Interference-aware TDMA Link Scheduling and Routing in Wireless Ad Hoc Networks

SHEN, Yuxiu

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摘要

在近幾十年裏，全世界的無綫通信和移動網絡已經經歷瞭舉世矚目地飛速增長。人們期望將來的寬帶無綫通訊繫統可以爲任何人、在任何地點、任何時間，以最低的價格提供多種不同類型的全新服務。具體而言，無綫 ad hoc 網絡由於其無需固定基礎設施支持、能快速、簡單組網，因此，正在成爲下一代無綫網絡繫統的有力競爭者。此網絡對于在生成科學、軍事、醫學、産業、辦公室、個人域等多種應用範圍都有重大的影響。在無綫 ad hoc 網絡中，鏈路調度（link scheduling）對於調整多條鏈路的傳輸是一個本質性的要素。大多數現存的鏈路調度方案假設一個過於簡化的物理層幹擾模型。實際上，每條鏈路的吞吐量很大程度取决於物理層幹擾，然而物理層幹擾受到鏈路調度方案（link scheduling scheme）地根本性影響。

在此論文中，我們提齣瞭一個普適框架，用以獲取最優的時分多阯訪問（time division multiple access）鏈路調度方案，此框架適用於任何拓撲結構的多跳無綫 ad hoc 網絡。與以前的文獻所不同的是，我們通過攷慮鏈路的傳輸速率和它的物理層信擾譟比（signal to interference and noise ratio）之間的直接聯繫來最大化點對點傳輸吞吐量。具體來說，我們通過傳輸速率矩陣，矩陣的每一項

都是對應信擾躁比的函數，而把鏈路調度問題錶達成一個綫性規劃（Linear Programming）問題。基於這種錶達，跨層鏈路調度問題可以在多項式時間內被解決。

爲瞭進一步減低計算復雜度，我們提齣瞭 BTSR (bad transmission set removal) 算法 來有傚縮減綫性規劃問題的規模。更進一步地，爲瞭處理在大規模無綫網絡中的問題，我們提齣瞭一個隨機分佈式鏈路調度算法 RDSA (randomized decentralized scheduling algorithm)，與原來的綫性規劃錶達相比，它隻需用相當低的計算復雜度，而得到相對最優的時分多阯訪問鏈路調度方案。防真和數值分析錶明我們提齣的跨曾鏈路調度方案比現存的在簡化物理層幹擾模型下的調度方案，例如協議幹擾模型，提高瞭 40.57%。

Abstract

Over the last decade, wireless communications and mobile networks have undergone impressive growth worldwide. The forthcoming broadband wireless communications systems are expected to provide a wide variety of new services for anyone, anywhere, anytime, and at the lowest possible cost. In particular, wireless ad hoc networks have been identified as one of the most promising candidates for next-generation wireless systems, thanks to its ability to be set up quickly and operate without a wired infrastructure. Such networks have a significant impact on a variety of applications spanning scientific, military, medical, industrial, office, and personal domains. In wireless ad hoc networks, link scheduling is an essential element to coordinate the transmission of multiple links. Most existing link scheduling schemes assumes an overly simplistic interference model in the PHY (physical) layer. In practice, the capacity of each link is highly dependent on PHY-layer interference, while PHY-layer interference is in turn affected by the underlying link scheduling scheme. Hence, conventional link scheduling schemes that ignore such relationship fail to achieve the optimal end-to-end throughput.

In this thesis, we propose a general framework for optimal TDMA (time division multiple access) link scheduling in multi-hop wireless ad hoc networks with general topologies. In contrast to existing works, we maximize the end-to-end throughput by taking into account the explicit relationship between the transmission rate of a link and its PHY-layer SINR (Signal to Interference and Noise Ratio). In particular, we formulate the scheduling problem into a LP (Linear Programming) problem based on the rate matrices with each entry being a function of SINR. With this formulation, the cross-layer link scheduling problem can be solved in polynomial time.

To further reduce the computational complexity we propose a BTSR (bad transmission set removal) algorithm to effectively reduce the size of the LP problem. Furthermore, to handle large-scale wireless networks, we present RDSA (randomized decentralized scheduling algorithm) that achieves a suboptimal TDMA scheduling solution with dramatically lower computational complexity compared with the original LP formulation. Numerical results show that the proposed cross-layer link scheduling schemes outperform the existing ones with the adoption of simplistic PHY-layer interference model, such as the protocol interference model, by 40.57%.

Acknowledgement

I would like to express my hearty gratitude to my supervisor Professor Ying Jun Zhang for her kindly providing valuable advice and professional guidance throughout my postgraduate study. She not only guided me the first step into research, from delivering a message in a paper, revising a sentence in a presentation, to breaking an intractable problem naturally and intuitively into tractable pieces, but also always helped me identify the right research topic and keep in the right track. Her enthusiasm in research, her deep insights and her high efficiency are highly impressive and have been encouraging me to keep on moving forward in my research.

I would sincerely appreciate my co-supervisor Professor Wing Shing Wong for his patient advice, suggestions and discussions in my research work. He provided me great helps and encouragements during my postgraduate study especially when I faced some obstacles in research.

I would also like to thank Professor Soung Chang Liew, Professor Bob Li, Professor Raymond Yeung and Professor Dah Ming Chiu for their helpful discussions and suggestions in my research. Sincere thanks are also given to my colleagues, my dear friends, especially Ms. Ma Jing for her great help in my thesis writing. Hearty thanks are given to Ms. Qian Liping, Mr. Yu Xi, Mr. Chen Darui, Mr. Zhang Shengli, Ms. Fu Liqun and Mr. Zhang Jialiang, for their encouragements and helps.

Finally, this thesis is dedicated to my dearest parents. Their endless love contributes to the source of my strength to face challenges and overcome difficulties.

External Publications

Parts of the work in this thesis were published in the paper "Cross-Layer Link Scheduling for End-to-End Throughput Maximization in Wireless Ad Hoc Networks", Proc. of IEEE Wireless Communication and Networking Conference (WCNC'07), 2007.

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Chapter 1 Introduction

1.1 Background Overview

Wireless networks have attracted tremendous attention in recent years due to their potential applications in a variety of areas. Wireless radio networks such as ad hoc networks, mesh networks and sensor networks are formed of distributed nodes communicating autonomously via radio without the support of an infrastructure device. In particular, wireless ad hoc networks are collections of mobile nodes connected together over a wireless medium. These nodes can freely and dynamically self-organize into arbitrary and temporary topologies, allowing people and devices to seamlessly inter-network in areas without preexisting communication infrastructure. Unlink ad hoc networks, wireless mesh networks introduces a hierarchy in the network architecture with the implementation of dedicated nodes (referred to as wireless routers) communicating among each other and providing wireless transport services to data traveling from users to either other users or access points. They are usually used to provide a low-cost range extension to backhaul. A wireless sensor network is made up with scattered sensors in an area, in purpose of collecting data through its sensor nodes in its application. Wireless sensor networks can be seen in commercial and industrial scenarios such as including monitoring, tracking, and controlling. They are especially preferable in applications like habitat monitoring, object tracking, nuclear reactor controlling, fire detection, traffic monitoring, where connecting sensors with wire is difficult or costly. Given the easy deployment of these devices, there is a tremendous interest in the research communities to develop robust and efficient solutions with QoS (quality of services) guarantee.

1.2 Motivation and Related Work

In wireless networks, communication channels are shared by all the wireless terminals. One of the major challenges faced by wireless networks is the loss in capacity due to interference caused by simultaneous transmission. Using multiple channels and multiple radios can only alleviate but still a distance from eliminating the interference. To make communication robust and free of collision on the other hand, either of the following protocol-related solutions can be adopted. One is to employ a random access MAC (Media Access Control) layer scheme. The other way is to carefully construct a transmission schedule which can avoid conflicts and reduce the co-channel interference efficiently. An example of the latter scheme is the link scheduling in the context of time division multiplexing (TDMA).

TDMA (Time Division Multiple Access) link scheduling plays an important role in achieving high spectrum efficiency in the wireless ad hoc networks. It has drawn tremendous attention from both networking and theory fields [1-12] for the past years, due to its application in TDMA MAC protocols, which are used to eliminate collision and guarantee fairness. Determining the feasibility of a set of link rates in ad hoc networks with arbitrary topology has been shown to be NP-complete in [13, 14]. In the literature, centralized [1, 2, 3], semi-centralized [4], and distributed [5, 6] heuristics have been proposed to solve the TDMA link scheduling problem. However, even for constant ratio approximation, polynomial-time algorithms appear unlikely for general graphs.

