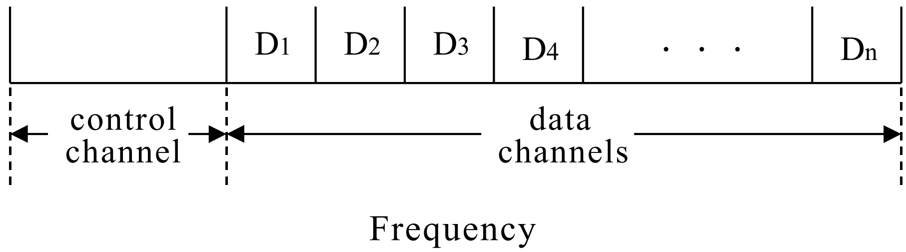


Figure 3.5: The channel model of our DCA protocol.

- *data transceiver:* This transceiver will dynamically switch to one of the data channels 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 3.2 lists the variables/constants used in our presentaiton.

Table 3.2: 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. 3.6 shows how the above timing is calculated.)

   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.

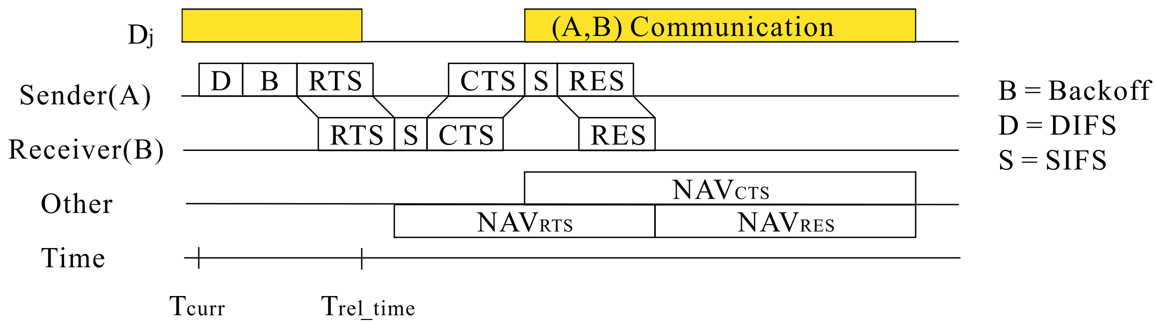


Figure 3.6: Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

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 → 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 $CTS(D_j, NAV_{CTS})$, 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.

3.4 Analysis and Simulation Results

3.4.1 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. 3.7, 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. 3.7 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 chapter, we consider two bandwidth models.

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

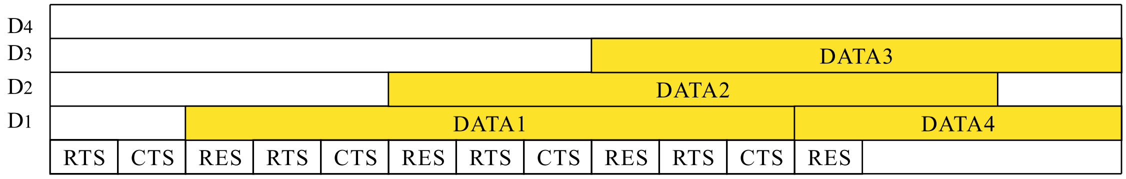


Figure 3.7: An example that the control channel is fully loaded and the data channel D_4 is not utilized.

a data packet by sending at least 3 control packets, the maximum number of data channels should be limited by

$$n \leq \frac{L_d}{3 \times L_c}. \tag{3.1}$$

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

$$U \leq \frac{n}{n+1}. \tag{3.2}$$

From Eq. (3.1) and Eq. (3.2), we derive that

$$\frac{U}{1-U} \leq n \leq \frac{L_d}{3 \times L_c} \Longrightarrow U \leq \frac{L_d}{3 \times L_c + L_d}. \tag{3.3}$$

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:

$$n \leq \frac{L_d/B_d}{3 \times L_c/B_c}. \tag{3.4}$$

Similarly, the utilization U must satisfy

$$U \leq \frac{n \times B_d}{n \times B_d + B_c}. \tag{3.5}$$

Combining Eq. (3.4) and Eq. (3.5) gives

$$\frac{UB_c}{B_d - UB_d} \leq n \leq \frac{L_d B_c}{3 \times L_c B_d} \Longrightarrow U \leq \frac{L_d}{3 \times L_c + L_d}. \tag{3.6}$$

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. (3.5), which gives

$$\frac{L_d}{3 \times L_c + L_d} = \frac{n \times B_d}{n \times B_d + B_c} \Longrightarrow \frac{B_c}{nB_d} = \frac{3L_c}{L_d}. \tag{3.7}$$

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.

3.4.2 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:

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

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

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 3.3. 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. 3.8 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 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 $((Ld+Lc)/3Lc)+1 = 11.3$

Table 3.3: 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

channels is unnecessary (see Eq. (3.1)). 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 [17]). 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 such probability).

Fig. 3.9 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

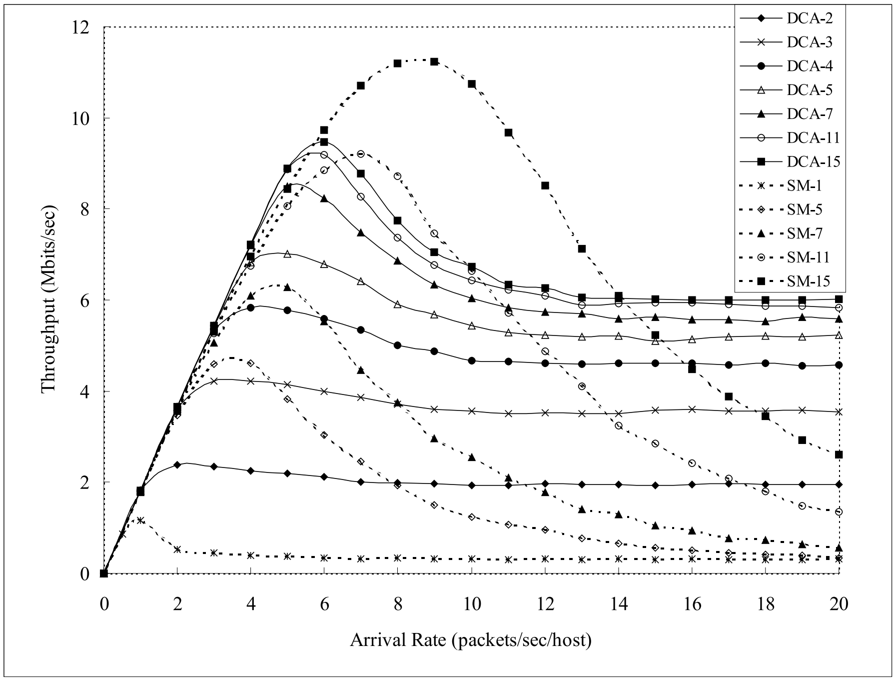


Figure 3.8: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

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 3.4.1, 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 performance 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. 3.10 shows the throughput under the fixed-channel-bandwidth model. According to Eq. (3.1),

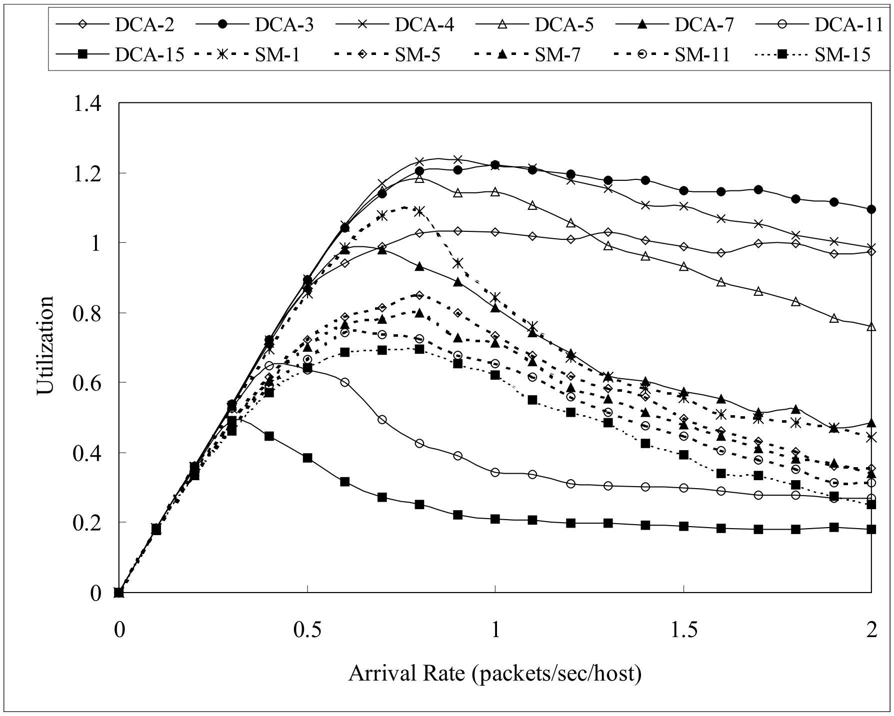


Figure 3.9: Arrival rate vs. utilization under the fixed-total-bandwidth model with different numbers of channels.

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. 3.10(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. 3.10(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. 3.11, 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.

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

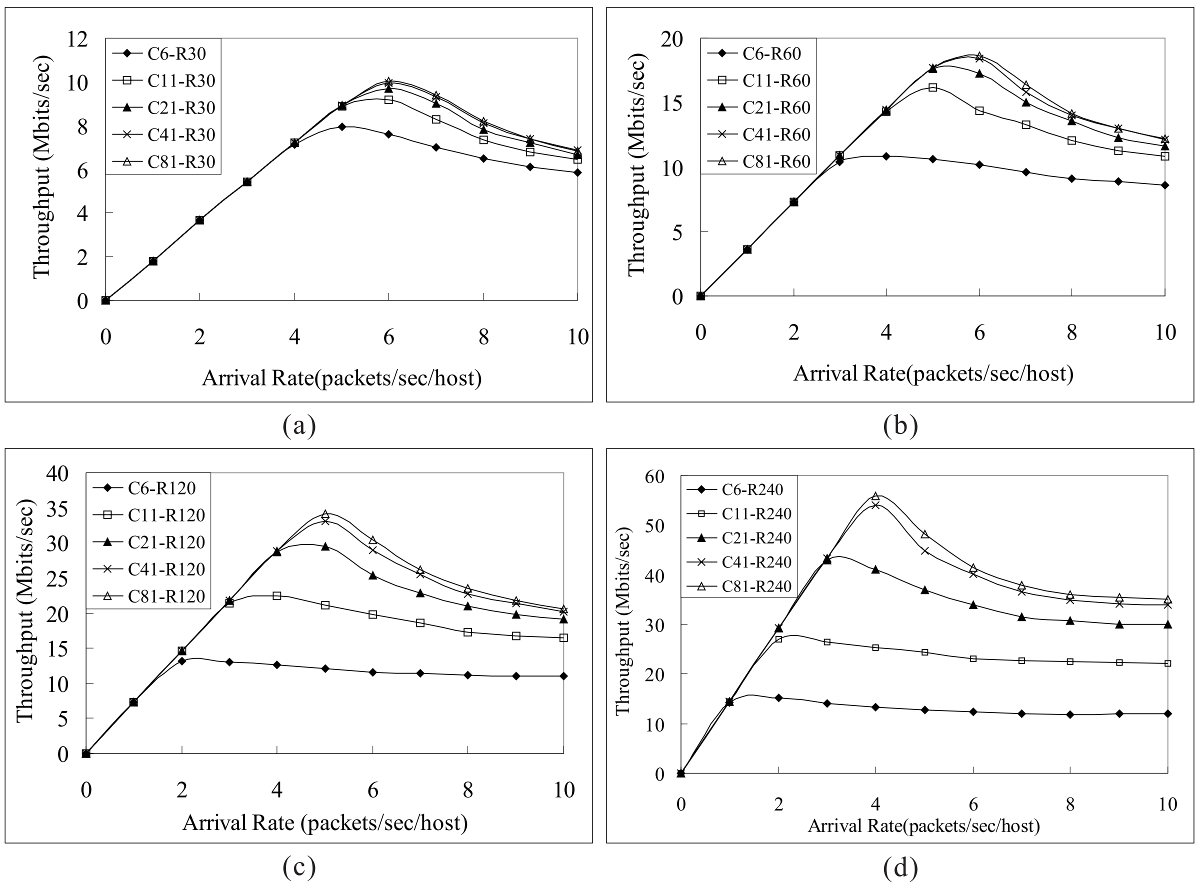


Figure 3.10: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different L_d/L_c ratios (Ci-Rj means using i channels, including control and data ones, with ratio $L_d/L_c = j$).

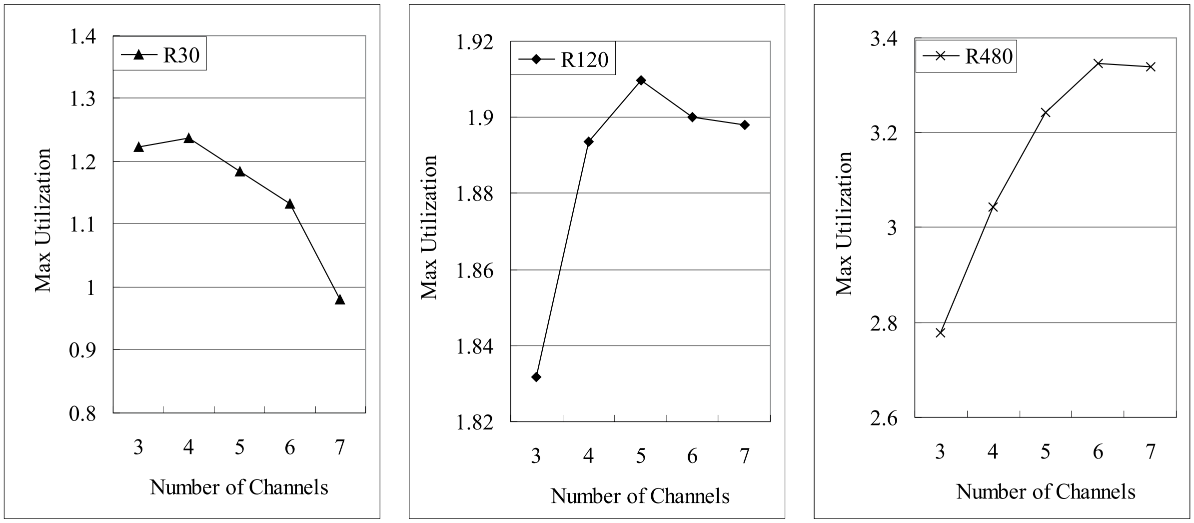


Figure 3.11: Number of channels vs. maximum utilization under the fixed-total-bandwidth model at different L_d/L_c ratios.

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. 3.12. 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. 3.13 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. This shows the practical value of our result.

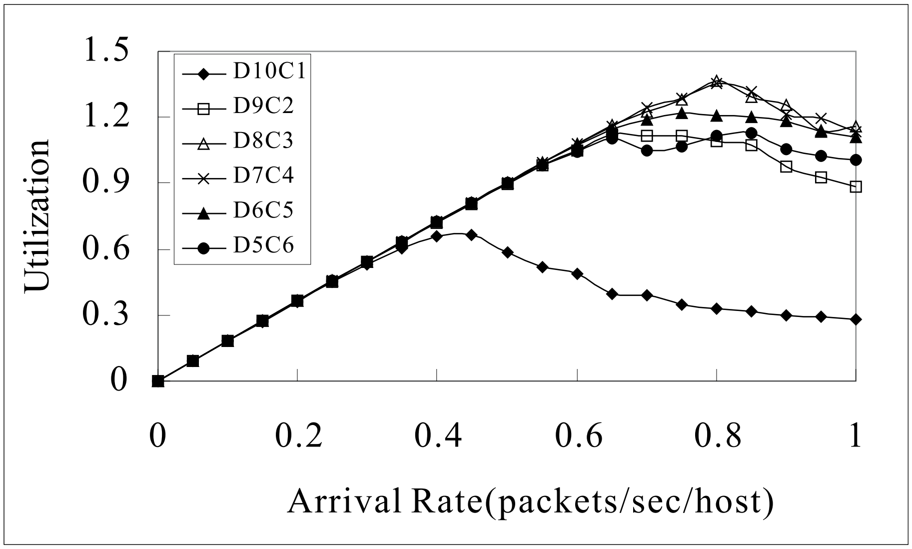


Figure 3.12: Arrival rate vs. throughput under the fixed-channel-bandwidth model given 11 channels (DiCj means using i data channels and j control channels).

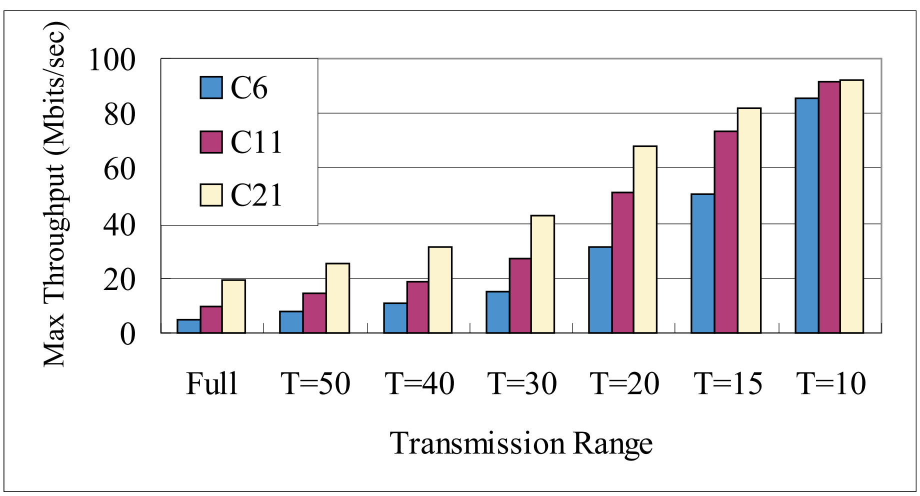


Figure 3.13: Transmission range vs. maximum throughput at different numbers of channels.