Most prior works on link scheduling assume an overly simplistic interference model in the PHY (physical) layer. In practice, per-link data rate is dependent on the SINR (signal to interference and noise ratio) of the link, while per-link SINR is in turn affected by the underlying link scheduling scheme. Hence, conventional link scheduling schemes [7] that ignore this relationship fail to achieve high end-to-end throughput. The relationship between per-link data rate and scheduling schemes is explicitly taken into consideration in [8], where capacity region of wireless ad hoc networks is investigated.

1.3 Our Contribution

This thesis proposes a generalized framework for the optimal TDMA link scheduling in multi-hop wireless ad hoc networks with general topologies and traffics.

In contrast to previous works, the per-link data rate is a function of the actual SINR of the link. This makes the link scheduling problem much more challenging, because now per-link data rate changes with scheduling decision. In particular, we formulate the link scheduling problem into a LP (Linear Programming) problem, which can typically be solved in polynomial time. In comparison with the existing TDMA scheduling schemes, the proposed scheme achieves a significantly higher end-to-end throughput which is proved by our simulation and numerical studies.

To further reduce the computational complexity, we propose a BTSR (Bad Transmission Set Removal) algorithm to reduce the size of the LP problem. Specifically, this algorithm endeavor to pre-remove obviously "bad" transmission sets. The numerical analysis and simulation show that BTSR can dramatically reduce the size of the LP problem with lower complexity while keep the throughput the same as the optimal one.

Based on the above formulation, our last contribution is the development of a decentralized scheduling algorithm, namely RDSA (Randomized Decentralized Scheduling Algorithm), to reduce the computational complexity of link scheduling in large-scale wireless networks. RDSA divides the global optimization problem into small sub-problems by partitioning all nodes into clusters. Our simulations and numerical analysis sho w that RDSA can achieve close-to-optimal results with a dramatically lower computational complexity.

1.4 Organization of the Thesis

With overview of various kinds of wireless networks and our motivations presented in Chapter 1, the rest of this thesis is organized as follows. While some preliminary knowledge is covered in Chapter 2, the system model is presented in Chapter 3. In Chapter 4, TDMA link scheduling is formulated into a LP problem. In Chapter 5, we present a BTSR algorithm that reduces the computation complexity of the LP problem. The low-complexity distributed algorithm RDSA is described in Chapter 6. In Chapter 7, we evaluate the performance of our cross-layer TDMA link scheduling and the proposed algorithms by numerical analysis and comparisons with some existing scheduling schemes. Finally, Chapter 8 concludes this thesis and proposes several potential directions for future research.

Chapter 2 Preliminaries

2.1 TDMA Technology

TDMA (Time Division Multiple Access) is one of the multiple access technology for shared medium (usually radio) networks. In TDMA, the channel time is partitioned into frames and a TDMA frame is further partitioned into time slots. It allows several users to share the same frequency channel by transmitting in their assigned slots from fame to frame. The length of a frame is long enough so that each user in service has an opportunity to transmit. This allows multiple stations to share the same transmission medium (e.g. radio frequency channel) while using only the part of its bandwidth they require. The time slot assignment can be fixed or dynamic. If the slot assignment is fixed from frame to frame for the whole period of the connection, users have to synchronize their respective timeslots. Another variation is to assign the transmission slots dynamically, where a user is allowed to transmit only when it has a packet to send. Dynamic assignment of timeslots is performed through a reservation access procedure.

TDMA, which can be either narrowband or wideband, is widely adopted in the digital Second Generation (2G) wireless standard such as Global System for Mobile

Communications (GSM), IS-136, Personal Digital Cellular (PDC), iDEN and Digital Enhanced Cordless Telecommunications (DECT) standard for portable phones. It is also used extensively in satellite systems and combat-net radio systems. In Fig.1, TDMA frame structure shows how a data stream is divided into frames and those frames are further divided into timeslots.

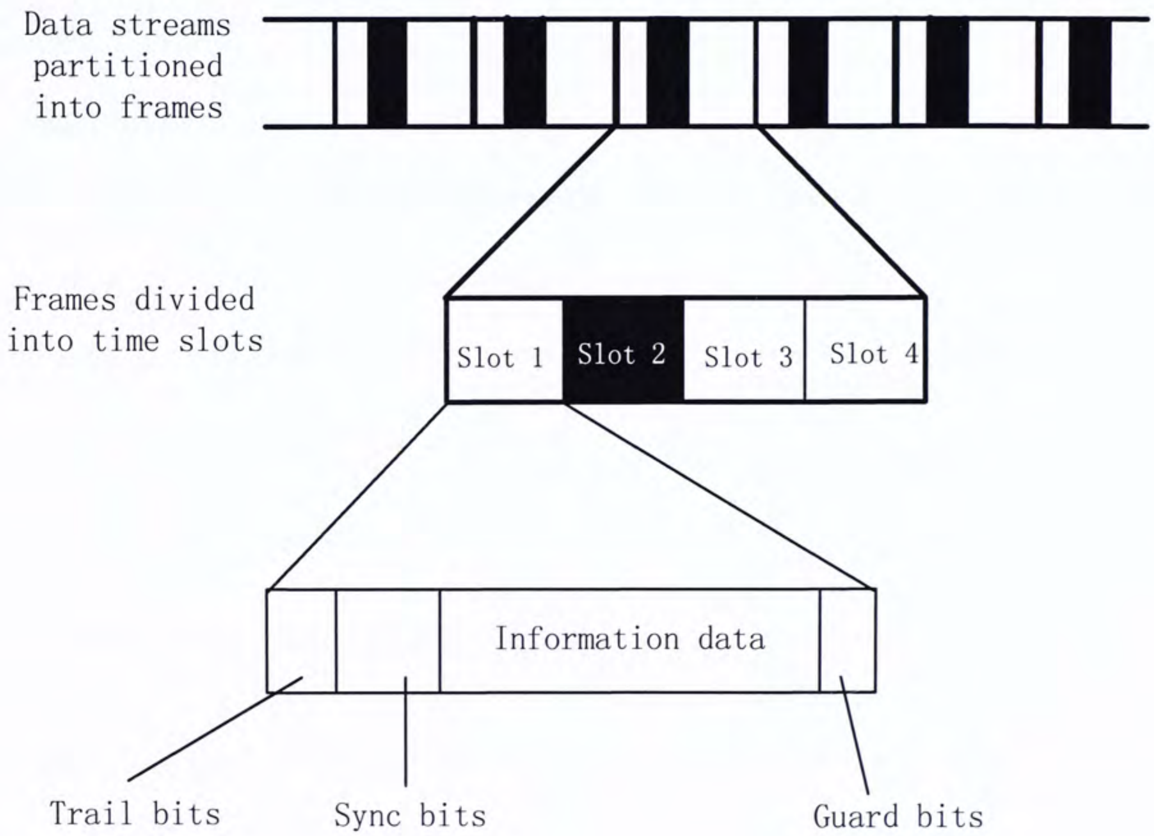


Fig. 1. TDMA frame structure

2.1.1 Features of TDMA

In TDMA, bandwidth is not divided, so all users share a single carrier frequency with multiple users. Transmission is based on time slots and data is sent in bursts. More overheads are needed including: (1) special data bursts needed to support frame synchronization; (2) preamble is used to support time slot synchronization; (3) guard time in a time slot. The advantages of TDMA include (i) it can support Frequency Division Duplex (FDD) or Frequency Division Duplex (TDD); (ii) TDMA/TDD has a relatively simple hardware architecture; (iii) it has good compatibility with digital systems; (iv) it can easily support different types of logical channels (with multi-data rates); (v) it supports mobile assisted handoff. However, TDMA also has the following disadvantages as (a) it has overhead for synchronization; (b) it has the guard time overhead; (c) channel allocation is needed.

2.2 Previous Study on TDMA Link Scheduling

The term scheduling has been used in different areas by different authors. In communication, scheduling refers to joint control of layers [9], i.e., link scheduling, power control, routing, etc.. In [10], a TDMA ad hoc network is considered and a problem of joint power control and scheduling is investigated. They propose a complex and highly centralized method to jointly solve the link scheduling, power control and routing. In their follow-up paper [11], an imperfect but simpler scheduling is introduced. However, only one-hop interference is considered as the cases in other papers [1-6].