3.5 Summaries

In this section, 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 chapter 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).

Chapter 4

Multi-Channel MAC Protocol with Power Control

In a MANET, one essential issue is 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 [11, 16, 17, 19, 23, 28, 34, 37, 52, 54, 67] and power control [15, 20, 39, 74] to improve the performance of MANET. In this chapter, 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.

4.1 Introduction

This section 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 [12, 21, 39, 41, 48, 49]. 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 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 [17, 31] 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 [84], 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, 54], 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 [50].

In this section, we treat channels in 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 channel. (Under current technology, it is possible for a transceiver to switch from one channel to another at a short time period of $1\mu sec$ [2, 22].) 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 section, 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 4.2 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 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. On the contrary, most existing protocols assign channels to a host statically even if it has no intention to transmit [11, 34, 37], require a number of channels which is a function of the maximum connectivity [11, 23, 34, 37], or necessitate a clock synchronization among all hosts in the MANET [37, 67].

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 to improve the performance of a MANET.

The rest of this chapter is organized as follows. Some reviews on multi-channel medium access and power control are in Section 4.2. Section 4.3 presents our new multi-channel MAC protocol. Simulation results are given in Section 4.4. Conclusions are drawn in Section 4.5.

4.2 Reviews

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

4.2.1 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 [11, 16, 17, 19, 23, 28, 34, 37, 52, 54, 67, 84] in the literature.

References [11, 16, 19, 34, 52] 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 [17, 84], 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 [37], 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 [28] 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 [23] 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 [54]. 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 [67]. 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 [80] 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 chapter we try to integrate the concept of power control into the DCA protocol in [80]. Through this study, we hope to understand how much more benefit can be obtained on top of the DCA protocol.

4.2.2 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. For example, consider Fig. 4.1(a), where a communication from A to B is ongoing. The communication from C to D can not be granted because A's signal will interfere D. Similarly, the communication from E to F can not be granted because E can hear A's signal too. However, as shown in Fig. 4.1(b), 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 [84]. 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

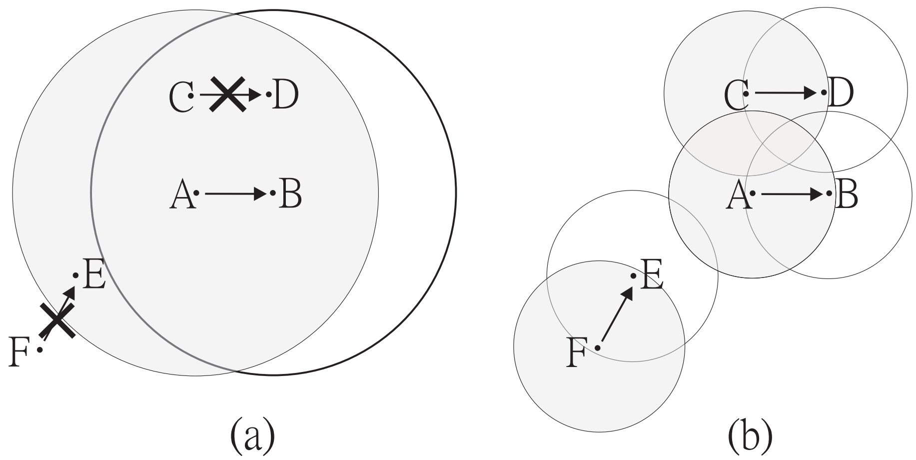


Figure 4.1: Transmission scenarios: (a) when there is no power control, and (b) when there is power control.

heard by Y with power P_r. According to [77], the following equation holds:

$$P_r = P_t(\frac{\lambda}{4\pi d})^n g_t g_r, \tag{4.1}$$

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:

$$P_Y = P_X(\frac{\lambda}{4\pi d})^n g_t g_r. \tag{4.2}$$

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. (4.2) by Eq. (4.1), which gives

$$\frac{P_X}{P_r} = \frac{P_Y}{P_t}. \tag{4.3}$$

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

The MACA [39] 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.

4.3 Our Multi-Channel MAC Protocol with Power Control

4.3.1 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 [80], 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:

- *control transceiver:* It operates on the control channel to exchange control packets with other mobile hosts and to obtain rights to access data channels.

- *data transceiver:* It 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 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 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, no matter the packets are intending for it or not (this is necessary in our protocol because the control channel is to serve this purpose). Then the formulation in Section 4.2.2 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. (4.3) 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. (4.3) 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 work, and one may incorporate any power-tuning scheme into our protocol.

4.3.2 The Protocol

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 four fields:
  - $CUL[i].host$: a neighbor host of X.

Table 4.1: 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

  - $CUL[i].ch$: a data channel used by $CUL[i].host$.
  - $CUL[i].rel\_time$: when channel $CUL[i].ch$ will be released by $CUL[i].host$.
  - $CUL[i].int$: whether the signals transmitted by $CUL[i].host$ on the data channel $CUL[i].ch$ will be overheard by X or not.

- $POWER[\,]$: 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.
- FCL: This 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 4.1 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

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

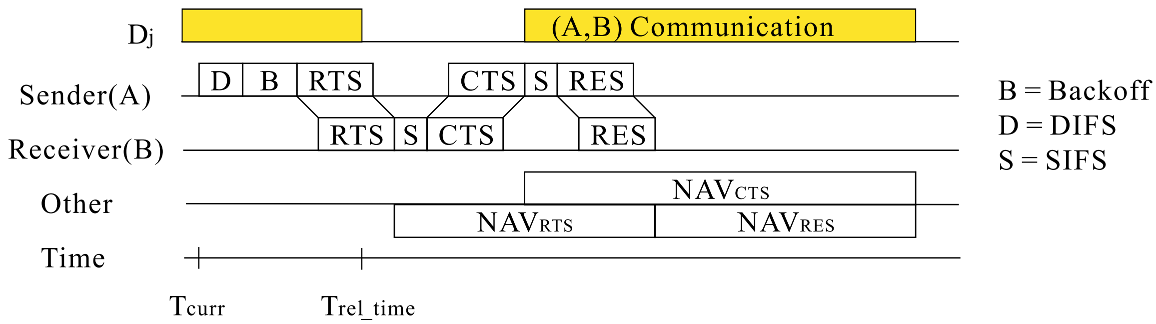


Figure 4.2: Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

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 exchange of RTS and CTS packets (Fig. 4.2 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 $\rightarrow$ 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 $CTS(D_j, NAV_{CTS}, P_{CTS})$, 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

$$NAV_{RES} = NAV_{CTS} - T_{SIFS} - T_{RES}$$
$$P_{RES} = POWER[B]$$

   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

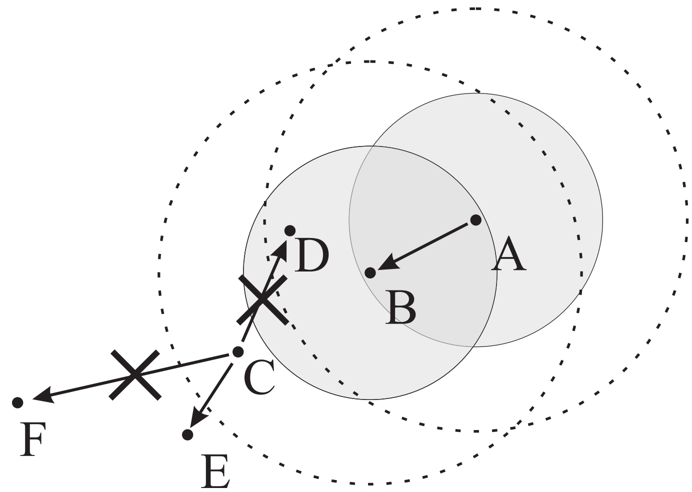


Figure 4.3: An example of our DCA-PC Protocol.

CUL such that:

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

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

Below, we show an example of our power control mechanism. In Fig. 4.3, 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 intending 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 intending 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 intending receiver is F, C will try to find a channel other than that used by A and B are using (again, this can be determined by C's $POWER[B]$ and $POWER[F]$).

4.4 Simulation Results

We have implemented a simulator to compare the performance of the proposed DCA-PC and our earlier DCA [84] 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. On the contrary, 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.

The parameters used in our simulations are listed in Table 4.2. 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

Table 4.2: Simulation parameters.

number of mobile hosts (except for part C)	200
no. of power levels (except for part D)	5
max. speed of a mobile host (except for part E)	36 km/hr.
physical area	100×100
transmission range	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

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. 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 more experiments, we will use 5 levels of power: $\frac{P_{max}}{5}, \frac{2P_{max}}{5}, \ldots, P_{max}$. 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.

A) Effect of the Number of Channels: In this experiment, we vary the number of channels to observe its effect. Fig. 4.4 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). So, under the fixed-total-bandwidth model, one must carefully pick the number of channels to maximize the benefit of our protocol. This is perhaps because the control channel is overloaded (it can not function well to distribute data channels to mobile hosts; the reason

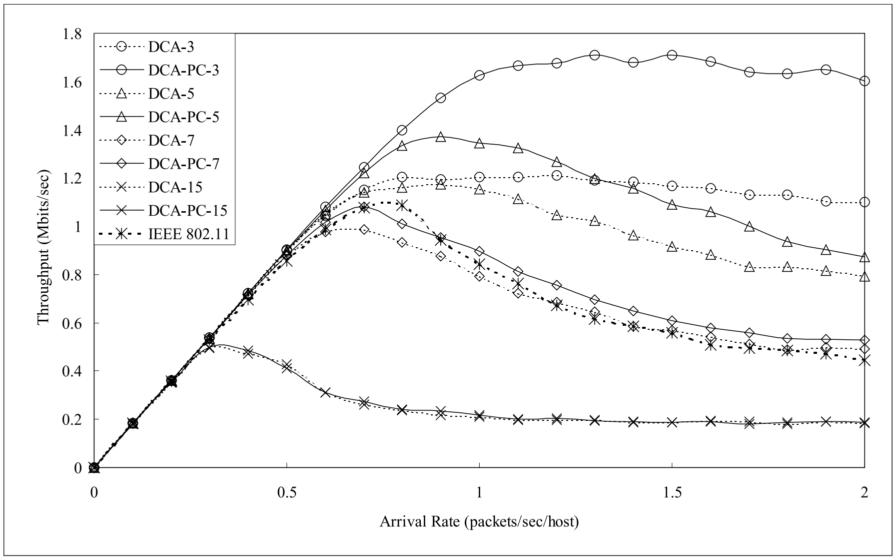


Figure 4.4: Arrival rate vs. throughput under the fixed-total-bandwidth model with different numbers of channels. (The number following each protocol indicates the number of channels, including control and data ones, used in the corresponding protocol.)

will become clear from simulation B).

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

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

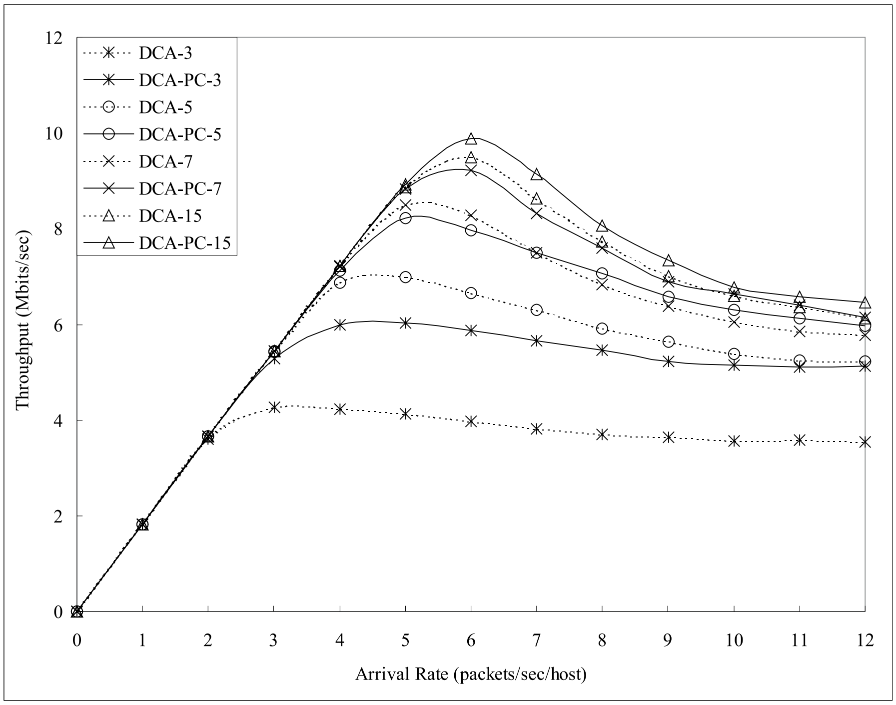


Figure 4.5: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of channels.

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_d/L_c under the fixed-channel-bandwidth model. The result is in Fig. 4.6, from which we see a clear trend that a larger ratio L_d/L_c is beneficial. We also observe that the gap between DCA-PC and DCA actually increases as the ratio L_d/L_c increases. This justifies our earlier reasoning. Also, note that in the experiment we didn't take transmission error rate into consideration, so the actual benefit may be saturated at a certain point of L_d/L_c ratio.

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 in Fig. 4.7, 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.

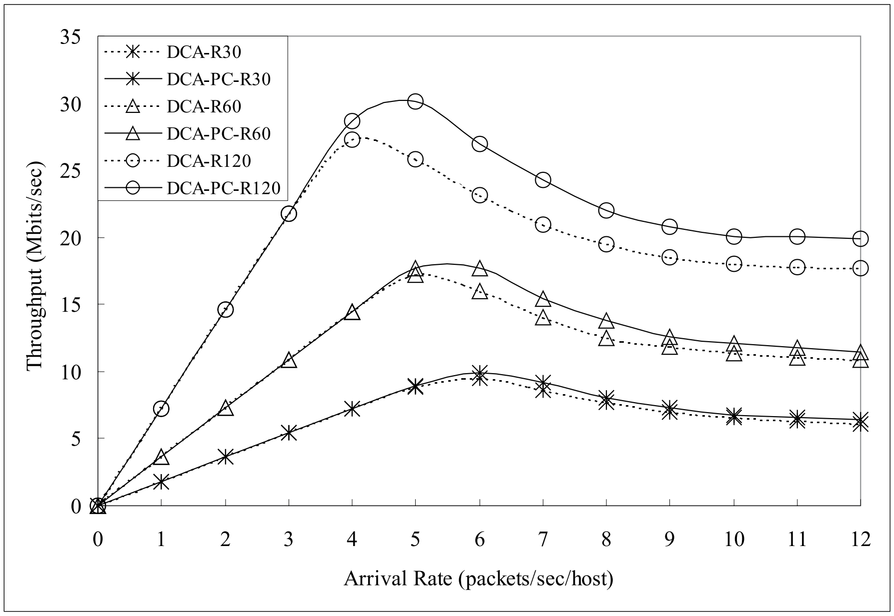


Figure 4.6: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different L_d/L_c ratios (Rj means the ratio $L_d/L_c = j$).

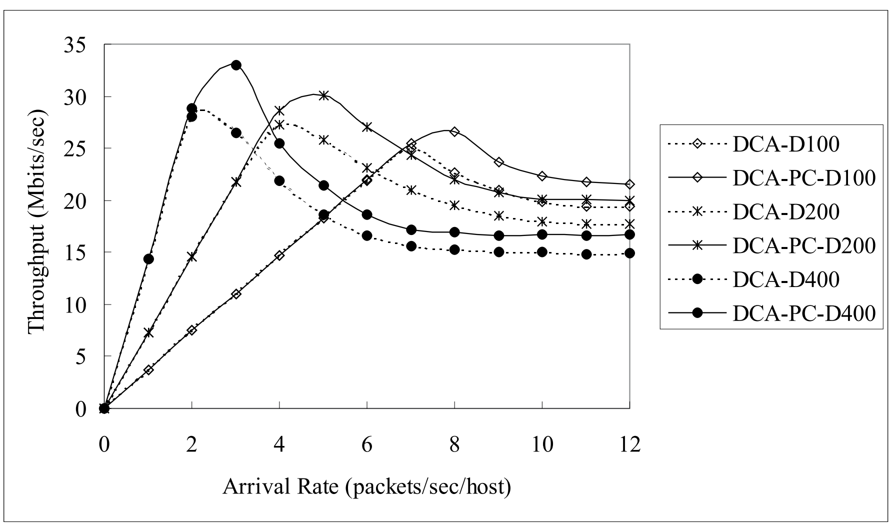


Figure 4.7: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different numbers of mobile hosts. (Di means i mobile hosts.)

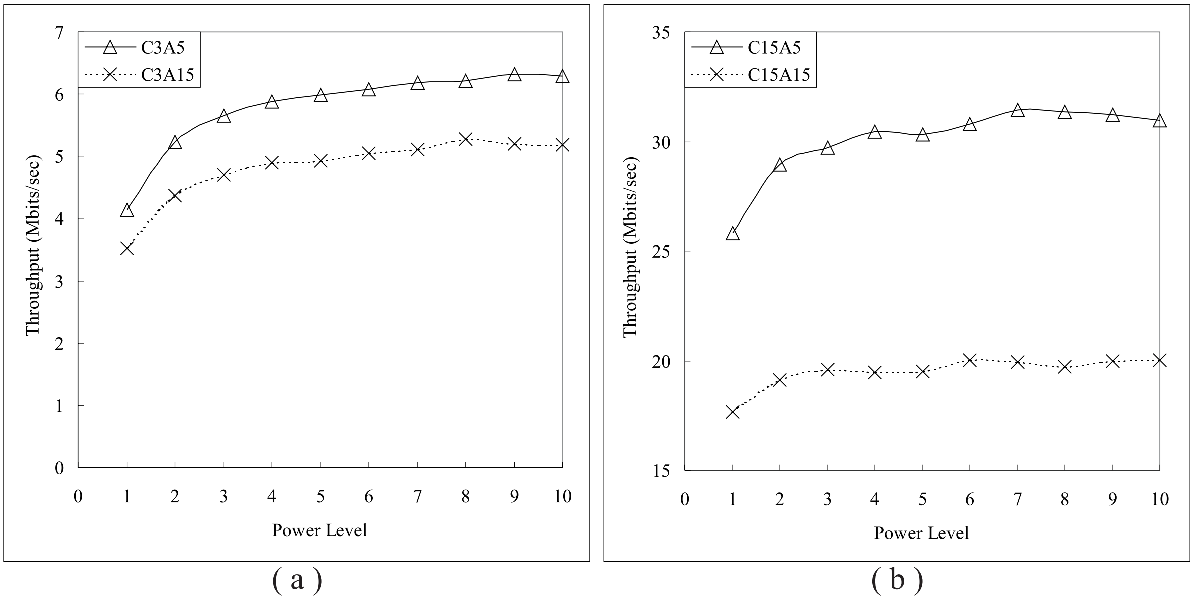


Figure 4.8: Number of power levels vs. throughput: (a) 3 channels with $L_d/L_c = 30$ and (b) 15 channels with $L_d/L_c = 120$. The number after "A" is the arrival rate (packets/sec/host). The peak throughput appears at around A5, while the saturated, but stable, throughput appears at around A15.