Link scheduling in general determines the links that can be active simultaneously without violating any network constraints, i.e., transmit/receive conflicts or non-tolerable interference. Many studies have addressed link scheduling in TDMA networks can be found in [1-12]. Most of these papers only consider one-hop interference, i.e., two adjacent links (with a common node) cannot be active at the same time and any two nodes that are more than two hops apart are assumed to be conflict-free, while some of them do consider secondary interference. In [15], the similar problem of joint routing, power control and link scheduling in ad hoc CDMA (Code Division Multiple Access) networks is considered. The authors of [15] show that when performing routing and link-scheduling in a cooperative manner, the network's resources can be used more efficiently. Link scheduling and power control in ad hoc networks have also been considered in [12]. One-hop conflicts (conflicts) and high levels of interference have been avoided in a TDMA/CDMA network. The system model used in [12] is similar to that in [15]. However, in [12, 15] the airtime is assumed to be slotted and in [12] the length of transmission schedule is fixed. In our thesis, the airtime allocated to each link is a real number and the length of the schedules, i.e., the total airtime needed to schedule all the demanding traffic, is a figure of merit which we attempted to minimized. To minimize the airtime for the whole schedule and consequently the communication time can maximize the network's throughput.

However, previous works except [8] either assume a specific interference model such as the unit disk graph or maintain the SINR of each node above a threshold. A unit disk graph model is idealistic as in practice two nearby nodes may still be unable to communicate due to various reasons like barrier and channel fading. Maintaining the SINR of each node above a threshold also does not take into consideration the explicit relationship between the transmission rate of a link and its PHY-layer SINR. It is widely accepted in the wireless networking community that simplistic PHY-layer interference model cannot accurately captures unique properties of wireless networks and thus fails to achieve the optimal end-to-end throughput.

2.3 Typical Network and Interference Models

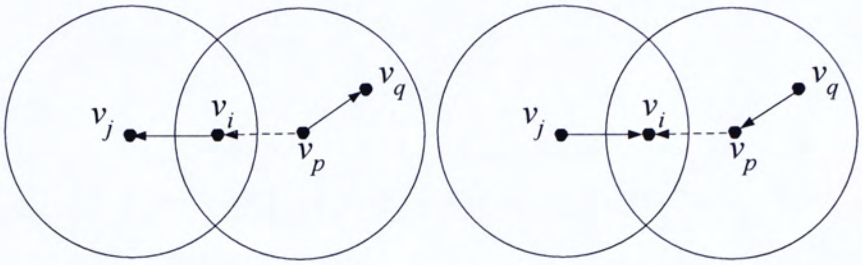
In link scheduling, to schedule two links activated at the same time, we must ensure that conflicts and large co-channel interference are avoided. In literature, several different models have been used to formulate the interference effect in wireless networks. Besides our adopted interference model which is labeled as physical interference model, there are some other typical interference models such as primary interference model, protocol interference model, IEEE802.11 protocol with request-to-send and clear-to-send (RTS/CTS) model etc.. Different interference models will lead to different link scheduling schemes which can heavily affect the throughput of the network. We briefly review them as follows.

Primary interference model is the most basic and simple model in wireless networks. In this model, the only constraint is that a node cannot transmit to or receive packets from more than one link at a time. In other words, any set of links can be activated simultaneously provided they do not have a common node. In this model, conflicts can be avoided because of the above constraint. However large co-channel interference may occur in a network with primary interference model.

In *Physical interference model*, SINR is used to describe the aggregate effect of interference in wireless networks. Traditionally, packets from node v_i can be successfully recovered at node v_j if and only if received SINR is above the minimum SINR threshold required by node v_j. The value of the SINR threshold is decided by the desired channel characteristics (e.g., data rate). In this thesis, we mainly focus on link scheduling for this model. However, our scheduling schemes are different from the previous works in that they maximizing the throughput according to the achievable SINR instead of the minimum SINR threshold. In other words, we study the optimal data rate according to the maximal SINR which can be obtained by link scheduling.

Protocol interference model was firstly introduced in [16]. In this model, packets from source node v_i are successfully received by a node v_j from the source v_i if and only if the intended destination v_j is sufficiently apart from any of the other simultaneously transmitting nodes, *i.e.*, $\|v_k - v_j\| \geq (1+\eta)\|v_i - v_j\|$ for any node $v_k \neq v_j$ and v_k is transmitting. Constant $\eta > 0$ models the scenario in which a guard zone is specified by the protocol to prevent a neighboring node from transmitting on the same channel at the same time. The protocol interference model has been widely used in the literature due to its simplicity and to the fact that it can be used to model the behavior of CSMA/CA networks. Performance of the protocol interference model heavily depends on the choice of constant parameter η. Simulation results [17] as well as analytical work [18] indicate that the protocol interference model does not necessarily provide a comprehensive view of reality due to the aggregation effect of interference in wireless networks. However, it does provide some good estimations of interference and enables the theoretical performance analysis for a number of protocols designed in literature.

RTS/CTS model has also been studied previously in literature [19]. In this model, each wireless node has its own interference range. For each pair of transmitter and receiver, all nodes within the interference range of either the transmitter or the receiver cannot transmit. The interference region, denoted by $I_{i,j}$, of the directed link v_iv_j is the union of interference region of nodes v_i and that of node v_j. When link v_iv_j is active, all other simultaneous transmitting links cannot have an end-point inside area $I_{i,j}$. For example, as shown in Fig. 2 (a), transmission from v_i to v_j and the transmission from v_p to v_q cannot take place simultaneously due to RTS. In Fig. 2 (b), transmission from v_j to v_i and transmission from v_q to v_p cannot take place simultaneously due to CTS. Although RTS/CTS is not the interference itself, we denote this communication restriction due to RTS/CTS as RTS/CTS interference model. Therefore, for every pair of simultaneous transmitting links, say v_iv_j and v_pv_q, it should be satisfied that (1) they are distinct four nodes, *i.e.*, $v_i \neq v_j \neq v_p \neq v_q$, (2) v_i and v_j do not reside in the interference ranges of v_p and v_q, and vice versa..



(a) Due to RTS (b) Due to CTS

Fig. 2. Transmission restriction due to RTS/CTS.

Chapter 3 System Model

3.1 Physical Layer Interference Model

We consider an ad hoc network with n nodes A_1, A_2, A_3,..., A_n, assuming that each node is equipped with an omni-directional antenna and that a node cannot transmit and receive at the same time. In addition, a node cannot transmit to or receive from more than one link at a time. Likewise, assume an AWGN (additive white Gaussian noise) channel with noise power density σ^2. The transmit power of node A_i is referred as P_i, the channel gain between A_i and A_j as G_{ij}, and the link between A_i and A_j as L_{ij}. Specifically, denoting the distance between A_i and A_j by d_{ij}, we can calculate G_{ij} as

$$G_{ij} = d_{ij}^{-\alpha}. \qquad (1)$$

where α is the path loss exponent [20]. Note that we adopt the AWGN channel assumption here for simplicity of presentation, though the algorithm applies to other channel models as well, e.g., fading channels.

3.2 Objective of the Problem

For such an ad hoc network, we aim at finding the optimal TDMA scheduling scheme that maximizes the end-to-end throughput. Specifically, we study two problems: (1) which nodes should transmit at the same time, and (2) how much airtime should be allocated to each group of simultaneously transmitting links. Defining S_k ($k = 1, 2, \ldots$) to be the set of links that are activated simultaneously. When S_k is active, the SINR received by node A_j from A_i ($L_{ij} \in S_k$), denoted by γ_{ij}, is given by

$$\gamma_{ij} = \frac{G_{ij} P_i}{\sigma^2 \Gamma + \sum_{\substack{A_x \in S_k \\ x \neq i}} G_{xj} P_x} . \tag{2}$$

where Γ is a constant determined by the specific coding and modulation scheme.

Consequently, the data rate that can be transmitted over link L_{ij}, denoted by $f(\gamma_{ij})$, is calculated as follows:

$$f(\gamma_{ij}) = \log(1 + \gamma_{ij}) \text{ bps/Hz} . \tag{3}$$

From Eqn. (2)-(3), it can be seen that the data rate of each link is highly dependent on the scheduling scheme, or more specifically, the co-channel links. This dependency, which is typically ignored in previous works, makes the TDMA scheduling problem in our analysis much more challenging.

Consider an illustrative example in Fig. 3. 3. Among the six nodes in the network, only node pairs (A_1, A_2), (A_2, A_3), (A_3, A_4), (A_5, A_2), (A_3, A_6) can communicate directly. Locations of the six nodes are represented by 2-D coordinates (0,0), (2,1), (4,1), (6,0), (0,2), and (6,2), respectively. The distance d_{ij}, can then be calculated from the coordinates, which is, $d_{12} = d_{52} = d_{34} = d_{36} = 2.24$, $d_{23} = d_{15} = d_{46} = 2.00$, $d_{13} = d_{53} = d_{24} = d_{26} = 4.12$, $d_{16} = d_{45} = 6.32$.

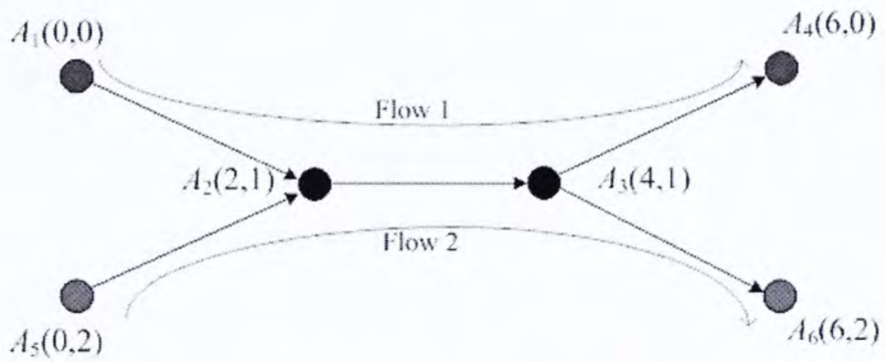


Fig. 3. A six-node wireless network with two flows of traffics: Flow 1: $A_1 \rightarrow A_2 \rightarrow A_3 \rightarrow A_4$; Flow 2: $A_5 \rightarrow A_2 \rightarrow A_3 \rightarrow A_6$.

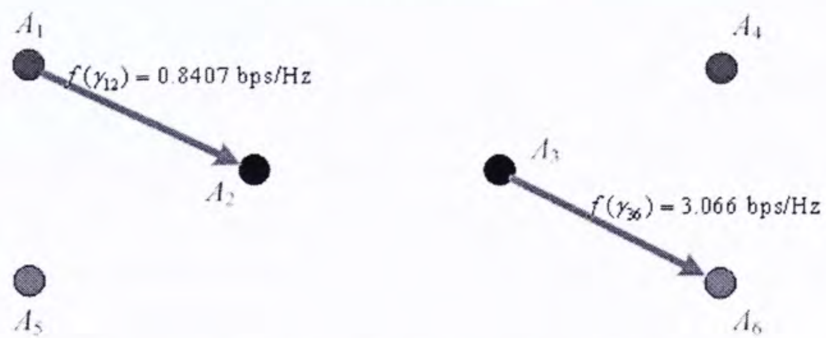


Fig. 4. One possible transmission scheme for the six-node wireless network.

For such a network, the data rate on each link can be calculated according to Eqn. (1)-(3). For example, if A_1 transmits to A_2 and A_3 transmits to A_6 simultaneously, then

$$\gamma_{12} = \frac{G_{12} P_1}{\sigma^2 + G_{32} P_3} \tag{4}$$

where G_{12} and G_{32} are calculated by Eqn. (1). Assuming $P_1 = P_2$ and $P_1/\sigma^2 = 20dB$, then γ_{12} = 0.7909 and $f(\gamma_{12})$ = 0.8407 bps/Hz, given $\Gamma = 1$. Likewise, we have $f(\gamma_{36})$ =3.066 bps/Hz.

In summary, the problem we want to solve can be defined as follows: given a wireless as hoc network with traffic requirements, our objective is to find the optimal link scheduling scheme such that the demanding traffics for all flows are satisfied and the total airtime needed is minimized. This formulation applies to any wireless network with general topologies and traffics.

3.3 Rate Matrices for Transmission Sets

For a network of size n, we define the rate matrix R for a transmission set S as an n-by-n square matrix with elements R(i,j) such that:

$$\mathbf{R}(i,j) = \begin{cases} r & \text{If node } A_j \text{ receives information at the rate of } r \\ & \text{bps/Hz with the node } A_i \text{ as the source node.} \\ -r & \text{If node } A_j \text{ transmits information at the rate} \\ & \text{of } r \text{ bps/Hz that originated at node } A_i. \\ 0 & \text{Otherwise.} \end{cases} \tag{5}$$

Positive entries R(i,j) = r in the rate matrix means node A_j receives information at rate r with node A_i being the source, while negative entries R(i,j) = -r means node A_j

transmits information at rate r originated from node A_i.

For example, if there are three possible transmission sets S_1, S_2 and S_3 in the six-node wireless network shown by Fig.3. S_1 contains transmissions from A_1 to A_2 and A_3 to A_6; S_2 contains transmissions from A_5 to A_2 and A_3 to A_4 simultaneously; S_3 contains transmission from A_2 to A_3. Then, the corresponding rate matrices R_1, R_2 and R_3 are given by

$$\mathbf{R}_1 = \begin{pmatrix} -0.8407 & 0.8407 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -3.0660 & 0 & 0 & 3.0660 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

$$\mathbf{R}_2 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -3.0660 & 3.0660 & 0 & 0 \\ 0 & 0.8407 & 0 & 0 & -0.8407 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

$$\mathbf{R}_3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -4.7004 & 4.7004 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

where non-zero entries are given by the data rates $f(\gamma)$. By such a formulation, conflicts can be automatically avoided, i.e., we avoid the case when a node transmits and receives at the same time as well as when a node transmits to or receives from more than one link at a time.

3.4 Airtime Allocation

We assume two traffic flows in the example network shown by Fig. 3: Flow 1 and Flow 2. One possible airtime allocation scheme is to allocate 0.42 units of airtime to transmission set S_1, 0.42 units to set S_2, and 0.16 units to set S_3. As a result, the end-to-end throughputs of Flow 1 and Flow 2 are both equal to 0.3531 bps/Hz, as shown in Fig.5.

Mathematically, the end-to-end throughput matrix **T** can be calculated as $\mathbf{T} = 0.42\mathbf{R}_1 + 0.42\mathbf{R}_2 + 0.16\mathbf{R}_3$,where $\mathbf{T}(1,1)$ = $\mathbf{T}(5,5)$ $= -0.3531$, $\mathbf{T}(1,2)$ $= \mathbf{T}(5,2)$ $= 0.3531$, $\mathbf{T}(2,2)$ $= -0.7520$, $\mathbf{T}(2,3)$ $= 0.7520$, $\mathbf{T}(3,3)$ $= -2.5754$, $\mathbf{T}(3,4)$ $= 1.2877$, $\mathbf{T}(3,6) = 1.2877$, and all other elements of **T** are equal to 0.

The example above just shows one possible TDMA scheduling. In the next chapter, we are going to find the optimal TDMA scheduling which can maximize the end-to-end throughput.

Chapter 4 Problem Formulation and Its Solution

Base on the rate matrices and transmission sets above we want to find the optimal air time allocation for each transmission set so that the end-to-end throughput can be maximized. Maximizing the network throughput within one unit of airtime is equivalent to minimizing the amount of airtime needed to satisfy the traffic requirements for all flows. In this chapter, we formulate this link scheduling problem into a LP problem which can minimize the total airtime under the constraints of the end-to-end traffic requirements. By solving the LP problem, we can find the optimal TDMA link scheduling solution within polynomial time. It can be easily seen that this formulation applies to any wireless ad hoc network with general traffics and topologies.

4.1 LP Formulation of Optimal TDMA Link Scheduling

Let $\mathbf{C}$ be an n-by-n traffic matrix with each entry $\mathbf{C}(j,k)$ being

$$\mathbf{C}(j,k)=\begin{cases} c & \text{If } A_k \text{ is a destination node and is expected to receive } c \text{ bits/Hz from node } A_j. \\ -c & \text{If } A_k \text{ transmit } c \text{ bits/Hz that originated from node } A_j. \\ 0 & \text{Otherwise.} \end{cases} \quad (6)$$

Note that the unit of $\mathbf{C}$ is different from that of $\mathbf{R}$. Likewise, let x_i denote the units of airtime allocated to transmission set S_i and N denote the total number of possible transmission sets. Then, link scheduling optimization problem can be formulated into

$$\min_{x_i} \sum_{i=1}^{N} x_i \quad (7.1)$$

$$\text{subject to: } \mathbf{C} \le \sum_{i=1}^{N} x_i \mathbf{R}_i \quad (7.2)$$

$$x_i \ge 0 \quad (7.3)$$

where $\mathbf{C} \le \sum_{i=1}^{N} x_i \mathbf{R}_i$ means $|\mathbf{C}(j,k)| \le \left|\sum_{i=1}^{N} x_i \mathbf{R}_i(j,k)\right|$ holds for all the entries in the traffic matrix $\mathbf{C}$ and the rate matrix $\mathbf{R}_i$ with $|x|$ denoting the absolute value of x.

Of the above equations, (7.1) corresponds to the objective function of minimizing total airtime. Eqn. (7.2) corresponds to the constraints on the end-to-end traffic requirements. Eqn. (7.3) corresponds to the fact that airtime is non-negative. In particular, $x_i = 0$ implies that transmission set S_i is not adopted in the optimal scheduling scheme.