D) Effect of the Number of Power Levels: The above simulations all used a fixed number of 5 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. 4.8 (a) and (b) show that using $4 \sim 6$ and $2 \sim 3$ 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.

E) Effect of Host Mobility: In all the above experiments, mobile hosts roam at a speed randomly chosen between 0 to 36 km/hr. 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 in Fig. 4.9. The trend does show that our DCA-PC

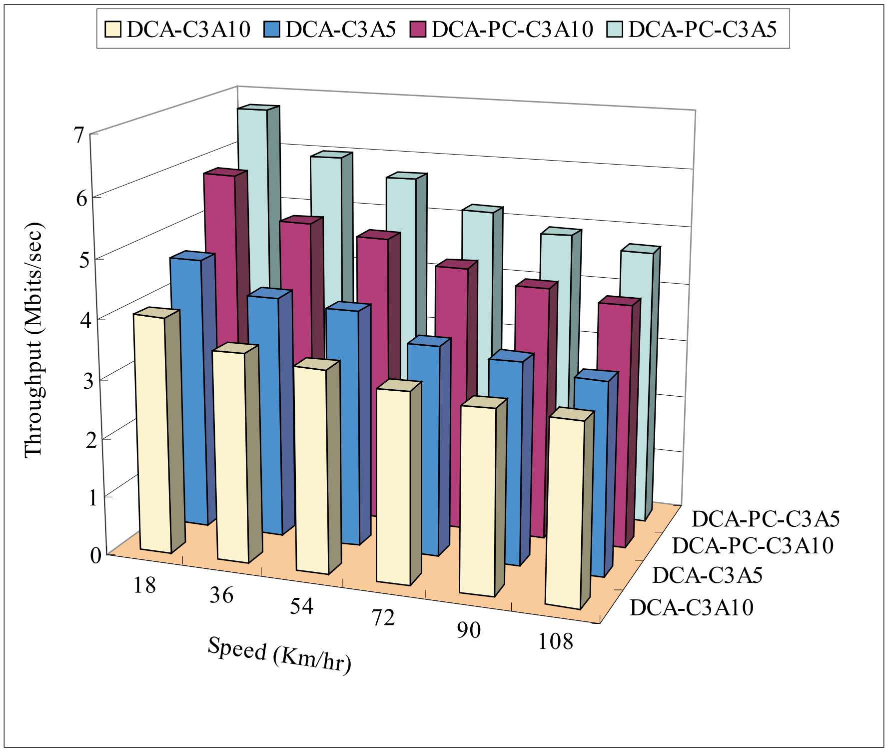


Figure 4.9: Mobility vs. throughput. The peak throughput appears at around A5, while the saturated, but stable, throughput appears at around A10.

protocol will degrade slightly faster than the DCA protocol, as reasoned above. Even so, DCA-PC still outperforms DCA at highly mobile environment (such as 108 km/hr).

4.5 Summaries

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, data packet length, host density, and host mobility, into consideration. The result shows a promising direction to improve the performance of MANET. Apparently, the importance of power control is not necessarily limited to the area of MANET. It is definitely a critical issue in many general aspects of mobile computing and wireless communication, and deserves further investigation.

Chapter 5

Multi-Channel MAC Protocol with Location-Aware Channel Assignment

This chapter considers the *channel assignment* problem in a MANET which has access to *multiple* channels. We propose a scheme called *GRID*, by which a mobile host can easily determine which channel to use based on its current location. In fact, following the GSM style, our GRID spends no communication cost to allocate channels to mobile hosts. We show that better *channel reuse* can be obtained with our GRID. To our knowledge, no location-aware channel assignment approach has been proposed before for a multi-channel MANET. Since a MANET should operate in a physical area, it is very natural to exploit location information in such an environment.

We then propose a multi-channel MAC protocol, which integrates GRID. 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. On the contrary, most existing protocols assign channels to a host statically even if it has no intention to transmit [11, 34, 37], require a number of channels which is a function of the maximum connectivity [11, 23, 34, 37], or necessitate a clock synchronization among all hosts in the MANET [37, 67]. Through simulations, we discuss several performance issues related to our protocol.

5.1 Introduction

A *MAC (medium access control)* protocol is to address how to resolve potential contention and collision on using the communication medium. Many MAC protocols have been proposed for wireless networks [12, 21, 39, 41, 49, 48], which assume a common channel shared by mobile hosts. We call such protocols *single-channel MAC protocols*. 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 quickly 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. The idea of using separate control and data channels was first found in [69], where the authors propose a protocol that uses only two channels, one control channel and one data channel. 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. 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, 54], 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 [50].

Here, we use "channel" upon a logical level. Physically, a channel can be a frequency band (under FDMA), or an orthogonal code (under CDMA). How to access multiple channels is thus technology-dependent. Disregarding the transmission technology (FDMA or CDMA), we can categorize a mobile host based on its capability to access multiple channels as follows:

- *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 transceiver is still capable of switching from one channel to another channel.

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

In this section, we propose a new multi-channel MAC protocol for MANET that is applicable to FDMA and CDMA technology. A multi-channel MAC typically needs to address two issues: *channel 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. These two issues are sometimes addressed separately, but eventually one has to integrate them to provide a total solution. Our channel assignment, called *GRID*, is characterized by two features: (i) it exploits location information by partitioning the physical area into a number of squares called *grids*, and (ii) it does not need to transmit any message to assign channels to mobile hosts. Several channel assignment schemes have been proposed earlier [23, 28, 37, 54, 67], but none of them explore in the location-aware direction. Our medium access 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. On the contrary, most existing protocols assign channels to a host statically even if it has no intention to transmit [11, 34, 37], require a number of channels which is a function of the maximum connectivity [11, 23, 34, 37], or necessitate a clock synchronization among all hosts in the MANET [37, 67]. A detail review will be given in Section 5.2.1. For an overview, Table 5.1 gives a comparison on existing and our protocols.

Since a MANET should operate in a physical area, it is very natural to exploit location information in such an environment. Indeed, location information has been exploited in several issues in MANET (such as location-aware routing [42, 43, 44, 47] and location-aware broadcast [55]), but not on channel assignment. GSM (Global System for Mobile Communications) is an instance which uses location information to exploit channel reuse, but MANET has quite different features (e.g., host has mobility and there is no base station). The availability of the physical location of a mobile host may be obtained from a positioning device such as GPS (global positioning systems) receiver attached to the host through an RS-232 port. GPS receivers are appropriate for outdoor use, and the positioning accuracy ranges in about a few tens of meters. To improve the accuracy, assistance from ground stations can be applied. Such systems, called *differential GPS (DGPS)*, can reduce the error to less than a few meters [44]. Recently, the US government ordered to discontinue the SA (Selective Availability), which intentionally degrades the civilian GPS signals [78]. This is expected to increase the accuracy of GPS significantly, which further motivates the work in this section. The price of a GPS module is less than US $100.

The rest of this section is organized as follows. Section 5.2 discusses some existing channel assignment schemes and our GRID scheme. Section 5.3 presents our MAC protocol by integrating the GRID assignment. Analysis and simulations are in Section 5.4. Conclusions will be drawn in Section 5.5.

5.2 Channel Assignment

As mentioned earlier, a multi-channel MAC needs to address two issues: channel assignment and medium access. In this section, we will consider the channel assignment problem. We will first review some existing protocols, which are all non-location-aware. Then we will present our location-aware channel assignment.

5.2.1 Non-Location-Aware Schemes

In this section, we review some channel assignment schemes that do not utilize the location information of mobile hosts. These schemes can be further divided to *static* and *dynamic*. The simplest static approach is to assign channels to mobile hosts when the system is first set up. For instance, channel i can be statically assigned to those hosts with ID's such that $i = ID \bmod n$ (supposing that we number channels as $0, 1, \ldots, n-1$).

A scheme based on *Latin square* is proposed in [37], which assumes a TDMA-over-FDMA technology. Each channel is divided into fixed-length frames. Each host is statically assigned to a time slot in each frame belonging to a frequency band. Since TDMA is used, clock synchronization among all hosts is necessary. Furthermore, each host has to be equipped with a number of transceivers equal to the number of frequency bands, so this approach is quite costly. Also, this scheme needs to know in advance the maximum number of mobile hosts as well as the maximum degree of the topology formed by the MANET.

The schemes in [11, 16, 19, 34, 52] are for channel assignment in the traditional packet radio network. Partial or even complete network topology has to be collected to perform channel assignment. These approaches can basically be classified as static, although some can handle dynamic failure of base stations. Since these schemes are not designed for MANET, which is typically characterized by high host mobility, they do not fit our need.

A protocol based on dynamic channel assignment is in [23]. It is assumed that the channel assigned to a host must be different from those of its two-hop neighbors. To maintain this condition, a large amount of update messages will be sent whenever a host determines any change on channel assignment in its two-hop neighbors. This is inefficient in a highly mobile system. Further, this protocol is "degree-dependent" in the sense that it dictates a number of channels equal to an order of the square of the maximum degree of the MANET. So the protocol is inappropriate for a crowded environment.

A "degree-independent" protocol called *multichannel-CSMA* protocol is proposed in [54]. Suppose that there are n channels. The protocol imposes that each mobile host must have n receivers which concurrently listen on all n channels. Also, there is only one transmitter which will hop from channel to channel and, if necessary, will send on any detected idle channel. Again, this protocol has high hardware cost. Further, since no RTS/CTS is used, the hidden-terminal problem may easily occur. A hop-reservation MAC protocol based on very-slow frequency-hopping spread spectrum is proposed in [67]. Its channel assignment employs RTS/CTS dialogue to reserve a channel. The protocol is also degree-independent but requires clock synchronization among all mobile hosts, which is difficult when the network

Table 5.1: Comparison of channel assignment schemes (n is the number of hosts, and m is the maximum network degree.

scheme	assignment	no. channels	info. collected	loc.-aware	assgn. cost	transceivers
[11, 16, 19, 34, 52]	static	deg.-dep.	global	no	$O(n^k), k \geq 2$	1
[37]	static	deg.-dep.	none	no	0	m
[23]	dynamic	deg.-dep.	2-hop	no	$O(n^3)$	2
[54]	dynamic	deg.-indep.	none	no	0	m
[67]	dynamic	deg.-indep.	none	no	$O(n)$	1
ours	dynamic	deg.-indep.	none	yes	0	2

is dispersed in a large area.

In Table 5.1, we summarize and compare existing schemes with our yet-to-be-presented GRID scheme.

5.2.2 Our Location-Aware Channel Assignment: GRID

Next, we introduce our location-aware channel assignment scheme. The MANET environment is the same, except that each mobile host must be installed with a positioning device. For outdoor positioning, we may use GPS (Global Positioning System) receivers. For indoor positioning, we may use custom-designed short-distance radios, such as the Active Badge [76]. As will be seen later, our approach will assign a channel to a host once the host knows its current location. As a result, in addition to the positioning cost, there is no communication cost for our channel assignment (no message will be sent for this purpose).

We will refer to our scheme as *GRID*. The MANET is assumed to operate in a pre-defined geographic area. The area is partitioned into 2D logical grids as illustrated in Fig. 5.1. Each grid is a square of size $d \times d$. Grids are numbered (x, y) following the conventional xy-coordinate. To be location-aware, a mobile host must be able to determine its current grid coordinate. Thus, each mobile host must know how to map a physical location to the corresponding grid coordinate.

Our channel assignment works as follows. We assume that the system is given a fixed number, n, of channels. For each grid, we will assign a channel to it. When a mobile host is located at a grid, say (x, y), it will use the channel assigned to grid (x, y) for transmission.

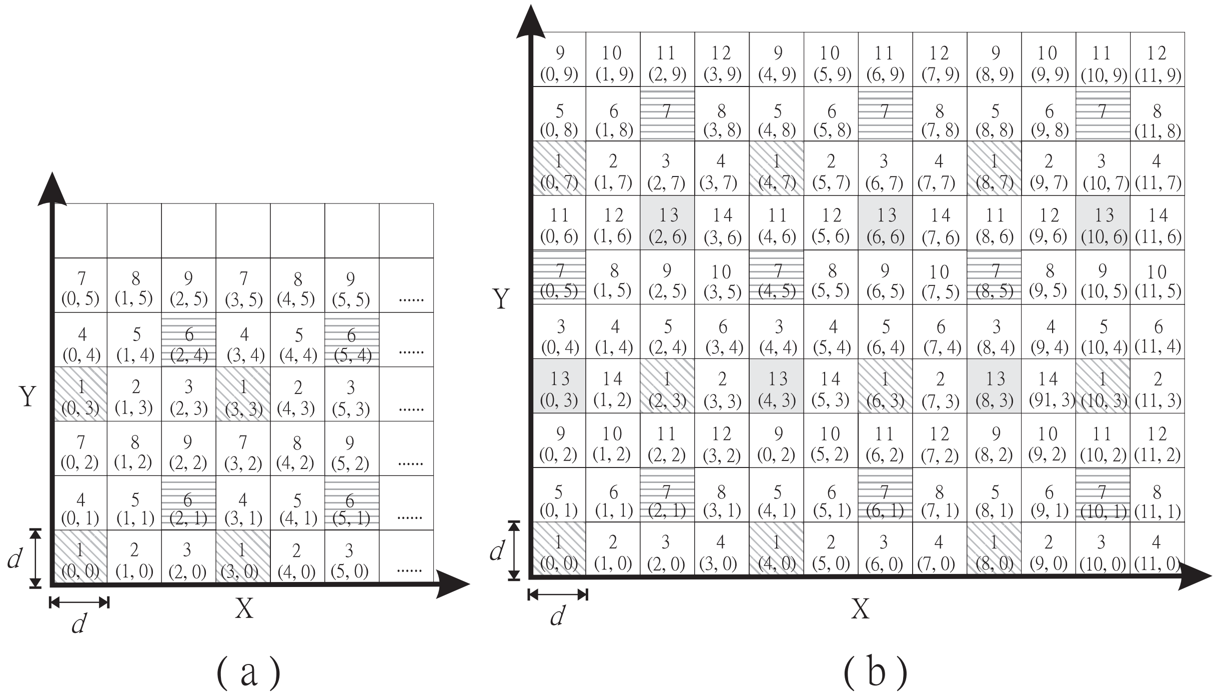


Figure 5.1: Assigning channels to grids in a band-by-band manner: (a) $n = 9$ and (b) $n = 14$. In each grid, the number on the top is the channel number, while those on the bottom are the grid coordinate. Here, we number channels from 1 to n.

One can easily observe that if we assign the same channel to two neighboring grids, then there will be high chance that the transmission activities on these two neighboring grids will contend, or even interfere, with each other. Thus, we should assign the same channel to grids that are spatially separated by some distance, but will exploit the largest frequency reuse.

The above formulation turns out to be similar to the channel arrangement in the GSM system. In the following, we propose a way to assign channels to grids. Let $m = \lceil \sqrt{n} \rceil$. We first partition the grids vertically into a number of *bands* such that each band contains m columns of grids. Then, for each band, we sequentially assign the n channels to each row of grids, in a row-by-row manner. In Fig. 5.1, we illustrate this assignment when $n = 9$ and $n = 14$. It can readily be seen that when n is a square of some integer, each channel will be regularly separated in the area.

Grid Size vs. Transmission Range

Let r be the transmission range of an antenna. Suppose the value of r is fixed. In this section, we discuss an important design issue: the relationship between r and the side length of grids, d. Below, we discuss several possibilities. For simplicity, let's assume that $m = \sqrt{n}$ is an integer.

- $d \gg r$: This means many hosts will stay in a grid and thus contend with each other on one channel. When $d = \infty$, this degenerates to the case of one single channel.
- $d > 2r/(m-1)$: This is the case that the transmission activities from two hosts choosing the same channel will never interfere with each other. As illustrated in Fig. 5.2(a), hosts A and B (both choosing the same channel) are located in the nearest possible locations, but their signals will not overlap in any location.
- $d = 2r/m$: This is the case that the transmission activities from two hosts which choose the same channel and which are each located in the center of a grid will not interfere with each other. This is illustrated in Fig. 5.2(b).
- $d = r/m$: This represents the minimal value of d such that two hosts (located at the grid centers) using the same channel will not hear each other. This is illustrated in Fig. 5.2(c). By simple calculus, we can find that each receiver of these two hosts will have a probability of 0.396 being interfered by the signals from the other sender.
- $d \approx 0$: This means that the grid size is infinitely small. This degenerates to the case that a mobile host will randomly choose a channel to transmit its packets, and thus little channel reuse can be exploited.

The above analysis has indicated a tradeoff. Let's use the ratio r/d for the discussion. If the ratio is too large, then the chance of co-channel interference will be high. On the contrary, if the ratio is too small, although co-channel interference can be reduced, the channel reuse will be reduced too since a channel will be unavailable in many locations. Thus, we need to carefully adjust the ratio of r/d so as to exploit the best network performance.

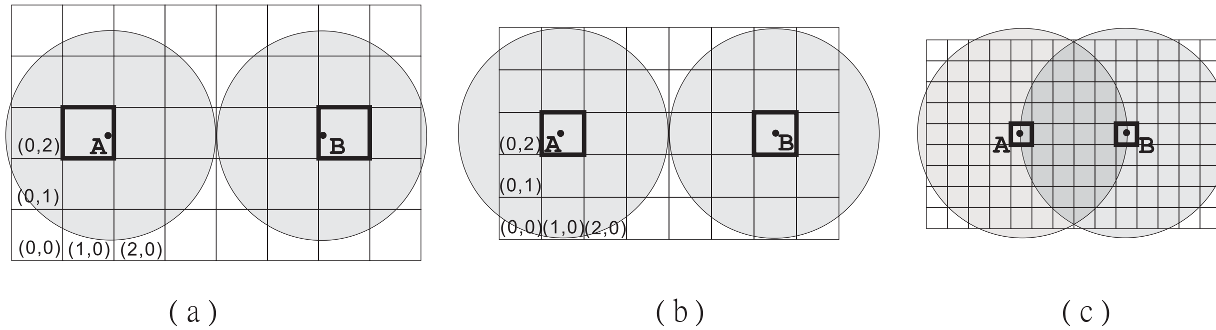


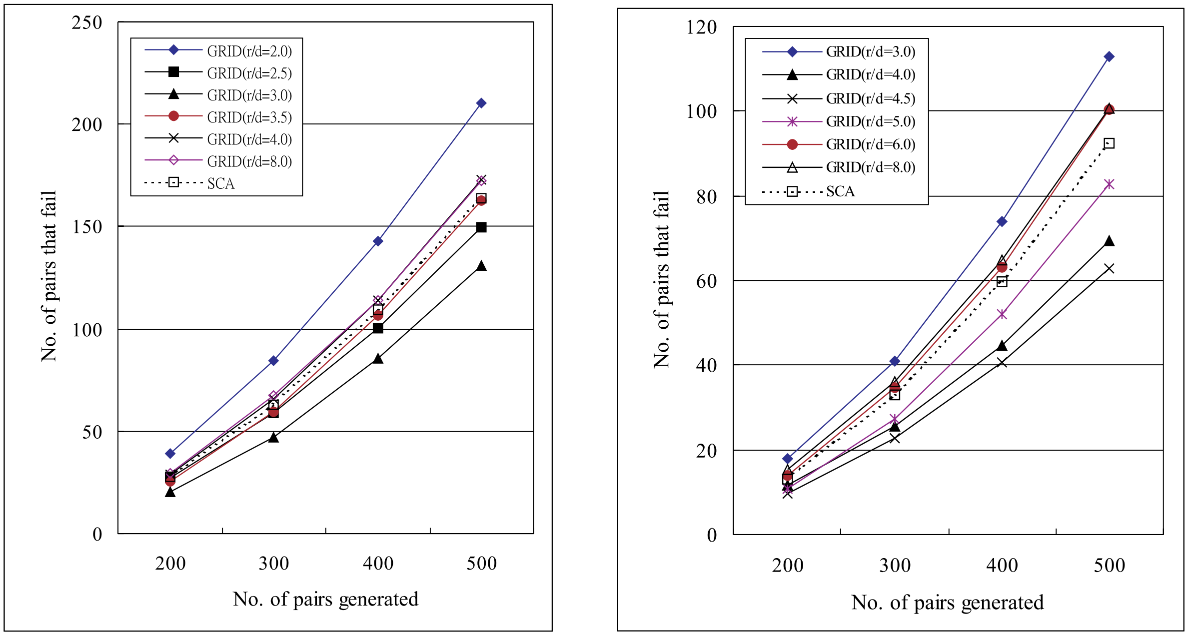
Figure 5.2: The effect of r/d ratio on channel co-interference when $n = 25$.

Some Experiments on the r/d Ratio

At this point, it deserves to predict, under ideal situations, how much benefit our location-aware channel assignment can offer over a non-location-aware one. We developed a simple simulation without concerning the details of medium access, such as collision, timing, etc. (this will be explored in Section 5.4). We simulated an area of size 1000×1000. On this area, we randomly generated a sender A and then randomly generated a receiver B in the circle of radius $r = 100$ centered at A. A transmitted using a channel selected by two methods: (i) a static one based on host ID (referred to as static channel assignment, or SCA), and (ii) our GRID approach. We then repeated this process to generate more sender-receiver pairs. However, for each pair generated, we tested whether this transmission will interfere any earlier ongoing pairs. If so, the current pair will be deleted; otherwise, it will be granted.

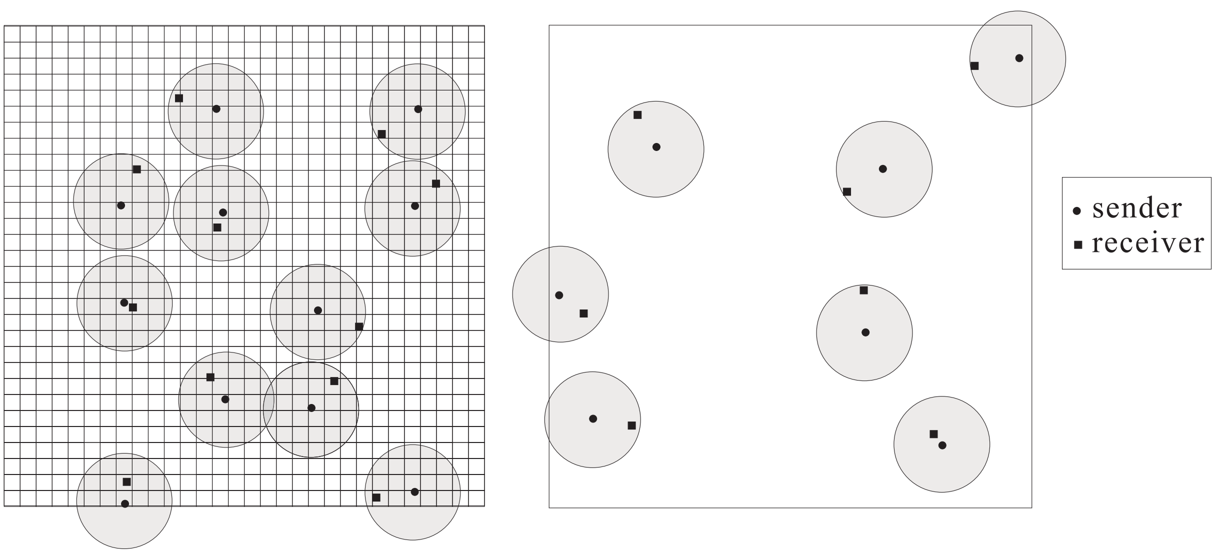
Through this ideal experiment, we intend to observe how many more sender-receiver pairs can be generated in the physical area by GRID than SCA. This will verify whether GRID has a better channel reuse. Another important issue we would like to explore here is: what is best ratio r/d to maximize channel reuse?

Fig. 5.3 shows our first experimental results. The x-axis is the number of sender-receiver pairs generated. The y-axis shows the number of pairs that fail and thus are deleted. For our GRID, we tested different r/d ratios. Fig. 5.3(a) uses a total number of $n = 36$ channels, and Fig. 5.3 (b) uses $n = 81$. Indeed, some r/d ratios are better than SCA, while some are worse. In Fig. 5.3(a), we see that the r/d ratios $2.5, 3.0$, and 3.5 will outperform SCA, while



(a) (b)

Figure 5.3: Tests of blocked sender-receiver pairs at different r/d ratios: (a) $n = 36$ and (b) $n = 81$.



(a) (b)

Figure 5.4: A snapshot of our experiment in Fig. 5.3 when $n = 36$ and $r/d = 3.0$: (a) GRID and (b) SCA. The snapshots are taken on a 1000×1000 area, and each circle means a sender-receiver pair.

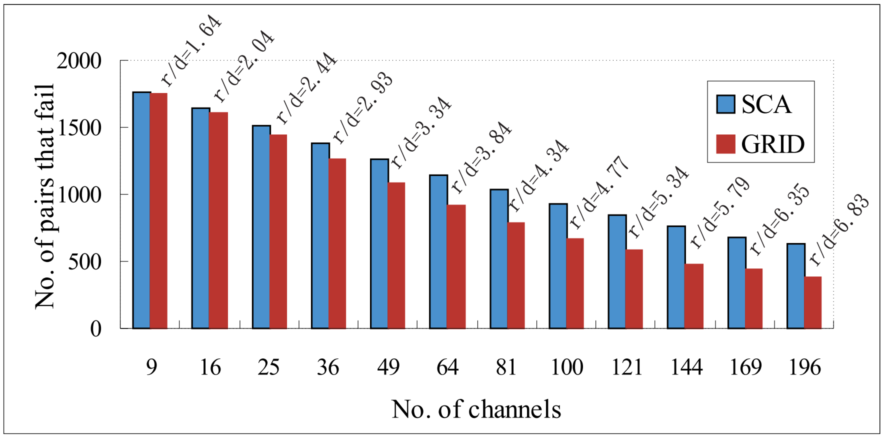


Figure 5.5: Tests of blocked sender-receiver pairs at various n's.

in Fig. 5.3(b), the r/d ratios $4.0, 4.5$, and 5.0 will outperform SCA.

We observe from the above experiments that $r/d = 3.0$ and 4.5 will give the most numbers of successful sender-receiver pairs when $n = 36$ and 81, respectively. This happens to fit the formula $r/d = \sqrt{n}/2$ that is illustrated in Fig. 5.2(b), where the two circles from sources A and B are tangent to each other. This intuitively indicates that at this ratio, it is more likely that we can place most circles (which represent transmission activities of this channel) in a physical area, while incurring the least overlapping among circles (which represents co-channel interference). This is how our GRID can offer better channel reuse. Fig. 5.4 shows a snapshot in our experiment when $n = 36$ and $r/d = 3.0$ on the use of channel 1. Clearly, the placement of circles by GRID is denser and more regular than that of SCA. At this point, we should note that this experiment is only based on an ideal situation without considering the control packets (such as RTS, CTS, and ACK) that might be sent. This will be further investigated in the later part of this chapter.

In Fig. 5.5, we further vary the value of n to observe the trend. In this figure, we have picked the best r/d ratio for each n. The number of sender-receiver pairs generated is 2000. As can be seen, the best ratios are all very close to $\sqrt{n}/2$, as we have predicted. Also, with more channels, there are less pairs being blocked by both GRID and SCA. But the gain of GIRD over SCA will enlarge as a larger n is used.

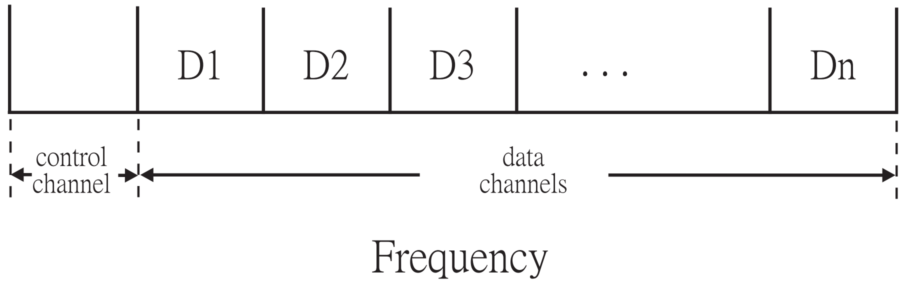


Figure 5.6: The channel model of our protocol under the FDMA technology.

5.3 The MAC Protocol

This section presents the medium access part of our protocol by integrating the channel assignment part in the previous section. The channel model is as follows. The overall bandwidth is divided into one control channel and n data channels $D_1, D_2, \ldots, D_n$. Each channel, including control and data ones, is of the same bandwidth. The idea of using separate control and data channels was first found in [69], where the authors propose a protocol that use only two channels, one control channel and one data channel. This is exemplified in Fig. 5.6, based on a FDMA model. (If CDMA is used, then each channel owns one CDMA code. Our protocol is not suitable for TDMA because we don't employ any form of time synchronization.) the bandwidth of the control channel should be the same as one data channel. Another possibility is to use multiple CDMA codes as *one* control. In this case, multiple transceivers should cooperate together as virtually one control channel. We do not consider this possibility in this chaper.) The data channels are considered equivalent and thus each has the same bandwidth. The purpose of data channels is to transmit data packets and acknowledgements, while that of the control channel is to schedule and synchronize the use of data channels among hosts.

Each mobile host is equipped with two half-duplex transceivers:

- *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 operate on one of the data channels, according to our channel assignment, to transmit data packets and acknowledgements.

Each mobile host X maintains the following data structure.

- $CUL[\,]$: This is called the *channel usage list*. Each list entry $CUL[i]$ keeps records of how and 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.

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. This RTS will also carry the channel number that A intends to use in its subsequent transmission. Then B will match this request with its in $CUL[\,]$ and, if granted, reply a CTS (clear-to-send) to A. All these will happen on the control channel. Similar to the IEEE 802.11 [3], the purpose of the RTS/CTS dialogue is to warn the neighborhood of A and B not to interfere their subsequent transmission, except that a host is still allowed to use the channels different from that indicated in the RTS and CTS packets. Finally, transmission of a data packet will occur on the data channel.

The complete protocol is shown below. Table 5.2 lists the variables/constants used in our presentaiton.

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.

Table 5.2: 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_{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
L_d	length of a data packet
L_c	length of a control packet (RTS/CTS)
B_d	bandwidth of a data channel
B_c	bandwidth of a control channel
τ	maximal propagation delay

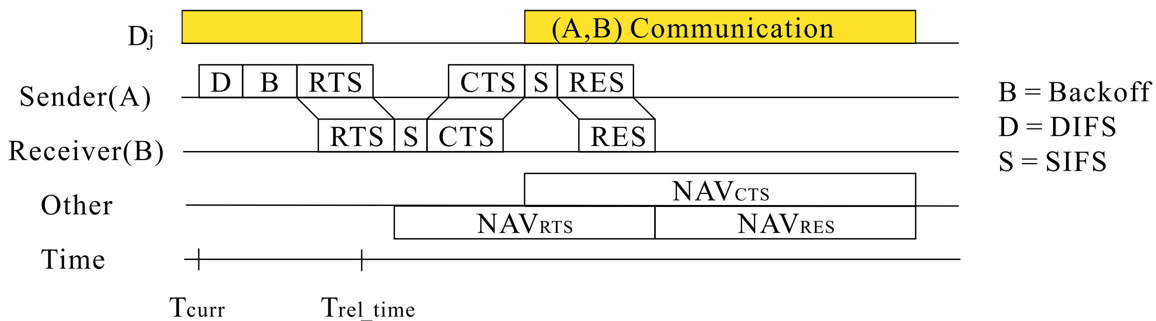


Figure 5.7: Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

b) Suppose A determines that its current data channel is D_A. Then for each $i = 1..n$,

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

If so, this means A's data channel is either not currently being used by any of its neighbors, or currently being occupied by some neighbor(s) but will be released after a successful exchange of RTS and CTS packets. (Fig. 5.7 shows how the above timing is calculated.)

If the above two conditions are true, proceed to step 2; otherwise, A must wait at step 1 until these conditions become true.

2. Then A can send a $RTS(D_A, L_d)$ 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 $RTS(D_A, L_d)$ from A, it has to check whether the following condition is true for each $i = 1..n$:

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

   If so, D_A is either not currently being used by any of its neighbors, or currently being used by some neighbor(s) but will be released after a successful transmission of a CTS packet. Then B replies a $CTS(D_A, NAV_{CTS})$ to A, where

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

   Then B tunes its data transceiver to D_A. Otherwise, B replies a $CTS(T_{est})$ to A, where T_{est} is the estimated time that B's data channel D_A will change minus the time for an exchange of a CTS packet:

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

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

   $$NAV_{RTS0} = T_{SIFS} + T_{CTS} + \tau.$$

   This is to avoid C from interrupting the RTS $\rightarrow$ CTS dialogue between A and B. Then, C senses channel D_A for a period of τ to determine whether this communication is success or not. If so, it appends an entry $CUL[k]$ to its CUL such that:

   $$\begin{aligned} CUL[k].host &= A \\ CUL[k].ch &= D_A \\ CUL[k].rel\_time &= T_{curr} + NAV_{RTS1} \end{aligned}$$

where

$$NAV_{RTS1} = T_{curr} + L_d/B_d + T_{ACK} + \tau.$$

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 $CTS(D_A, NAV_{CTS})$, it performs the following steps:

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

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

   b) Send its DATA packet to B on the data channel D_A.

   On the contrary, if A receives B's $CTS(T_{est})$, it has to wait for a time period T_{est} and go back to step 1.

7. On an irrelevant host $C \neq A$ receiving B's $CTS(D_A, NAV_{CTS})$, 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 B completely receiving A's data packet, B replies an ACK on D_A.

To summarize, our protocol relies on the control channel to negotiate the transmissions among hosts using the same data channel. Also, note that although our protocol will send timing information in packets, these are only relative time intervals. No absolute time is sent. So there is no need of clock synchronization in our protocol.

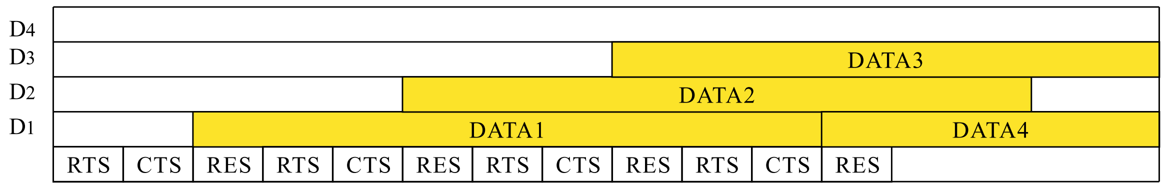


Figure 5.8: An example that the control channel is fully loaded and the data channel D_4 is not utilized.

5.4 Analysis and Simulation Results

5.4.1 Arrangement of Control and Data Channels

One concern in our protocol is: Can the control channel efficiently distribute the communication jobs to data channels? For example, in Fig. 5.8, we show an example with 5 channels, one for control and four for data. For simplicity, let's assume that the lengths of all control packets (RTS, and CTS) are L_c, and lengths of all data packets $L_d = 6L_c$. Then Fig. 5.8 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 can serve at most three data channels. Although L_d is typically larger than L_c by an order of at least tens or hundreds, it still deserves to analyze this issue to understand the limitation.

The above example shows that how to arrange the control and data channels is a critical issue. In the following, 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 have 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. On the contrary, 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.