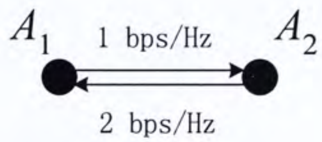


Fig. 4b. The network with flows of opposite directions.

If multiple flows are transmitted through one link, this formulation can also represent the flows very clearly. For example, in Fig. 4b, A_1 wants to transmit 1 bps/Hz data to A_2, while A_2 wants to transmit 2 bps/Hz data to A_1 at the same time. Then the traffic matrix for Fig. 4b is as follows by our definition. The values of entries in the matrix will NOT be cancelled for flows of opposite directions. It is the same for the definition of rate matrix.

$$\mathbf{C} = \begin{pmatrix} -1 & 1 \\ 2 & -2 \end{pmatrix}.$$

4.2 Solution to the Optimal Air Time Allocation Problem

The formulation in the previous subsection applies to wireless networks with general topologies and general traffics. Take the 6-node network in Fig. 3 for example, following the assumption that required traffics for the two flows are both 2 bits/Hz, the traffic matrix **C** is thus a 6-by-6 matrix, in which $\mathbf{C}(1,1) = \mathbf{C}(5,5) = -2$, $\mathbf{C}(3,4) = \mathbf{C}(3,6) = 2$, $\mathbf{C}(1,2) = \mathbf{C}(5,2) = 2$, $\mathbf{C}(3,3) = -4$, $\mathbf{C}(2,2) = -4$, $\mathbf{C}(2,3) = 4$, and all the other elements of **C** are equal to 0. In this network, there are altogether 9 possible conflict-free† transmission sets, as listed in Table 1.

Transmission Set	Links activated
S_1	L_{12}
S_2	L_{52}
S_3	L_{23}
S_4	L_{34}
S_5	L_{36}
S_6	L_{12}, L_{36}
S_7	L_{52}, L_{34}
S_8	L_{12}, L_{34}
S_9	L_{52}, L_{36}

TABLE 1 THE TRANSMISSION SETS FOR THE SIX-NODE WIRELESS NETWORK

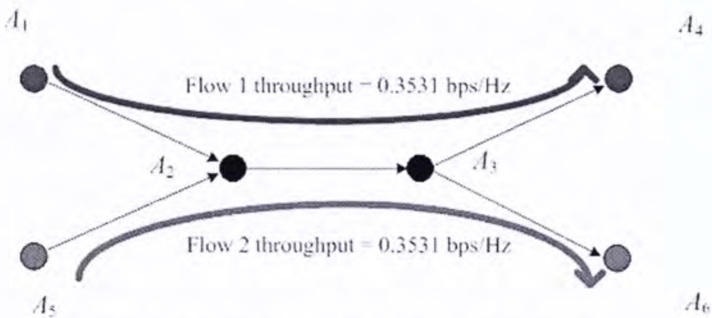


Fig. 5. The resulting traffic rates for one possible air time allocation.

†Conflict-free means a node does not transmit and receive at the same time, and a node cannot transmit to and receive from more than one node.

Assuming $P_1 = P_2 = ... = P_6$, $P_1/\sigma^2 = 20dB$ and $\alpha =$ 2, then the rate matrices $\mathbf{R}_1, \mathbf{R}_2, ..., \mathbf{R}_9$ can be calculated from Eqn. (1)-(3). For example, $\mathbf{R}_1(1,1) = -4.3870$, $\mathbf{R}_1(1,2) =$ 4.3870 , $\mathbf{R}_1(i, j) = 0$ for all $(i, j) \notin \{(1,1),(1,2)\}$.

Substituting $\mathbf{R}_1, \mathbf{R}_2, ..., \mathbf{R}_9$ to the optimization problem (7.1)-(7.3), we get a LP problem with 9 variables. Solving the problem using standard LP methodologies, we obtain the optimal airtime allocation as listed in Table 2. It is easily seen that the total airtime usage is $\sum x_i = 2.6746$ units of airtime, which leads to an end-to-end throughputs of $2/2.6746 =$ 0.7478 bps/Hz for both flows. Compared with the scheduling scheme in Fig. 5, the optimal TDMA scheduling yields a dramatic throughput improvement of 111.8%.

4.3 *n*-length Chain Network

In this section, we consider an extreme case which is the chain network with infinite length, i.e., a chain of length *n*, where $n \to +\infty$. Purpose of this study is to find some typical efficient transmission patterns which can be reused in other networks. We then compare the performance of these useful patterns with that of the existing scheduling schemes. The result shows that by adapting the transmission rate to the achievable SINR the optimal throughput can be achieved, in comparison with other transmission schemes.

We consider the scenario of a TDMA ad hoc wireless network with n+1 nodes, A_1, A_2, A_3,.....A_n, A_{n+1} and n link, L_{12}, L_{23}, L_{34},..., L_{nn+1} as shown in Fig.6. The traffic goes from node A_1 to A_{n+1}. Lengths of links are $d_{12} = d_{23} = \ldots = d_{nn+1} = d_0$. Power setting for all the nodes are $P_1=P_2=\ldots=P_{n+1}=P_0$. The optimization target is to maximize the end-to-end throughput, i.e. to maximize the achievable data rate.

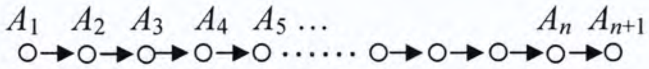


Fig. 6. The n-length chain example

Since $n \to +\infty$, all the nodes become identical. Thus we can group these nodes into M groups. Each group is assigned one unit of airtime and links within the same group are transmitting simultaneously in the time slot allocated to this group. As to grouping, we need to find the optimal number of groups M so that the throughput is maximized. Firstly, we adapt the rates to the corresponding SINRs in the transmission. Secondly, we study the fixed rate transmission case and compare the results with those of the existing scheduling schemes.

4.3.1 Adaptive Rate Transmission

For adaptive rate transmission, we want to maximize the end-to-end throughput. As each link in the chain network under this scenario is identical, all the links will have the same throughput. Thus the end-to-end throughput is equal to throughput of each link. To maximize the end-to-end throughput, we want to find the optimal M by numerical analysis. For different number of groups M, the end-to-end throughput is plotted in Fig. 7.

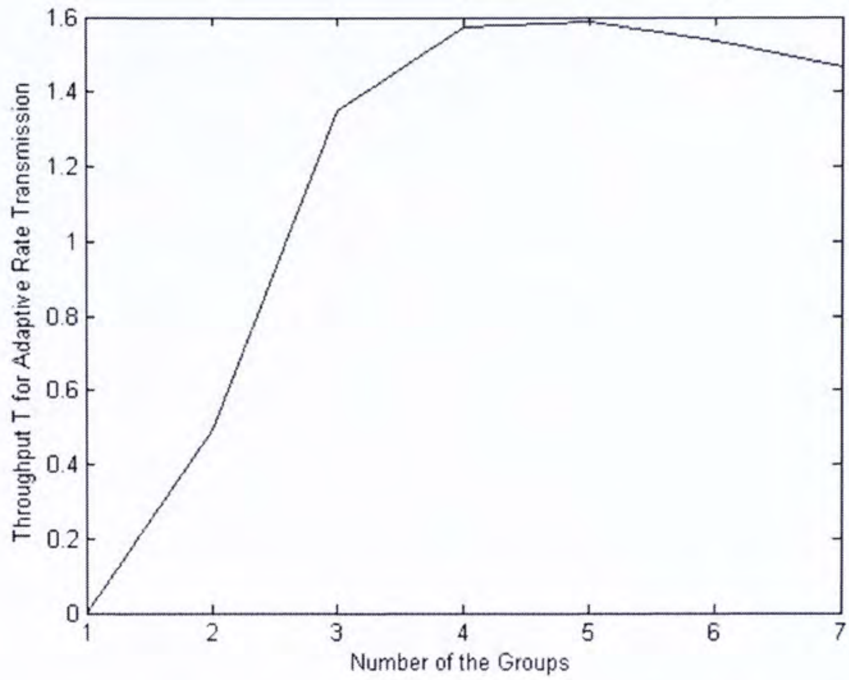


Fig. 7. The end-to-end throughput for different number of groups in the adaptive rate transmission

We conclude from Fig. 7 that the throughput increases as M increases when $M \leqslant 5$ and decreases when $M > 5$. We get $M^{opt} = 5$, i.e., the optimal number of groups is 5, which means that with all the co-channel interferences being considered, the optimal scheme for simultaneous transmission is to form links over 5 nodes.