We will show how to arrange the control and data channels under these models so as to well utilize a given bandwidth. Let's consider the fixed-channel-bandwidth model first. Apparently, since the control channel can arrange a data packet by sending 2 control packets of total length $2L_c$, the maximum number of data channels should be limited by

$$n \leq \frac{L_d}{2 \times L_c}. \tag{5.1}$$

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

$$U \leq \frac{n}{n+1}. \tag{5.2}$$

From Eq. (5.1) and Eq. (5.2), we derive that

$$\frac{U}{1-U} \leq n \leq \frac{L_d}{2 \times L_c} \Longrightarrow U \leq \frac{L_d}{2 \times L_c + L_d}. \tag{5.3}$$

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. 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 consider the fixed-total-bandwidth model. Suppose that we are given a fixed bandwidth. The problem is: how to assign the bandwidth to the control and data channels to achieve the best utilization. Also, how many data channels (n) will be most efficient? 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 assignment capability of the control channel:

$$n \leq \frac{L_d/B_d}{2 \times L_c/B_c}. \tag{5.4}$$

Similarly, the utilization U must satisfy

$$U \leq \frac{n \times B_d}{n \times B_d + B_c}. \tag{5.5}$$

Combining Eq. (5.4) and Eq. (5.5) gives

$$\frac{UB_c}{B_d - UB_d} \leq n \leq \frac{L_d B_c}{2 \times L_c B_d} \Longrightarrow U \leq \frac{L_d}{2 \times L_c + L_d}. \tag{5.6}$$

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 may improve the utilization. To understand how to arrange the bandwidth, we replace the maximum utilization into Eq. (5.5), which gives

$$\frac{L_d}{2 \times L_c + L_d} = \frac{n \times B_d}{n \times B_d + B_c} \Longrightarrow \frac{B_c}{nB_d} = \frac{2L_c}{L_d}. \tag{5.7}$$

Thus, to achieve the best utilization, the ratio of the control bandwidth to the data bandwidth should be $2L_c/L_d$. Furthermore, since the maximum utilization is independent of the value of n, theoretically once the above ratio ($2L_c/L_d$) is used, it does not matter how many data channels that we divide the data bandwidth into. (Thus, one can even adjust the value of n according to the number of mobile hosts or host density.)

Finally, we comment on several minor things in the above analysis. First, if the control packets are of different lengths, the $2L_c$ can simply be replaced by the total length of RTS, and CTS. Second, the L_d has included the length of ACK packets. So the real data packet length should be L_d minus the length of an ACK packet. Third, we did not consider many protocol factors (such as propagation delay, SIFS, DIFS, collision, backoffs, etc.) in the analysis. In reality, these factors will certainly affect the performance. In the next section, we will explore this through simulations.

5.4.2 Experimental Results

We have implemented a simulator to evaluate the performance of our GRID protocol. We mainly used the SCA protocol as a reference for comparison. SCA only differs from our GRID

Table 5.3: Experimental parameters.

physical area	1000×1000
no. of hosts	400
transmission range r	200
max. no. of retrials to send a RTS	6
length of DIFS	50 μsec
length of SIFS	10 μsec
backoff slot time	20 μsec
control packet length L_c	100 bits
data packet length L_d	a multiple of L_c

in its channel assignment strategy. Specifically, in SCA, there are also a control channel and n data channels. But each host is statically assigned to a data channel. To use its data channel, a host must go through a RTS/CTS exchange with its intending receiver before using the data channel. Since both SCA and GRID use the same channel model and medium access approach, we believe that the experiment can give a clear indication how much more channel reuse that GRID can offer. Also, whenever appropriate, we will include the performance of IEEE 802.11, which is based on a single-channel model, to demonstrate the benefit of using multiple channels.

The parameters used in our experiments are listed in Table 5.3. Packets arrived at each mobile host in an Poisson distribution with arrival rate λ packet/sec. For each packet arrived at a host, we randomly chose a host at the former's neighborhood as its receiver. Both of the earlier bandwidth models are used. If the fixed-channel-bandwidth model is assumed, each channel's bandwidth is 1 Mbps/sec. If the fixed-total-bandwidth model is assumed, the total bandwidth is 1 Mbps/sec. In the following, we make observations from four aspects.

A) Effect of the r/d Ratios: In this experiment, we change the r/d ratio to observe the effect. We use $n = 16$ data channels and $L_d/L_c = 200$. Fig. 5.9 shows the network throughput under different loads under the fixed-channel-bandwidth model. We can see that both SCA and GRID have similar throughput curves. When $r/d = 0.5$, 1.0, and 1.5, our GRID protocol is worse than the SCA protocol. When $r/d \geq 2.0$, our GRID will outperform SCA. At $r/d = 3.5$, GRID will deliver the highest throughput, which is about 25% more than

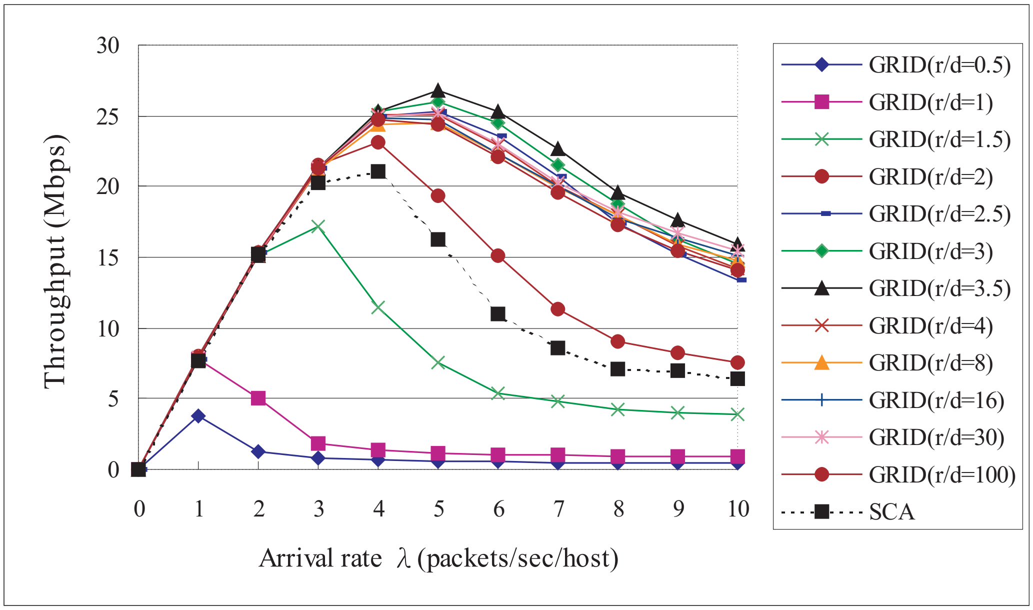


Figure 5.9: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different r/d ratios.

the highest throughput of SCA. After $r/d > 3.5$, GRID will saturate and degrade slightly, but still outperform SCA. It is worth to mention that according to our earlier ideal analysis in Section 5.2, the best performance of GRID will appear when $r/d = \sqrt{n}/2 = 2$. This ratio is somewhat smaller than the ratio 3.5 that we obtain here. We believe that this is because in this experiment we have taken timing into consideration, while in Section 5.2 we have disregarded this factor. Thus, different sender-receiver pairs may be time-differentiated, and thus more pairs may coexist. In fact, this is a favorable result to GRID because a higher r/d ratio means more signal overlapping, and thus higher channel reuse.

Fig. 5.10 shows the similar experiment under the fixed-total-bandwidth model. Again, the best r/d ratio appears at around 2.5 to 4. The trend is similar to that of the fixed-channel bandwidth model. Also, as a reference point, this figure contains the performance of IEEE 802.11.

B) Effect of the Number of Channels: In this experiment, we still use $L_d/L_c = 200$, but vary the number of channels n, to observe its effect. Fig. 5.11 shows the result under the

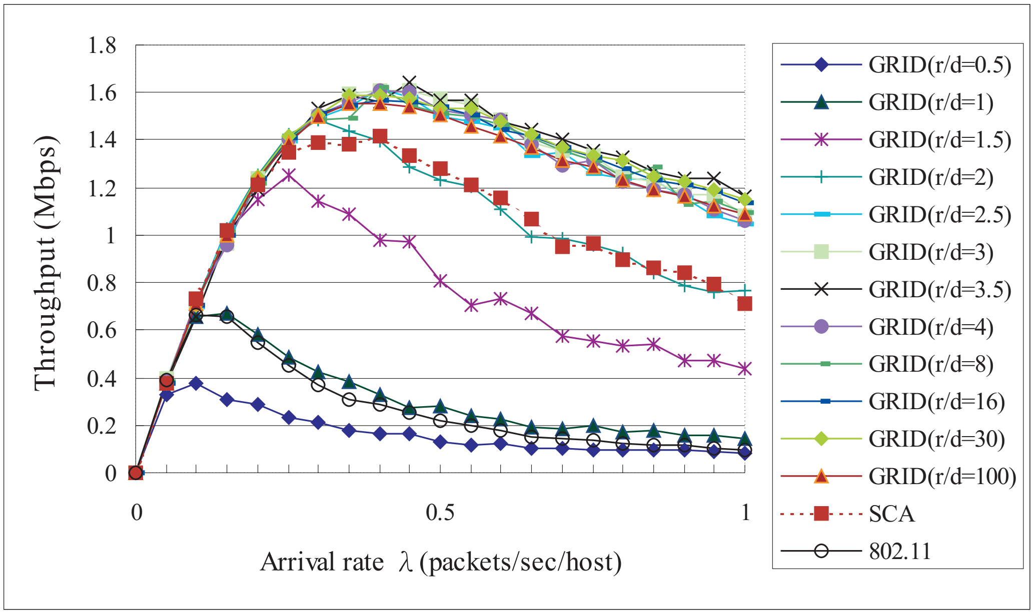


Figure 5.10: Arrival rate vs. throughput under the fixed-total-bandwidth model at different r/d ratios.

fixed-channel-bandwidth model. Note that in this figure we have picked the best r/d ratio (through experiments) for each given n for our GRID protocol. We see that both SCA's and GRID's throughputs will increase as more data channels are used. This is quite reasonable because under the fixed-channel-bandwidth model, a larger n means more total bandwidth being provided. As n enlarges, the gap between GRID and SCA will increase slightly.

Fig. 5.12 shows the same simulation under fixed-total-bandwidth model. The trend is similar. One important observation is that the best performance for both SCA and GRID will appear at around $n = 4$ data channels. With more channels, the throughput will degrade significantly. Also, as comparing GRID and SCA, we see that when n is too large (e.g., $n = 49$), The gap between GRID and SCA will decrease significantly. This may due to two reasons: either the control channel is overloaded, or the control channel has not been fully loaded but there are too few mobile hosts to fully utilize these data channels.

C) Effect of the L_d/L_c ratios: As discussed earlier, the performance of GRID will be limited by the use of the control channel. One way to increase performance is to increase

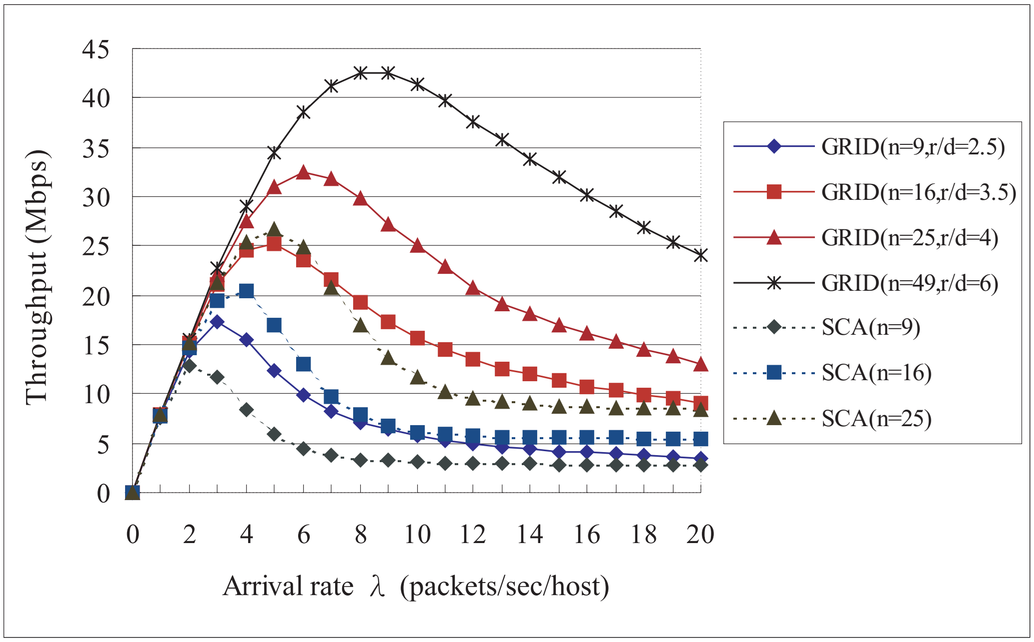


Figure 5.11: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different numbers of data channels.

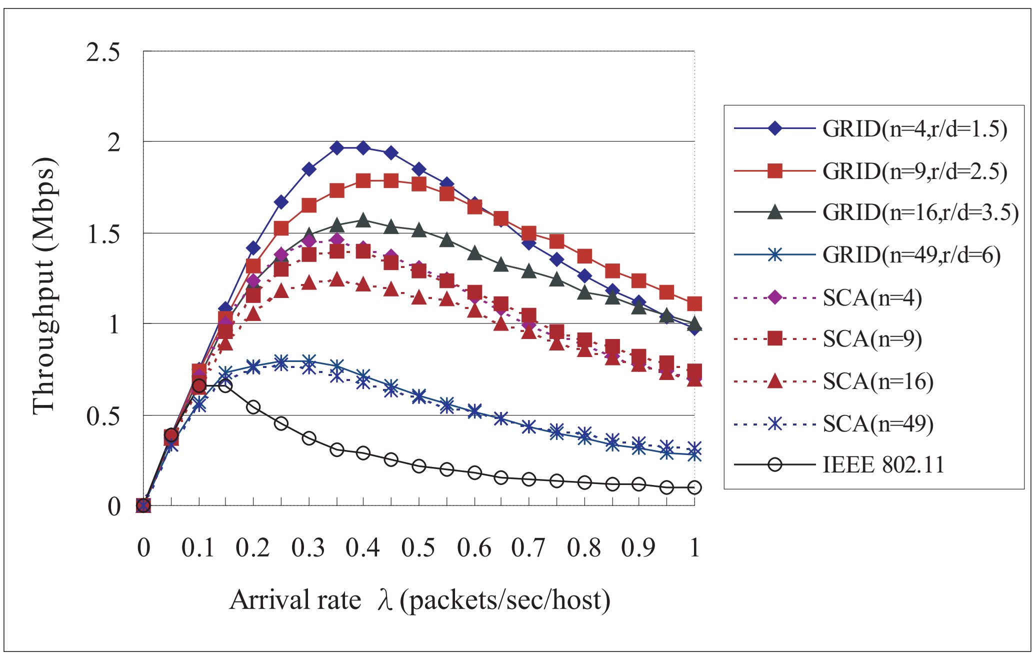


Figure 5.12: Arrival rate vs. throughput under the fixed-total-bandwidth model with different numbers of data channels.

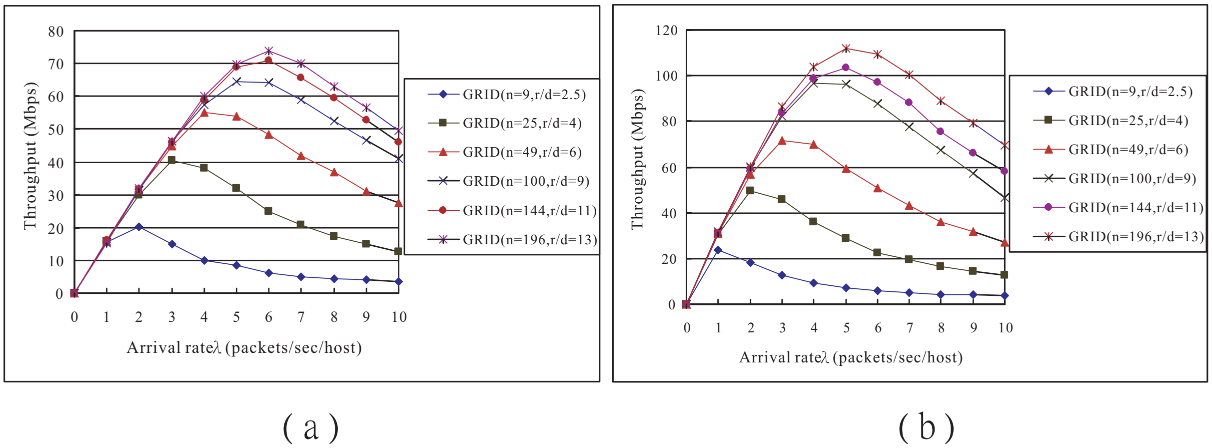
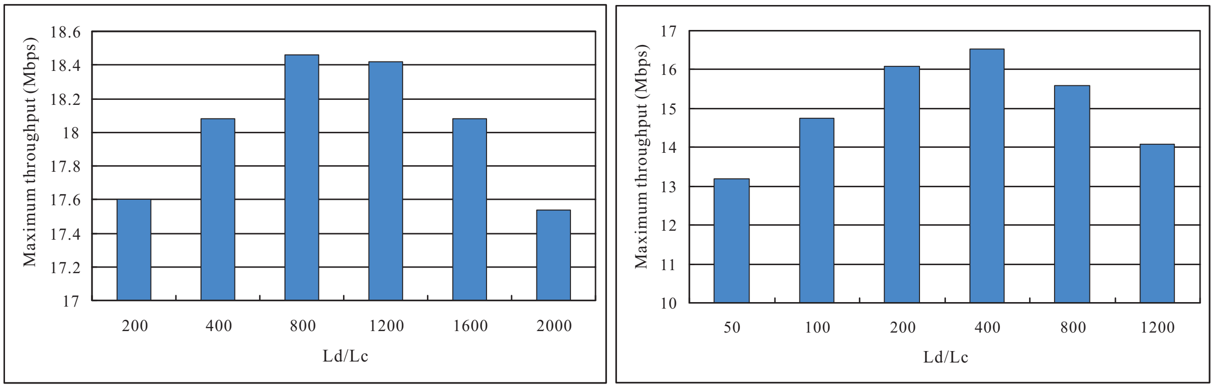


Figure 5.13: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different numbers of data channels: (a) $L_d/L_c = 50$ and (b) $L_d/L_c = 200$.

the data packet length in order to reduce the load on the control channel. To understand this issue, observe Fig. 5.13(a), which assumes $L_d/L_c = 50$ and the number of hosts = 1600 under the fixed-channel-bandwidth model. Comparing the curves in this figure, we see that there is a large performance improvement between using $n = 9$ channels and $n = 25$ channels. However, the improvement reduces significantly from using $n = 25$ to using $n = 49$ channels. When using $n = 100$ channels, the gain relative to using $n = 49$ is very limited (note that under the fixed-channel-bandwidth model, this means much bandwidth being wasted). To resolve this problem, in Fig. 5.13(b), we increase L_d/L_c to 200. Now the improvements all enlarge. This has justified our argument. As a result, given an n, one has to wisely adjust the ratio L_d/L_c so as to get the best throughput.

D) Effect of Transmission Error Rates: In the previous experiment, we have made a strong assumption: the transmission is error-free. To take this into consideration, we further assume a bit error rate during transmission. Under the fixed-channel-bandwidth model with $n = 9$ channels, Fig. 5.14(a) and (b) show our simulation results under the transmission bit error rates of 10^{-6} and 5×10^{-6}, respectively. Under an error rate of 10^{-6}, $L_d/L_c = 800$ has the best maximum throughput. With a larger error rate of 5×10^{-6}, the best maximum throughput will appear at the smaller ratio $L_d/L_c = 400$.



(a) (b)

Figure 5.14: Ratio L_d/L_c vs. maximum throughput under the fixed-channel-bandwidth model: (a) bit error rate = 10^{-6} and (b) bit error rate = 5×10^{-6}.

5.5 Summaries

We have developed a new MAC protocol for multi-channel MANET. Our channel assignment is characterized by location awareness capability and it incurs no communication cost to perform the assignment. Moreover, we have conquered the deficiency in many existing protocols which require clock synchronization or which dictate a number of channels as a function of the maximum degree in the MANET topology. Our simulation results have also indicated that it is worthwhile to consider using multiple channels under both the fixed-channel-bandwidth model and the fixed-total-bandwidth model.

We believe that there are many future research problems that can be stimulated by this work in the MANET research society. In our simulations, we have used a number of data channels (n) which is a square of some integer. Given any n, it will be interesting to investigate how to assign channels to grids to exploit the best channel reuse. It also deserves investigating the possibility that channels can be borrowed among grids. Our simulations have used a circle to model the radio coverage of antennas to determine the best r/d ratio. In practice, the best ratio may change due to many factors such as shadowing and obstacles. However, we believe that location information is still very important for channel assignment in a multi-channel MAC. In the medium access part, we have used only one control channel.

Other control mechanisms are possible too. As to positioning devices, GPS is widely accepted for outdoor use. How to integrate with indoor positioning mechanisms (such as [27, 76]) is a challenging problem. The radio coverage of an antenna in an indoor environment will be more irregular. One possibility is to pre-assign channels to different locations, and then we can use location information to assist mobile hosts to choose channels to use.

Chapter 6

Dynamic Channel Allocation MAC Protocol with Location Awareness

This chapter considers the *channel assignment* problem in a MANET which has access to *multiple* channels. Although a MANET does not have the infrastructure of base stations, interestingly its channel assignment can be conducted efficiently in a way very similar to that in cellular systems (such as GSM). In this chapter, we propose a new *location-aware* channel assignment protocol called *GRID-B* (read as GRID with Channel Borrowing), which is a sequel of our earlier *GRID* protocol [83]. The protocol assigns channels to mobile hosts based on the location information of mobile hosts that might be available from the positioning device (such as GPS) attached to each host. According to our knowledge, no location-aware channel assignment protocol has been proposed before for MANETs. Several channel borrowing strategies are proposed to dynamically assign channels to mobile hosts so as to exploit channel reuse and resolve the unbalance of traffic loads among different areas (such as hot and cold spots). We then propose a multi-channel MAC protocol, which integrates GRID-B. Extensive simulation results are presented to show the advantage of the new GRID-B protocol.

6.1 Introduction

It this chapter, we propose to resolve the channel assignment problem based on the location information of mobile hosts. As far as we know, existing works related to channel assignment for MANET [37, 54, 67] are all non-location-aware. Since a MANET should operate in a physical area, it is actually very natural to exploit location information in such an environment. Indeed, location information has been exploited in several issues in MANET (such as location-aware routing [42, 43, 44, 47] and location-aware broadcast [55]), but not on channel assignment. GSM (Global System for Mobile Communications) is an instance which uses location information (based on a cellular structure) to exploit channel reuse, but MANET has quite different features (e.g., host has mobility and there is no base station). The availability of the physical location of a mobile host may be obtained from a positioning device such as GPS (global positioning systems) receiver attached to the host through an RS-232 port. GPS receivers are appropriate for outdoor use, and the positioning accuracy ranges in about a few tens of meters. To improve the accuracy, assistance from ground stations can be applied. Such systems, called *differential GPS (DGPS)*, can reduce the error to less than a few meters [44]. Recently, a new law has been passed by the US government to eliminate the SA (Selective Availability) contraint on GPS, which is expected to significantly improve the positioning accuracy by about an order [78].

The channel assignment protocol proposed in this chapter is called *GRID-B* (read as GRID with channel borrowing). Similar to the cellular structure in GSM, the physical area covered by the MANET is first partitioned into a number of squares called *grids*. A mobile host, on needing a channel to communicate, will dynamically compute a list of channels based on the grid where it is currently located. The list of channels is in fact sorted based on location information. We propose four strategies for the sorting: *sequential-sender-based borrowing*, *sequential-receiver-based borrowing*, *distance-sender-based borrowing*, and *distance-receiver-based borrowing*. The basic idea is that we will assign to each grid a default channel, and a list of channels owned by its neighboring grids from which it may borrow. The purpose is twofold: (i) we dynamically assign channels to mobile hosts so as to take care of the load unbalance problem caused by differences among areas (such as hot and cold spots), and (ii) we sort channels based on mobile hosts' current locations so as to exploit larger channel reuse. This work is in fact a sequel of our previous work [83], where a protocol called GRID was proposed. In GRID, channels are assigned to grids statically, and we find that using a dynamic assignment in GRID-B can further improve the throughput of channels.

We then propose a medium access protocol, which integrates the above channel assignment strategies. The MAC 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. On the contrary, most existing protocols assign channels to a host statically even if it has no intention to transmit [11, 34, 37], require a number of channels which is a function of the maximum connectivity [11, 23, 34, 37], or necessitate a clock synchronization among all hosts in the MANET [37, 67] Extensive simulation results are presented to investigate the performance of the proposed protocols.

The rest of this chapter is organized as follows. Section 6.2 discusses our dynamic channel assignment and borrowing strategies. Section 6.3 integrates our channel assignment strategies into a MAC protocol. Simulation results are presented in Section 6.4. Conclusions are drawn in Section 6.5.

6.2 GRID-B: A Dynamic Channel Assignment Protocol

As mentioned earlier, a multi-channel MAC protocol needs to address two issues: channel assignment and medium access. In this section, we discuss the channel assignment part. We assume that each mobile host is installed with a positioning device. (For outdoor positioning, we may use GPS receivers. For indoor positioning, we may use custom-designed short-distance radios, such as the Active Badge [76].)

The MANET is assumed to operate in a pre-defined geographic area. The area is partitioned into 2D logical grids as illustrated in Fig. 6.1. Each grid is a square of size $d \times d$. Grids are numbered (x, y) following the conventional xy-coordinate. To be location-aware, a mobile host must be able to determine its current grid coordinate. Thus, each mobile host must know how to map a physical location to the corresponding grid coordinate.

For convenience of explanation, we briefly review the channel assignment of GRID works.

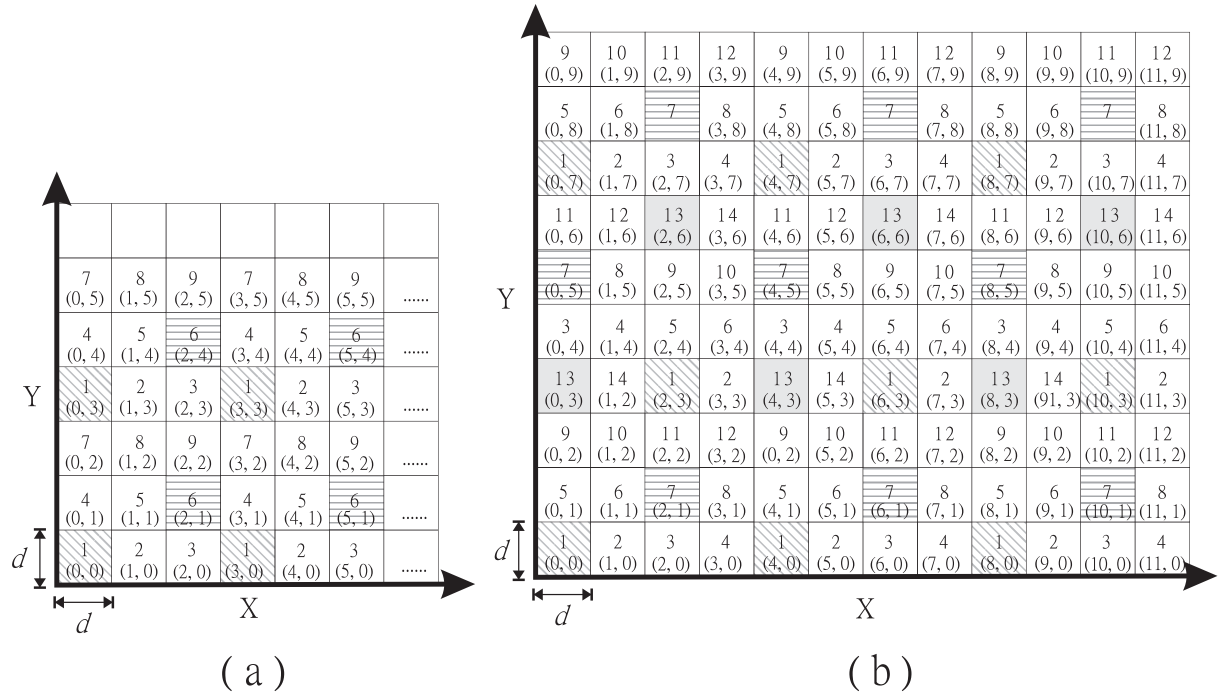


Figure 6.1: Assigning channels to grids in a band-by-band manner: (a) $n = 9$ and (b) $n = 14$. In each grid, the number on the top is the channel number, while those on the bottom are the grid coordinate. Here, we number channels from 1 to n.

We assume that the system is given a fixed number, n, of channels. For each grid, we will assign a channel to it. When a mobile host is located at a grid, say (x, y), it will use the channel assigned to grid (x, y) for transmission. The assignment of channels to grids should follow two rules: (i) we should avoid interfere among grids by assigning different channels to neighboring grids, and (ii) the grids which use the same channel should be spatially separated appropriately so as to exploit the largest frequency reuse. The formulation turns out to be similar to the channel arrangement in the GSM system. One heuristic to do the assignment is to let $m = \lceil \sqrt{n} \rceil$. We first partition the grids vertically into a number of *bands* such that each band contains m columns of grids. Then, for each band, we sequentially assign the n channels to each row of grids, in a row-by-row manner. In Fig. 6.1, we illustrate this assignment when $n = 9$ and $n = 14$. It can readily be seen that when n is a square of some integer, each channel will be regularly separated in the area.

We know that GRID assigns a channel to a host based on the grid where the host is currently located. Thus, beside the positioning cost, there is no communication cost for our channel assignment (no message will be sent for this purpose). However, channels are assigned to grids statically in GRID.

In real world, some grids could be very crowded and thus “hot,” while some could be “cold.” Apparently, it will be more flexible if channels can be borrowed among grids to resolve the contention in hot spots. This issue has been studied quite a lot in the area of cellular systems [18, 9, 53]. This has motivated us to investigate the possibility of dynamically assigning channels to grids in this chapter.

What we have done in the GRID protocol is to carefully arrange the usage pattern of each channel so as to exploit the largest channel reuse (and thus the throughput of each channel). As channels are borrowed among grids, the usage pattern will be disturbed and thus the channel usage pattern will not be so “compact.” For example, in Fig. 6.1, if grid (0, 2) borrows channel 1, the two grids (0, 0) and (0, 3) may be deprived of the right of using that channel, due to possible interference. Thus the potential number of users of channel 1 may be decreased (of course, the lending grids may be “cold” and do not need that channel). This is the cost of flexibility. As a result, the borrowed channels should always be returned to the owner grids whenever necessary to maintain a compact channel usage pattern.

In this work, we will let channels be borrowed among grids such that when looking from a global view, the usage pattern of each channel is as compact as possible. However, no global channel usage status will be collected. In the following, we propose four channel borrowing strategies. Let A be a mobile host located at grid (x, y) who intends to communicate with a mobile host B located at grid (x', y'). The channels that may be borrowed by A are given different priorities as follows.

1. *sequential-sender-based borrowing (denoted as GRID-B_{ss}):* Let i be the channel assigned to grid (x, y). Host A will try to borrow channels $i+1, i+2, \ldots, n, 1, 2, \ldots, i-1$, in that order. Intuitively, this will make all grids who also use channels i to borrow channels in the same order.

2. *sequential-receiver-based borrowing (denoted as GRID-B_{sr}):* Let i be the channel assigned to grid (x', y'). Host A will try to borrow channels $i+1, i+2, \ldots, n, 1, 2, \ldots, i-1$, in that order.

3. *distance-sender-based borrowing (denoted as GRID-B_{ds}):* For convenience, let's denote by $c(p, q)$ the channel assigned to grid (p, q). For each channel i, define a distance function as follows:

$$dist1(i) = \min_{\forall (p,q)::c(p,q)=c(x,y)} \{\sqrt{(p-x)^2 + (q-y)^2}\}.$$

   Intuitively, this is the distance from (x, y) to the nearest grid that is also assigned the same default channel. Then we sort all channels that can be borrowed by A based on a descending order of their distance functions. The underlying idea of the borrowing is to incur as little interference to A's neighborhood as possible.

4. *distance-receiver-based borrowing (denoted as GRID-B_{dr}):* This is similar to the distance-sender-based borrowing, except that we will define for each channel i, a different distance function based on where B is located:

$$dist2(i) = \min_{\forall (p,q)::c(p,q)=c(x',y')} \{\sqrt{(p-x')^2 + (q-y')^2}\}.$$

   Then we sort all channels that can be borrowed by A based on a descending order of their distance functions. The underlying idea of the borrowing is to incur as little interference to B's neighborhood as possible.

For example, Fig. 6.2 shows a scenario where A wants to communicate with B in a MANET with $n = 16$ channels. The channels to be used, from higher priority to lower priority, for the four strategies are (note that the default channel is always at the beginning of the list):

- GRID-B_{ss}: {15, 16, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 }

- GRID-B_{sr}: {12, 13, 14, 15, 16, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 }

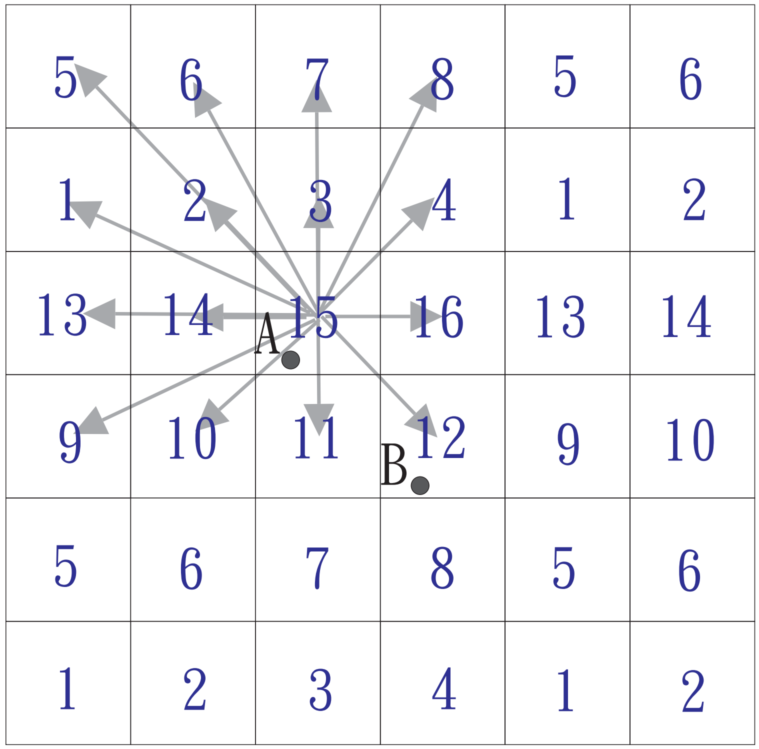


Figure 6.2: An example to determine the channel borrowing sequences in our strategies. The arrows radiated from A and B indicate the values of the distance functions $dist1$ and $dist2$, respectively.

- GRID-B$_{ds}$: {15, 5, 1, 6, 8, 9, 7, 13, 2, 4, 10, 12, 3, 11, 14, 16 }
- GRID-B$_{dr}$: {12, 2, 1, 3, 6, 14, 4, 10, 5, 7, 13, 15, 8, 9, 11, 16 }

6.3 The MAC Protocol

This section presents the medium access part of our protocol by integrating the channel assignment part in the previous section. The channel model is as follows. The overall bandwidth is divided into one control channel and n data channels $D_1, D_2, \ldots, D_n$. Each channel, including control and data ones, has the same bandwidth. This is exemplified in Fig. 6.3, based on a FDMA model. (If CDMA is used, then each channel owns one CDMA code.) The purpose of data channels is to transmit data packets, while that of the control channel is to schedule and synchronize the use of data channels among hosts.