The throughput plotted in Fig.7 is derived from the classic formula of Shannon

Capacity. However, in practical implementations, real capacity cannot always reach Shannon Capacity, but takes the form of log(1+γ_{ij} /C) due to fading or some other reasons, where C = 2/3ln(1/5*BER). C usually moves from 5 to 10 depending on the adopted coding and modulation schemes. We also apply the above analysis over fixed C and find the following results: when C = 1, use Shannon Capacity formula and we get $M^{opt} = 5$ as show in Fig.7. When C = 5, M^{opt} = 6. When C = 8, M^{opt} = 6. When C = 10, M^{opt} = 7.

From this result, we observed that M^{opt} increases as C increases. The reason of this phenomenon is clear: increasing C is equal to decreasing the received signal power as seen by SINR; thus the neighborhood nodes should be more polite to the weak one, i.e., M increases.

4.3.2 Fixed Rate Transmission

In some existing transmission schemes such as the schemes under the protocol interference model and RTS/CTS model, the optimal way for transmission is let M to be 3. The reason for this inconsistence is that we adapt the transmission rate to the corresponding SINR instead of fixing the data rate.

For fixed rate transmission, we should use another formula, Eqn. (8), to calculate the throughput T.

$$T = R * (1 - P_b) * 1 / M. \qquad (8)$$

where R is the transmission data rate and P_b is the bit error probability which is related to SINR. The relation between P_b and $SINR$ depends on the coding and modulation schemes. According to [21], bit error probability can be calculated from the corresponding SINR value. Using 16-QAM we fix the transmission rate at R = 10 bps/Hz and $P_b = C_1 * e^{-C_2 * \gamma_{ij}}$, where the values of constants C_1 and C_2 are $C_1 = 0.8$, $C_2 = 0.25$. End-to-end throughputs can be calculated for different values of M and are plotted in Fig.8.

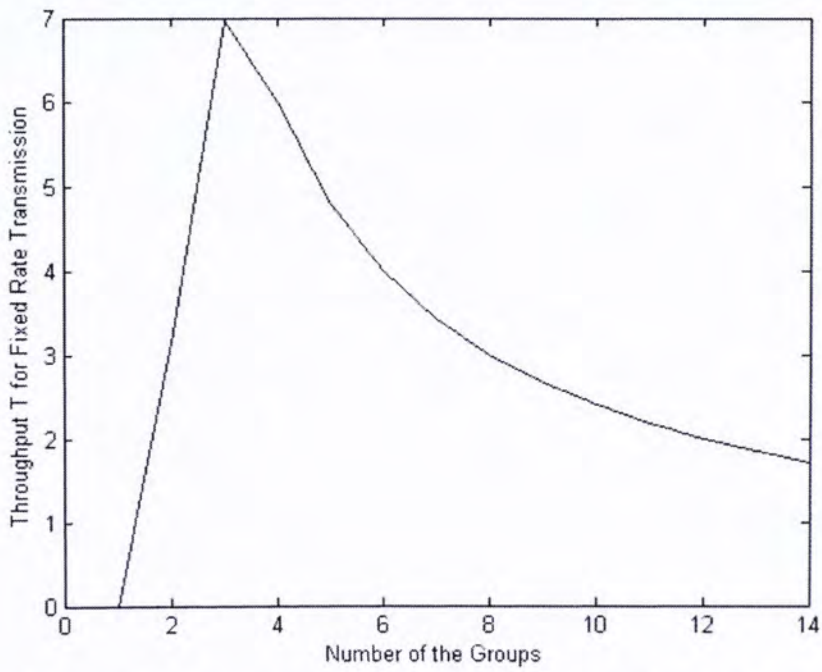


Fig. 8. The end-to-end throughput for different number of groups in the fixed rate transmission.

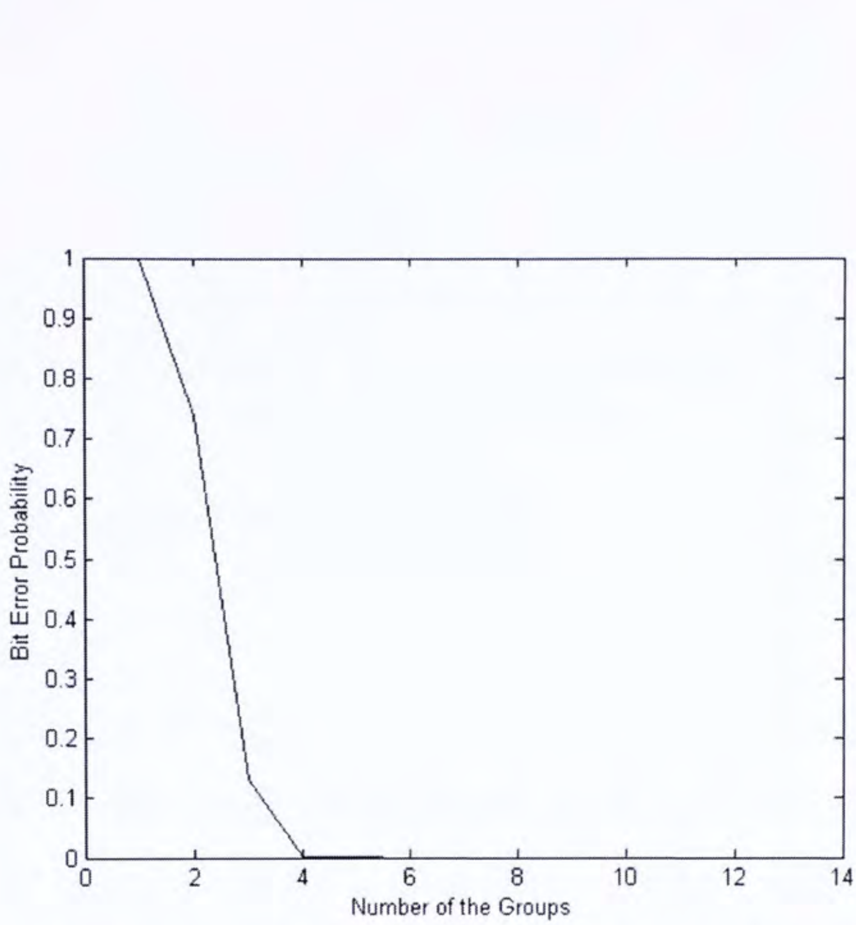


Fig. 9. Bit error probability for different number of groups in the fixed rate transmission

The corresponding bit error probabilities are also plotted in Fig.9 for different values of M. From Fig. 8 and Fig. 9, we can see that for fixed rate transmission, $M^{opt} = 3$, which coincides with the results from traditional transmission schemes. We also compute M^{opt} for 64-QAM and R = 54 bps/Hz as well as some other coding and modulation schemes, where M^{opt} also equals to 3. However, using adaptive transmission rate can further improve the end-to-end throughput which has been shown in Section 4.3.1.

Chapter 5 Bad Transmission Set Removal Algorithm (BTSR)

The above formulated LP problem can typically be solved in polynomial time. However, the problem size grows exponentially with the number of links in the network. For example, when there are m links in the network, the total number of possible transmission sets N is in the order of $O(2^m)$. In order to further reduce the optimization complexity, we propose a BTSR (Bad Transmission Set Removal) algorithm to reduce the problem size in this chapter. The algorithm is illustrated using a typical chain example. However, the principle of the proposed algorithm is applicable to other general topologies.

5.1 A 7-node Chain Example

We use a 7-node chain network, as shown in Fig. 10, to illustrate the low-complexity algorithm. There is one flow from source node A_1 to destination node A_7 with a traffic requirement of 2 bits/Hz. In this network, there are in total 20 conflict-free transmission sets. By substituting the corresponding 20 rate matrices into

(7.1)-(7.3), we get a LP problem of 20 variables. If $P_1 = P_2 = ... = P_7$, $P_1/\sigma^2 = 20dB$, $\Gamma = 1$, $\alpha = 2$, and $d_{12} = d_{23} = d_{34} = ... = d_{67}$ =1m, then the optimal scheduling solution is listed in Table 3.

Transmission Set	Airtime	Links activated
S_1	0.4559	L_{12}
S_2	0.4559	L_{52}
S_3	0.8511	L_{23}
S_4	0.4559	L_{34}
S_5	0.4559	L_{36}
S_6	0	L_{12}, L_{36}
S_7	0	L_{52}, L_{34}
S_8	0	L_{12}, L_{34}
S_9	0	L_{52}, L_{36}

Table 2 Results for the six-node wireless network

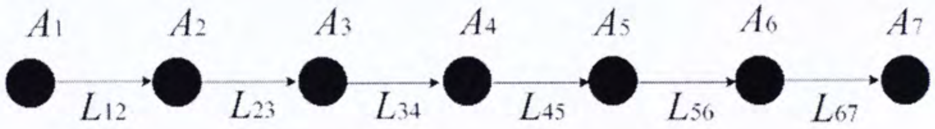


Fig. 10. A 7-node chain network.