Each mobile host is equipped with two half-duplex transceivers, as described below.

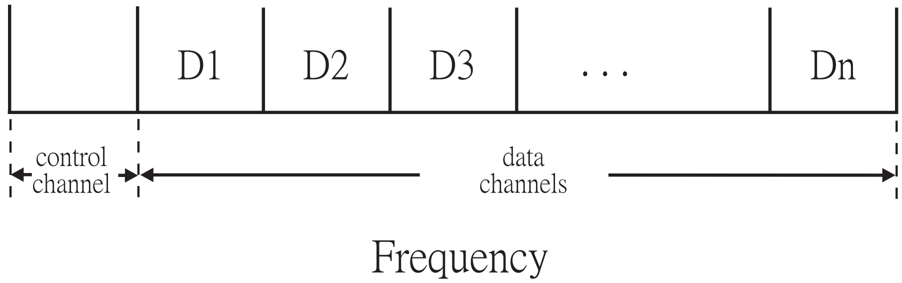


Figure 6.3: The channel model of our protocol under the FDMA technology.

- *control transceiver:* This transceiver will operate on the control channel to exchange control packets and acknowledgements with other mobile hosts and to obtain rights to access data channels.

- *data transceiver:* This transceiver will dynamically operate on one of the data channels, according to our channel assignment strategy, to transmit data packets.

Each mobile host X maintains the following data structure.

- $CUL[\,]$: This is called the *channel usage list*. Each list entry $CUL[i]$ keeps records of how and when a host neighboring to X uses a channel. $CUL[i]$ has four fields:

  - $CUL[i].host$: a neighbor host of X.
  - $CUL[i].ch$: a data channel used by $CUL[i].host$.
  - $CUL[i].type$: 'RTS' or 'CTS', indicating that $CUL[i].host$ is sending data (RTS) or receiving data (CTS).
  - $CUL[i].rel\_time$: 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 an RTS (request-to-send) to B. This RTS will carry a list of available

Table 6.1: 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_{EIFS}	length of extended inter-frame spacing
T_{RTS}	time to transmit an RTS
T_{CTS}	time to transmit a CTS
T_{curr}	the current clock of a mobile host
T_{ACK}	time to transmit an ACK
NAV_{RTS}	network allocation vector on receiving an RTS
NAV_{CTS}	network allocation vector on receiving a CTS
L_d	length of a data packet
L_c	length of a control packet (RTS/CTS)
B_d	bandwidth of a data channel
B_c	bandwidth of the control channel
τ	maximal propagation delay

channels that A may use based on its neighborhood status. On receiving the RTS, B will match the list with its $CUL[\,]$ to choose a channel for their subsequent communication by replying a CTS. How the channel is selected will depend on the channel borrowing strategy. The purposes of the RTS/CTS dialogue are thus: (i) to exchange A's and B's channel usage information to select an appropriate channel, and (ii) to warn the neighborhood of A and B not to interfere their subsequent transmission on the channel they selected to use.

The complete protocol is shown below. Table 6.1 lists the variables/constants used in our presentaiton.

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 busy after a successful exchange of RTS and CTS packets. That is, B is not equal to any $CUL[i].host$ such that

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

   b) There is at least one sending-available channel D_j for A after a successful exchange of RTS and CTS packets, where a channel D_j is *sending-available* for A if D_j is

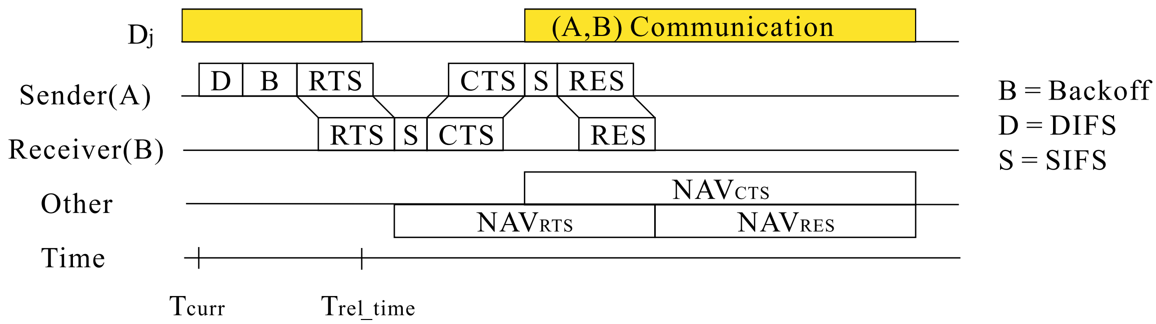


Figure 6.4: Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

not used for receiving by any neighbor of A. Formally, to be a sending-available, D_j must satisfy the following statement for all i:

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

Intuitively, this is to ensure that D_j is either not currently being used for receiving by any neighbor of A, or currently being occupied by some neighbor(s) but will be released after a successful exchange of RTS and CTS packets. (Fig. 6.4 shows how the above timing is calculated.)

If both of the above conditions hold, A puts all D_j's satisfying condition b) into its FCL. Otherwise, A must wait at step 1 until these conditions become true. Note that if the borrowing strategy is GRID-B$_{ss}$ or GRID-B$_{ds}$, then the FCL should be sorted appropriately.

2. Then A can send an $RTS(FCL, L_d)$ 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} or T_{EIFS} plus a random backoff time period. If the control channel is busy, A has to go back to step 1. Note that the waiting time will be T_{DIFS} if the FCL contains A's default channel; otherwise, the waiting time

should be T_{EIFS}. The goal is to preserve a higher priority for the owners of default channels, and to enforce a lower priority for those who intend to use borrowed channels.

3. On a host B receiving the $RTS(FCL, L_d)$ from A, it has to check whether there is any receiving-available channel D_j for B, where a channel D_j is *receiving-available* for B if no neighbor of B will be sending data using D_j after a successful exchange of RTS and CTS packets. Formally, D_j must satisfy the following statement for all i:

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

   This is to ensure that D_j is either not currently being used for sending by any neighbor of B, or currently being occupied by some neighbor(s) but will be released after a successful exchange of RTS and CTS packets. If the borrowing strategy is GRID-B$_{ss}$ or GRID-B$_{ds}$, B picks the first available channel D_j. If the borrowing strategy is GRID-B$_{sr}$ or GRID-B$_{dr}$, B picks the available channel D_j based on its borrowing strategy. Then B replies a $CTS(D_j, NAV_{CTS})$ to A after a T_{SIFS} period, where

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

   Then B tunes its data transceiver to D_j.

   On the contrary, if no receiving-available channel is found, 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 $RTS(D_j, L_d)$, it has to inhibit itself from using the control channel for a period

$$NAV_{RTS0} = T_{SIFS} + T_{CTS} + \tau.$$

This is to avoid C from interrupting the RTS/CTS dialogue between A and B. Then, C appends an entry $CUL[k]$ to its CUL such that:

$$\begin{aligned} CUL[k].host &= A \\ CUL[k].ch &= D_j \\ CUL[k].type &= \text{`RTS'} \\ CUL[k].rel\_time &= T_{curr} + NAV_{RTS1} \end{aligned}$$

where

$$NAV_{RTS1} = T_{curr} + L_d/B_d + T_{ACK} + \tau.$$

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

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

   b) Send its DATA packet to B on the data channel D_j.

   On the contrary, if A receives B's $CTS(T_{est})$, it has to wait for a time period T_{est} and go back to step 1.

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 B completely receiving A's data packet, B replies an ACK on the control channel if there is no carrier in a T_{SIFS} period.

Also, note that although our protocol will exchange timing information by packets, these are only *relative* time intervals. No *absolute* time is sent. So there is no need of clock synchronization in our protocol.

6.4 Simulation Results

We have implemented a simulator to evaluate the performance of our GRID-B protocol. 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 have 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. On the contrary, 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.

The parameters used in our experiments are listed in Table 6.2. Packets arrived at each mobile host in an Poisson distribution with arrival rate λ packet/sec. 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 Mbps/sec. If the fixed-total-bandwidth model is assumed, the total bandwidth is 1 Mbps/sec. In the following, we make observations from four aspects.

A) Determining the Grid Size: Let the radio transmission distance be r and the grid size be $d \times d$. According to our experience in [83], the ratio of r/d has significant impact to

Table 6.2: Experimental parameters.

physical area	1000×1000
no. of hosts	400
transmission range r	200
max. no. of retrials to send an RTS	6
length of DIFS	50 μsec
length of SIFS	10 μsec
backoff slot time	20 μsec
additional waiting time after T_{DIFS}	20 μsec
control packet length L_c	100 bits
data packet length L_d	$200 \times L_c$

the network throughput. So here we repeat some of the simulation results in [83] to avoid confusion. In this experiment, we change the r/d ratio to observe the effect. We use $n = 16$ data channels. Fig. 6.5 shows the network throughput with different loads under the fixed-channel-bandwidth model. We see that GRID will deliver the highest throughput at $r/d = 2$. Fig. 6.6 shows the similar experiment under the fixed-total-bandwidth model. The highest throughput is still at $r/d = \sqrt{n} = 2$. According to our experience, the best performance appears at about $r/d = \sqrt{n}$. So in the rest of the presentation, this implicit r/d ratio will be used by both GRID and GRID-B protocols.

B) GRID-B vs. GRID: In this experiment, we investigate the throughput improvement of GRID-B over GRID. We use $n = 16$ and $n = 49$ data channels here. Recall that the physical area is 1000×1000. We simulate a hot spot of 200×200 located at the center of the area, which will be resident by one forth of the mobile hosts. Fig. 6.7 shows the result under the fixed-channel-bandwidth model. GRID-B has around over 25% increase in throughput. Among the four borrowing strategies, the distance-sender-based and sequential-sender-based borrowing strategies have the best performance.

Fig. 6.8 shows the same simulation under the fixed-total-bandwidth model. We see that the throughput improvement is not as large as those under the fixed-channel-bandwidth model. GRID-B only outperforms GRID by about 10% increase in throughput under the fixed-total-bandwidth model. We conjecture that this is because channel borrowing will dis-

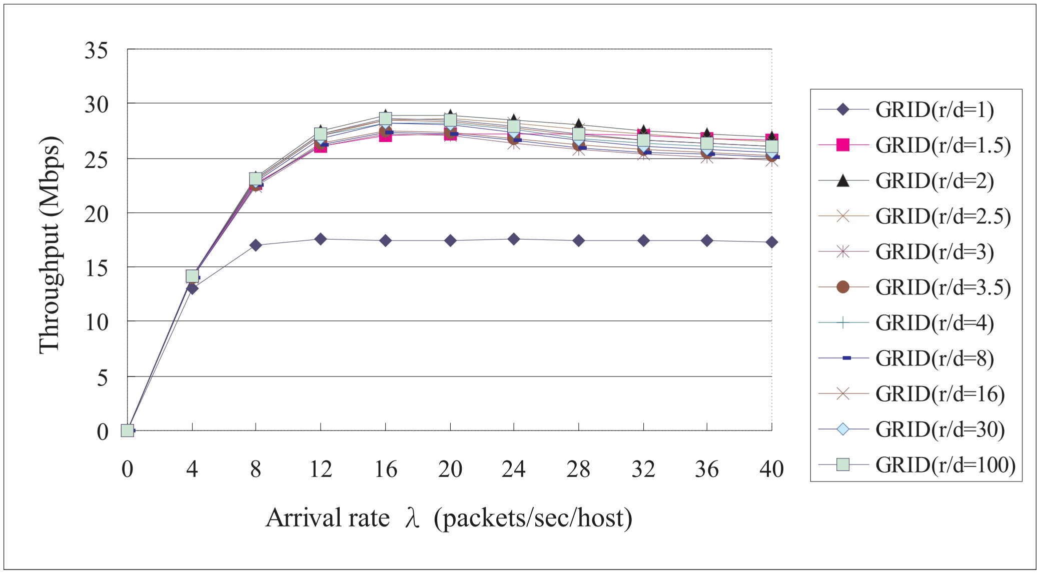


Figure 6.5: Arrival rate vs. throughput under the fixed-channel-bandwidth model at different r/d ratios.

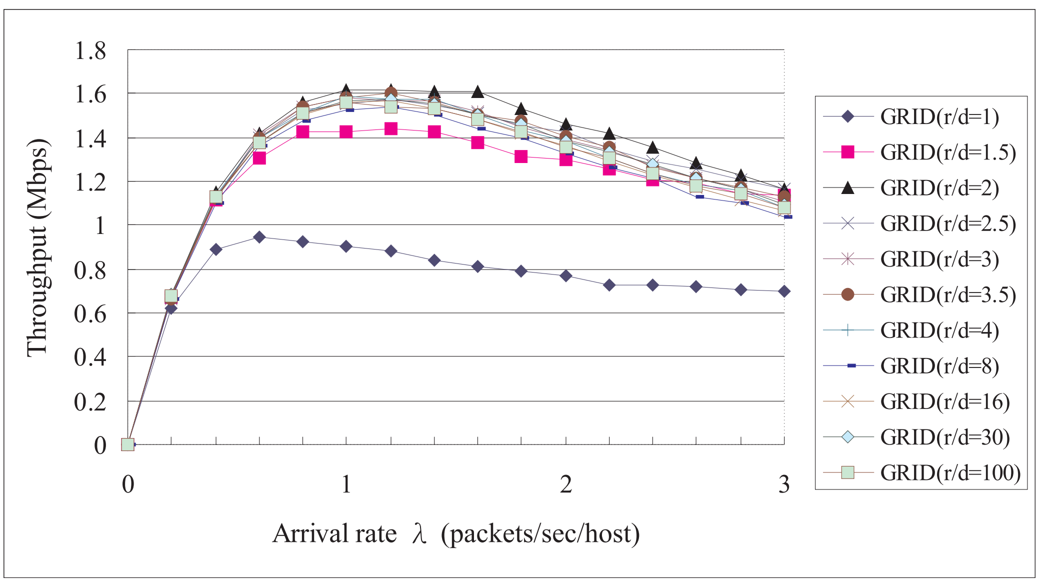


Figure 6.6: Arrival rate vs. throughput under the fixed-total-bandwidth model at different r/d ratios.

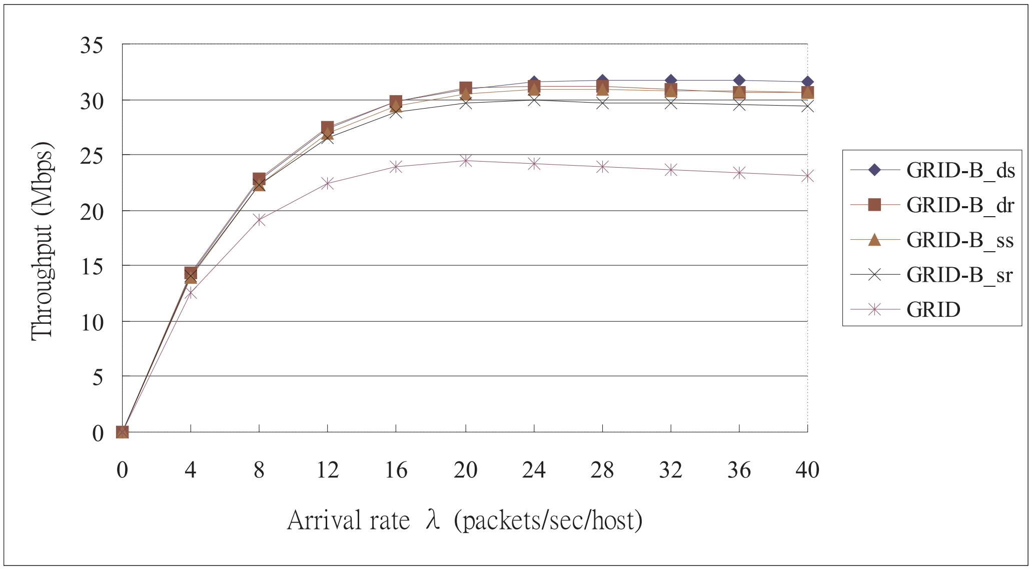
turb the channel reuse pattern, and under the fixed-total-bandwidth model, the disturbance will sustain for longer time (each channel has less bandwidth under this model).

Also, as a referential point, we show the performance of the IEEE 802.11 in Fig. 6.8. This helps us to see the motivation of using multiple channels when we are given a fixed amount of bandwidth. Fig. 6.8 verifies the benefits of using multiple channels over single channel. In the single-channel environment, any packet collision will waste the whole bandwidth of the channel. While in the multi-channel environment, a collision will only waste a faction of the total bandwidth. Taking $n = 9$ as an example, only one tenth (one control channel and 9 data channels) of the total bandwidth will be wasted. This effect is more significant when the arrival rate enlarges, where more contentions will happen.

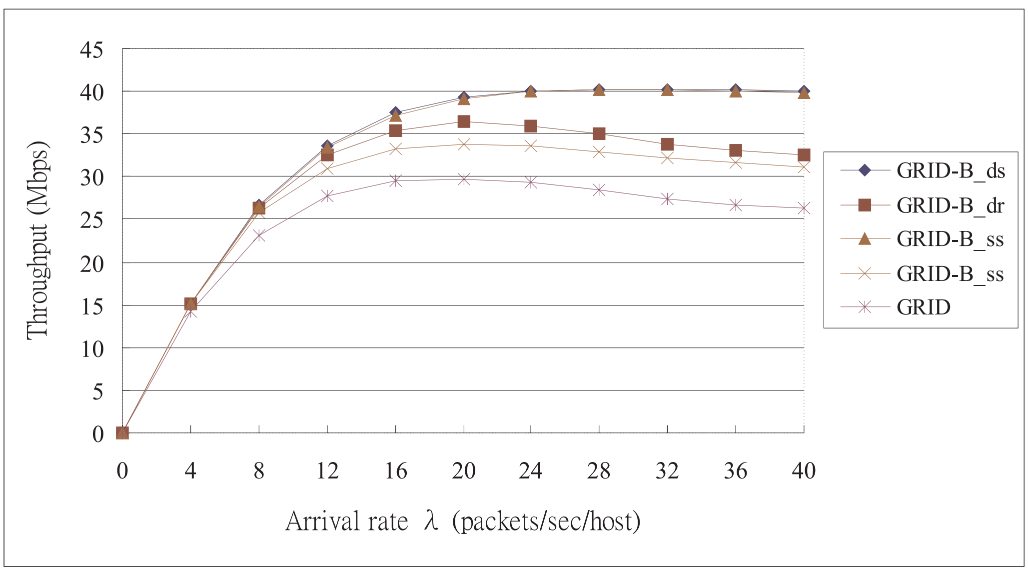
C) Effect of Hot Spots: To understand the effect of the existence of hot spots, Fig. 6.9 shows the throughput of GRID and GRID-B under the fixed-channel-bandwidth model. The design of hot spots is the same as the previous experiment. Hot spots will in fact decrease the performance of both GRID and GRID-B because the channel reuse pattern will be disturbed. As shown in the figure, the throughput degradation (peak throughput) is about 15% in GRID, and about 10% for GRID-B. It indicates our GRID-B protocol is more resilient to hot spots.