Airtime	Links activated
0.1535	L_{23}
0.3004	L_{34}
0.3004	L_{45}
0.4553	L_{12}, L_{56}
0.3047	L_{23}, L_{67}
0.1384	L_{12}, L_{67}

Table 3 The optimal scheduling for 7-node chain example

The objective function of optimization is $\sum x_i = 1.6527$ units of air time, corresponding to an end-to-end throughput of $2/1.6527 = 1.2101$ bps/Hz. We compare this optimal throughput with conventional link scheduling schemes [7] with assumption of a simplistic PHY-layer interference model and no consideration of the secondary interference. Using their algorithms, the end-to-end throughput achieved in the 7-node chain network is 0.7589 bps/Hz. The proposed TDMA link scheduling yields a throughput improvement of 59.45%.

5.2 BTSR Algorithm

The low-complexity algorithm, namely BTSR (Bad Transmission Set Removal) algorithm, reduces the size of the LP problem by removing obviously "bad" transmission set s. We now describe the BTSR algorithm in detail as follows.

For the 7-node chain example in Fig. 10, consider a transmission set $\{L_{12}, L_{34}\}$. For such a transmission set, the transmission rates on the two links are equal to 0.9928 bps/Hz and 3.2105 bps/Hz, respectively, according to Eqns. (1)-(3). Consider another two transmission sets $\{L_{12}\}$ and $\{L_{34}\}$, in which L_{12} and L_{34} are activated during different time periods. In this case, the transmission rates on both links are equal to 6.6582 bps/Hz. To deliver the same amount of traffic as set $\{L_{12}, L_{34}\}$ transmit within one unit of airtime, we can activate set $\{L_{12}\}$ for 0.1491 units of airtime and $\{L_{34}\}$ for

0.4822 units. That is, the amount of airtime needed is reduced to 0.6313 units as opposed to 1 unit if L_{12} and L_{34} are activated at different time but not simultaneously. In this case, we can remove transmission set $\{L_{12}, L_{34}\}$, as it can obviously be replaced by other better transmission schemes. Similarly, many other sets such as $\{L_{23}, L_{45}\}$, $\{L_{45}, L_{67}\}$, $\{L_{12}, L_{34}, L_{56}\}$, ... can also be removed.

Mathematically, the BTSR algorithm is described as follows.

BTSR Algorithm: *If there exist transmission sets* $S_0, S_1, \cdots, S_K$ *such that*

$$S_0 = \bigcup_{k=1}^{K} S_k ,$$

$$\mathbf{R}_0 = \sum_{k=1}^{K} x_k \mathbf{R}_k ,$$

and

$$\sum_{k=1}^{K} x_k < 1,$$

then transmission set S_0 *can be removed.*

The pseudo code of BTSR algorithm is as follows:

Algorithm 1 BTSR Algorithm before LP formulation
Input: A wireless as hoc network with communication graph $G = (V, E)$, where $V = \{A_i\}$, $E = \{L_{ij}\}$.
Output: Transmission sets $S_1, S_2, \ldots, S_N$ without "bad" ones.
1: Generate all the possible transmission sets $S_1, S_2, \ldots, S_N$ and their corresponding rate matrices $\mathbf{R}_1, \mathbf{R}_2, \ldots, \mathbf{R}_N$ according to G;
2: **Let** $\Phi = \{ S_1, S_2, \ldots, S_N \}$;
3: **for** $i = 1$ to N **do**
4: **if** $\forall S_{j_1}, S_{j_2}, \ldots, S_{j_k} \in \Phi$ **and** $\bigcup_{u=1}^{k} S_{j_u} = S_i$

and $\sum_{u=1}^{k} x_{j_u} \mathbf{R}_{j_u} = \mathbf{R}_i$ **and** $\sum_{u=1}^{k} x_{j_u} < 1$ **then**

$\Phi = \Phi - \{S_i\}$;

end

end for

return Φ

This algorithm also applies to networks with more general topologies. For example, for the 6-node network in Fig. 3, transmission sets S_6, S_7, S_8, and S_9 in Table 1 is no better than the linear combination of sets S_1, …, S_5, and hence can be removed.

Chapter 6 Randomized Decentralized Scheduling Algorithm (RDSA)

When the size of network becomes large, it is impossible to calculate exactly the optimal scheduling due to prohibitively high computational complexity. To handle this issue, in this chapter, we develop a decentralized scheduling algorithm, referred to as RDSA (Randomized Decentralized Scheduling Algorithm). As we will show later, RDSA achieves a suboptimal scheduling solution with dramatically lower computation complexity compared with the original LP formulation.

6.1 RDSA Algorithm

The idea of RDSA is to divide the whole network into small clusters. Optimal link scheduling solution is calculated locally for each cluster. Scheduling in adjacent links is coordinated in such a way that conflicts and larger co-channel interference are avoided. The three steps are described in detail in the following.

Step 1: Clustering

Given a wireless ad hoc network, we divide the whole network into a number of clusters according to their locations. Each cluster has a cluster head, which is responsible of computing the optimal TDMA link scheduling within the cluster using the proposed algorithms in Chapter 4 and Chapter 5. Let $W = \{ S_1, S_2, \ldots S_K \}$ be a set consisting of the transmission sets that are included in the optimal link scheduling for a cluster, and $\{ x_1, x_2, \ldots x_K \}$ be the set of corresponding airtime allocation.

Step 2: Randomized scheduling based on the boundary interferences

This step is carried out within each cluster.

2.1. The cluster head randomly picks one transmission set S_u from W to transmit.

2.2. If S_u does not cause conflicts for the boundary nodes and SINR for all receiving nodes within S_u is larger than a threshold, let S_u transmit for x_u units of air time and set $W = W - \{S_u\}$. Otherwise, randomly pick another transmission set S_v in W and repeat Step 2.2.

2.3. The cluster sleeps for a short period to let other clusters have chance to transmit and repeat the sub steps 2.1 and 2.2 until W is empty.

When all the clusters finish the Step 2 as above, we will get a suboptimal TDMA link scheduling for the whole wireless ad hoc network with low co-channel interferences and conflict- free.

Step 3: Finding the Best Suboptimal Scheduling

To further improve the performance, we run Step 2 for several times and pick the best one with highest throughput i.e., using the shortest airtime. This best suboptimal TDMA scheduling will lead to a close-to-optimal airtime allocation. This suboptimal scheduling scheme is preferable for wireless networks with relatively stable traffic and topology. If the network changes fast, we can eliminate Step 3 and just use Step 1 and Step 2 in RDSA to find a suboptimal scheduling.

6.2 Pseudo Code of RDSA

The pseudo code of RDSA algorithm is as follows:

Algorithm 2 RDSA Algorithm

Input: A wireless as hoc network with communication graph $G = (V, E)$, where $V = \{A_i\}$, $E = \{L_{ij}\}$, Repetition time R, Number of clusters M.

Output: Best suboptimal TDMA link scheduling O^{opt} .

***Clustering*:**

1: Partition G into M disjoint clusters according to the locations of the nodes with cluster heads $H_1, H_2, ..., H_M$ correspondingly

Within each cluster

2: Each cluster head H_i computes the optimal TDMA link scheduling locally by calling Algorithm 1 and solving the LP problem with reduced size. Then H_i gets the sets W = $\{S_1, S_2, ...S_K\}$ containing all the transmission sets adopted in the optimal link scheduling and $\{x_1, x_2, ...x_K\}$ which is the set of corresponding airtime allocations for W.