Fig. 6.10 shows the same simulation under fixed-total-bandwidth model. Similarly, we see a degradation 18% in GRID if there are hot spots, and a degradation of 12% in GRID-B if there are hot spots.

D) Packet Turnaround Time: The packet turnaround time is the time interval from a packet being initiated to the packet being completely received. We are interested in the impact of channel borrowing on the turnaround time. Fig. 6.11 shows the results under fixed-channel-bandwidth model with $n = 49$ data channels. We can see that GRID-B does have shorter packet delay than GRID, in addition to its higher throughput. Fig. 6.11 shows the same simulation under fixed-total-bandwidth model with $n = 9$ data channels.

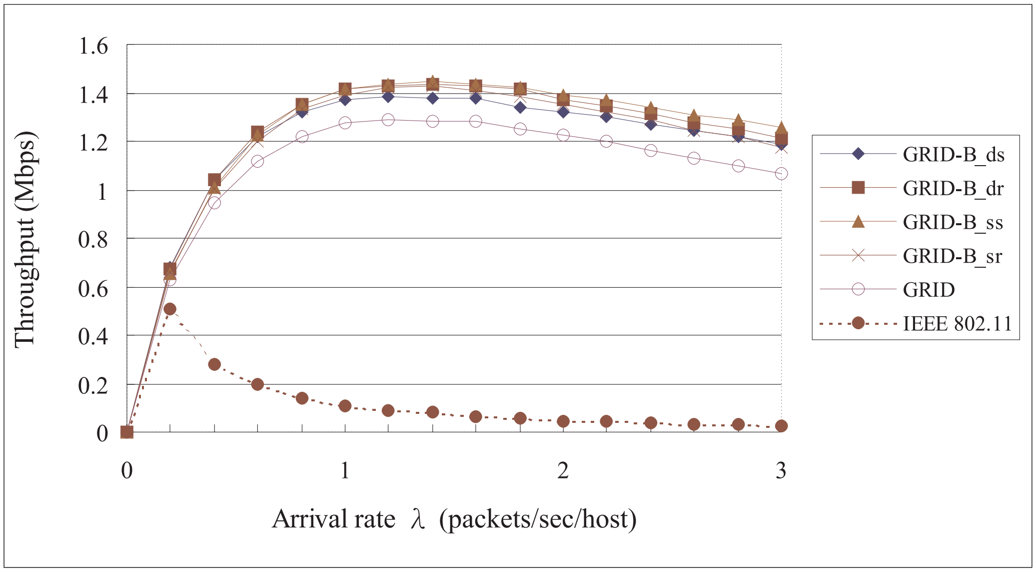


(a)

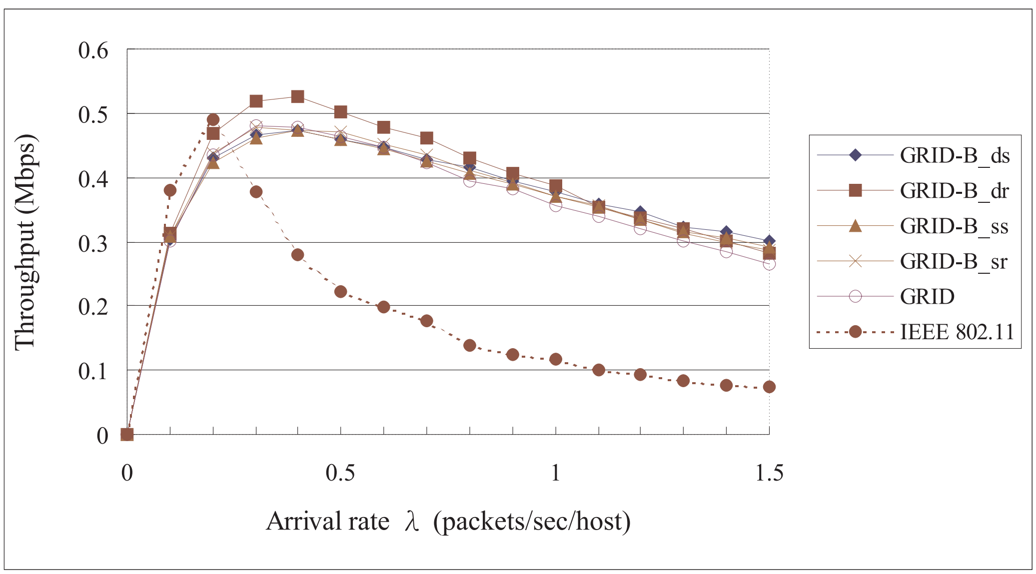


(b)

Figure 6.7: Arrival rate vs. throughput under the fixed-channel-bandwidth model with different channel borrowing sequence: (a) $n = 16, r/d = 2$ and (b)$n = 49, r/d = 4$.



(a)



(b)

Figure 6.8: Arrival rate vs. throughput under the fixed-total-bandwidth model with different channel borrowing sequence: (a) $n = 16, r/d = 2$ and (b)$n = 49, r/d = 3$.

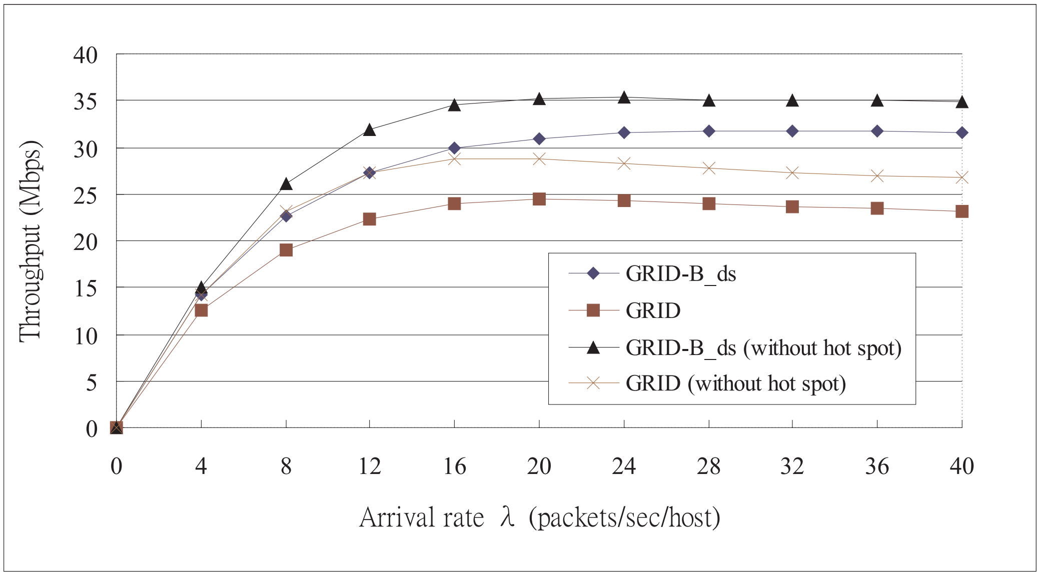


Figure 6.9: Arrival rate vs. throughput under the fixed-channel-bandwidth model with and without hot spots ($n = 16$).

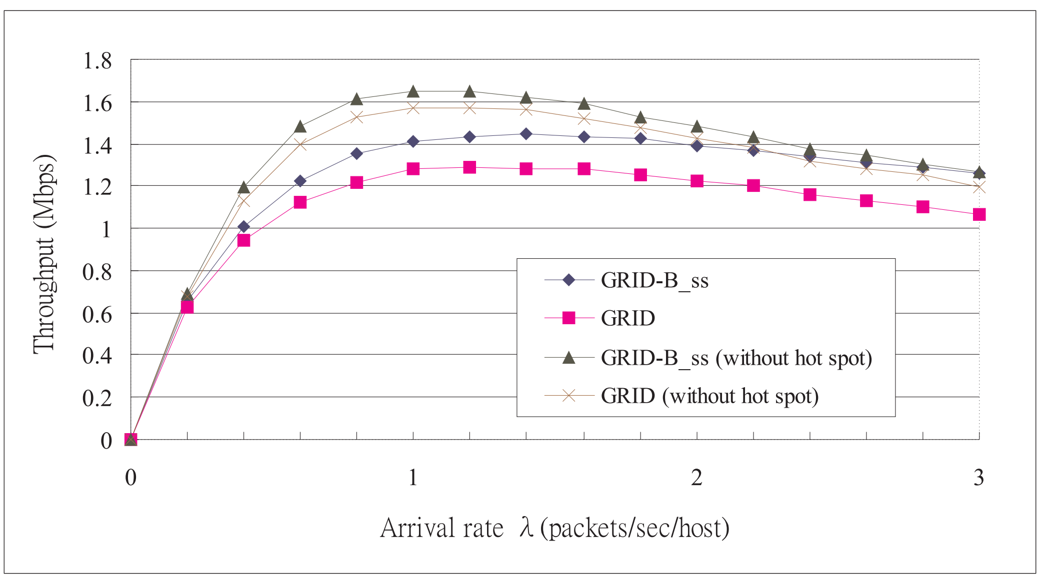


Figure 6.10: Arrival rate vs. throughput under the fixed-total-bandwidth model with and without hot spots ($n = 16$).

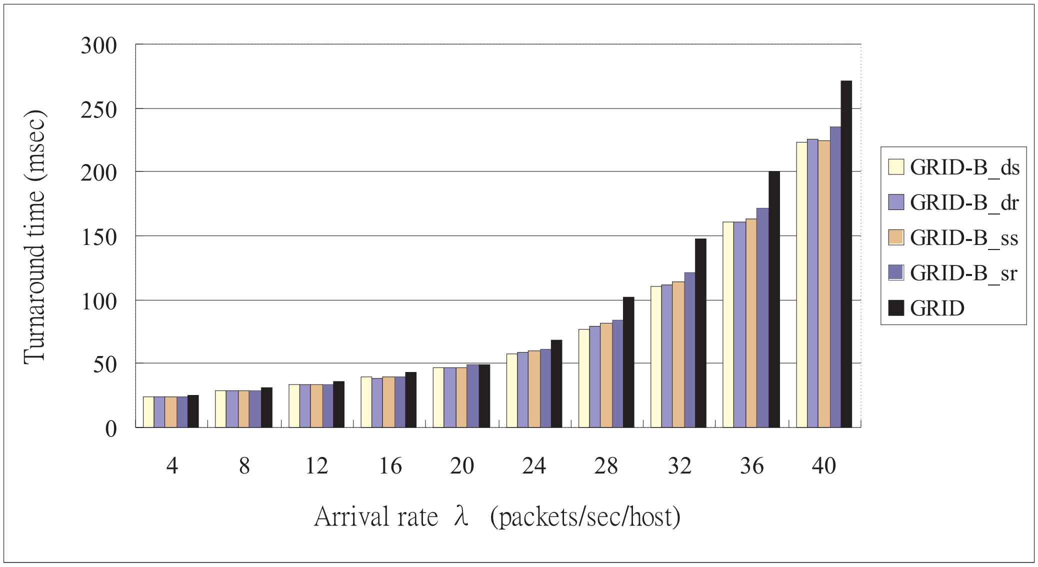


Figure 6.11: Arrival rate vs. packet turnaround time under the fixed-channel-bandwidth model for different protocols ($n = 49$).

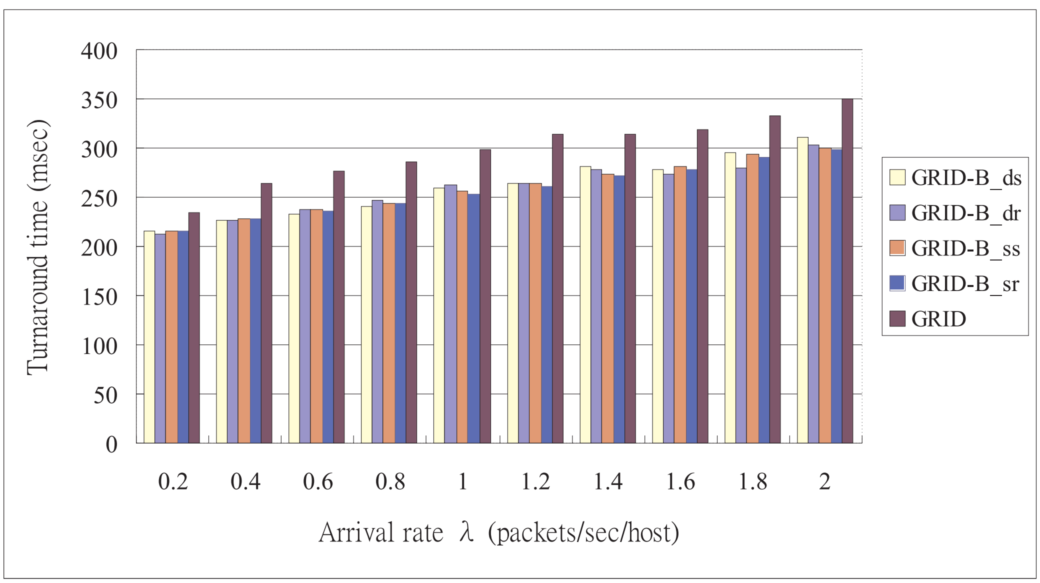


Figure 6.12: Arrival rate vs. packet turnaround time under the fixed-total-bandwidth model for different protocols ($n = 9$).

6.5 Summaries

We have proposed a new channel assignment and medium access GRID-B protocol for MANET that is characterized by interesting on-demand, dynamic, and location-aware properties. Most existing protocols do not have these properties. Simulation results show significant improvements, in both throughput and delay, over the GRID protocol, which uses static channel assignment. For future research, we are currently considering using multiple channels to provide Quality-of-Service guarantees for real time traffic. As to positioning devices, GPS is quite satisfactory for outdoor use. How to provide accurate indoor positioning (such as [27, 76]) and how to integrate location-aware protocols with such positioning systems deserve further investigation.

Chapter 7

Conclusion and Future Work

The main objective of MAC protocols is to arbitrate the accesses of communication medium among multiple mobile hosts. This is of more challenge in a MANET environment since radio signals from different antennas are likely to overlap with each other in many areas, thus serious wasting the medium. In this dissertation, we have proposed five protocols for single-channel and multi-channel MAC environment to improve system performance. These significant results with future works are summaries as following.

In Chapter 2, we have proposed a new MAC protocol for MANETs that utilizes the intelligence of power control on top of the RTS/CTS dialogues and busy tones. Channel utilization can be significantly increased because the severity of signal overlapping is reduced. Analyses and simulation results have all shown the advantages of using our protocol. As to future work, RTS/CTS is only one of the many possibilities to access wireless medium. Future research could be directed to applying the power-control concept to other domains. Recently, some works have addressed the possibility of using an intermediate relay node to transmit a packet in an indirect manner [32, 60], instead of transmitting a packet directly. It will be interesting to investigate further applying power control on this issue.

Chapter 3 has 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 chapter 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).

Based on the proposed protocol in Chapter 3, Chapter 4 further proposes 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, data packet length, host density, and host mobility, into consideration. The result shows a promising direction to improve the performance of MANET. Apparently, the importance of power control is not necessarily limited to the area of MANET. It is definitely a critical issue in many general aspects of mobile computing and wireless communication, and deserves further investigation.

Since a MANET should operate in a physical area, it is very natural to exploit location information in such an environment. In Chapter 5, we have developed a new MAC protocol for multi-channel MANET. Our channel assignment is characterized by location awareness capability and it incurs no communication cost to perform the assignment. Moreover, we have conquered the deficiency in many existing protocols which require clock synchronization or which dictate a number of channels as a function of the maximum degree in the MANET topology. Our simulation results have also indicated that it is worthwhile to consider using multiple channels under both the fixed-channel-bandwidth model and the fixed-total-bandwidth model.

We believe that there are many future research problems that can be stimulated by this work in the MANET research society. In our simulations, we have used a number of data channels (n) which is a square of some integer. Given any n, it will be interesting to investigate how to assign channels to grids to exploit the best channel reuse. It also deserves investigating the possibility that channels can be borrowed among grids. Our simulations have used a circle to model the radio coverage of antennas to determine the best r/d ratio. In practice, the best ratio may change due to many factors such as shadowing and obstacles. However, we believe that location information is still very important for channel assignment in a multi-channel MAC. In the medium access part, we have used only one control channel. Other control mechanisms are possible too. As to positioning devices, GPS is widely accepted for outdoor use. How to integrate with indoor positioning mechanisms (such as [27, 76]) is a challenging problem. The radio coverage of an antenna in an indoor environment will be more irregular. One possibility is to pre-assign channels to different locations, and then we can use location information to assist mobile hosts to choose channels to use.

In the above GRID protocol, channels are assigned to grids statically. In real world, some grids could be very crowded and thus "hot," while some could be "cold." Apparently, it will be more flexible if channels can be borrowed among grids to resolve the contention in hot spots. In Chapter 6, We have proposed a new channel assignment and medium access GRID-B protocol for MANET that is characterized by interesting on-demand, dynamic, and location-aware properties. Most existing protocols do not have these properties. Simulation results show significant improvements, in both throughput and delay, over the GRID protocol, which uses static channel assignment.

For future research, we are currently considering using multiple channels to provide Quality-of-Service guarantees for real time traffic. As to positioning devices, GPS is quite satisfactory for outdoor use. How to provide accurate indoor positioning (such as [27, 76]) and how to integrate location-aware protocols with such positioning systems deserve further investigation.

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