3. **for** $j = 1$ to R **do**
4. **Let** $O_{ij} = \{\}$
5. **while** W is not empty **do**
6. H_i randomly picks one transmission set S_u from W
7. Measure the SINRs for all the receiving nodes within S_u
8. **if** S_u does not cause any conflicts for the boundary nodes and SINRs for all receiving nodes within S_u is larger than the threshold δ ,
9. **then** let S_u transmit for x_u units of air time and set $W = W - \{S_u\}$, $O_{ij} = O_{ij} \cup \{(S_u, x_u)\}$.
10. **end if**
11. H_i sleeps for a short period
12. **end while**
13. **end for**

In the whole network

14. For each cluster with cluster head H_i its optimal scheduling $O_i^{opt} = O_{ij}$, where $j = \arg\min_w(\max_i \sum_{(S_u, x_u)\in O_{iw}} x_u)$
15. $O^{opt} = \{O_1^{opt}, O_2^{opt}, ..., O_M^{opt}\}$

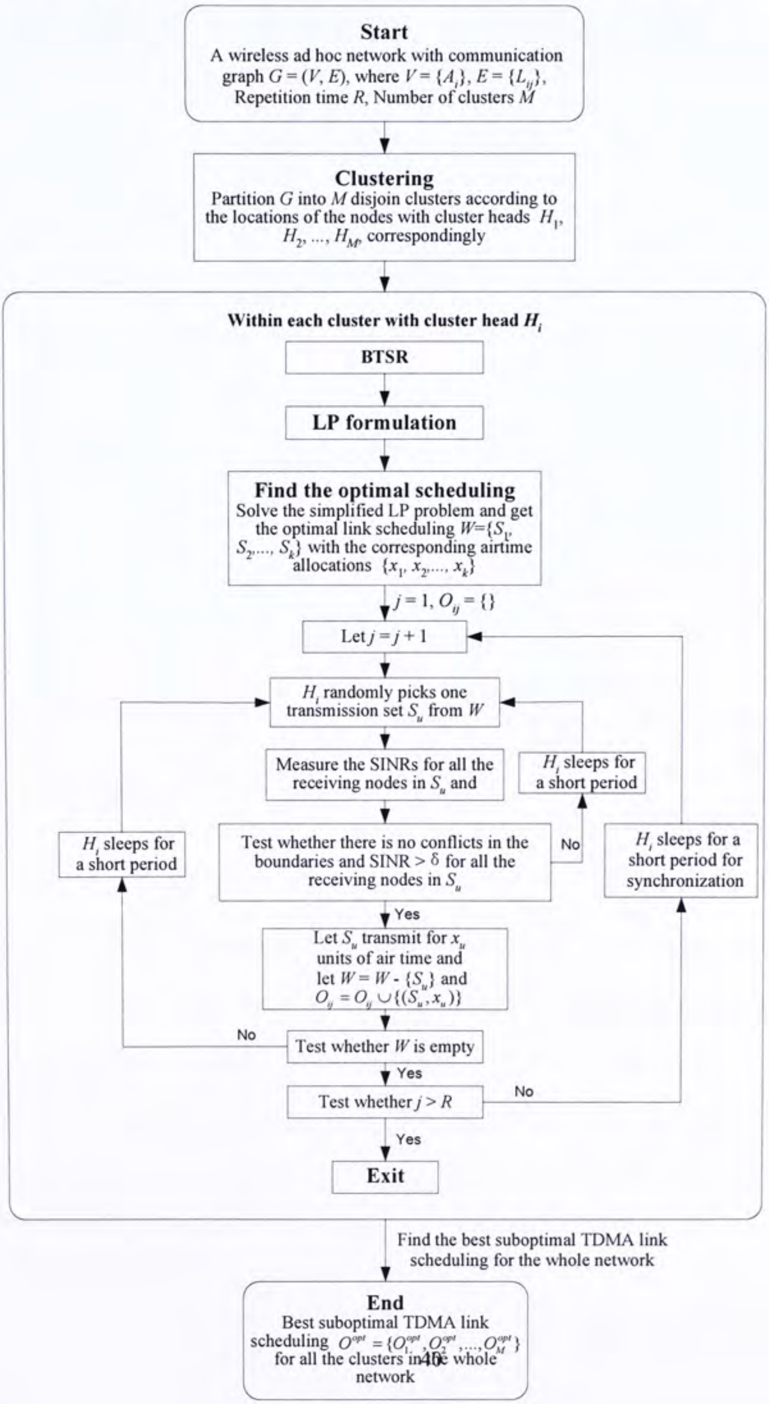
Using RDSA, the computational complexity can be reduced from O(2^m) to O($M 2^{\frac{m}{M}}$) where M is the number of clusters compared with the original LP problem. When M is large, the computational complexity will be dramatically decreased. When M is small, RDSA scheduling will be closer to the optimal one at a price of higher computational complexity. In practice, we can tradeoff between the performance and computational complexity.

Take the 6-node network in Fig. 3 for example. We divided the network into two small clusters, namely Cluster 1 = $\{L_{12}, L_{52}\}$ and Cluster 2 = $\{L_{23}, L_{34}, L_{36}\}$. Cluster 1 finds its optimal scheduling $W_1 = \{\{L_{12}\}, \{L_{52}\}\}$ with airtime {0.4558, 0.4558}. Cluster 2 finds its optimal scheduling $W_2 = \{\{L_{23}\}, \{L_{34}\}, \{L_{36}\}\}$ with airtime {0.4558, 0.4558, 0.4255}. Cluster 1 randomly chooses $\{L_{12}\}$ to transmit for 0.4558 units of airtime first, and W_1 becomes $\{\{L_{52}\}\}$. When Cluster 2 starts to transmit, it finds that $\{L_{23}\}$ has a conflict with Cluster 1 at the boundary. Therefore, it chooses $\{L_{34}\}$ in W_2 to transmit and W_2 becomes $\{\{L_{23}\}, \{L_{36}\}\}$. When the transmission of $\{L_{12}\}$ and $\{L_{34}\}$ is finished, Cluster 1 sleeps and Cluster 2 chooses $\{L_{23}\}$ to transmit, and then W_2 becomes $\{\{L_{36}\}\}$. Custer 1 waits until $\{L_{23}\}$ is finished and transmits $\{L_{52}\}$. Then W_1 = empty set. Cluster 2 transmits $\{L_{36}\}$ and W_2 = empty set. The steps stop when both W_1 and W_2 are empty. Then we get a suboptimal scheduling which avoids conflicts and larger co-channel interferences for the whole network.

6.3 The Flow Chart of RDSA

The flow chart of the RDSA algorithm is as follows:

The flow chart of the RDSA algorithm



Chapter 7 Performance Evaluation

In this chapter, the performance of our cross-layer TDMA link scheduling scheme and the proposed algorithms is evaluated by conducting simulations in several wireless ad hoc network examples with different topologies. We compare the throughput and computational complexity for the proposed scheme with that of the existing schemes which assume a simplistic PHY-layer interference model, e.g., the primary interference model, the protocol interference model.

7.1 Performance of Cross-layer TDMA Link Scheduling

In this section, we illustrate the gains of using our cross-layer TDMA link scheduling framework through a series of wireless ad hoc network examples with different topologies. We focus on several simple but typical examples in an attempt to gain insight from optimal link scheduling. We show that our cross-layer TDMA scheduling can improve the throughput by 40.57% in average compared with the scheme under protocol interference model.

Example 3: Chain topology with the equal link length (*n* nodes)

A TDMA wireless ad hoc network of size *n* with chain topology is considered as in Fig. 6. We do comparisons for different values of *n*, i.e., different lengths of the chain networks. Furthermore, two simple networks with grid topology are also considered. The length of links are the same, i.e., $d_1 = d_2 = \ldots = d_N = 1$m. The traffic is from A_1 to A_n for the chain networks. For the grid networks, the traffic is from the most left-bottom node to the node in the most right-top corner. Powers are fixed at the same level for all the nodes for the simplicity of computation however they can differ.

We compare the throughput our cross-layer TDMA link scheduling scheme using real number airtime allocation with that of the scheduling scheme under the protocol interference model which we mentioned in Section 2.4 with slotted air time in both chain networks and grid networks. In protocol interference model, for its constraint $d > (1+\eta)*L$, $\eta = 0.9$, where *L* is length of the link, *d* is the distance for any other simultaneous transmissions. The throughputs for different examples with the percentages of the throughput improvements are listed as follows in Table 4. The average percentage of throughput improvements is 49.49%.

Size of the network	Protocol interference Model with slotted time (bps/Hz)	Cross-layer TDMA link scheduling scheme with real number airtime allocation (bps/Hz)	Throughput improvement
Chain $n = 5$	0.7589	1.3316	76.05%
Chain $n = 7$	0.7589	1.2101	59.45%
Chain $n = \infty$ (bps/Hz/m)	1.3484	1.5873	17.71%
Grid $n = 16$	1.2633	2.2194	75.68%
Grid $n = 49$	1.1510	1.3645	18.55%

Table 4 Comparisons of end-to-end throughputs for different scheduling schemes

Example 4: Chain topology with variable link length (6 nodes)

In this example, a TDMA wireless network with chain topology is considered as in Fig. 11. Unlike the previous chain topology chain network examples, the length of the links vary from each other, i.e., $d_{12} = d_{23} = d_{45} = d_{56} = 1$m, $d_{34} = 2$m. The traffic is from A_1 to A_6. We calculate the throughput of the network within one unit of airtime. The target is to compare the throughput of our cross-layer TDMA link scheduling with that under protocol interference model as well as primary interference model.

Fig. 11. Chain topology with variable link length

The simulation results are as follows:

(1) Under primary interference model with real number air time allocation, the resulting throughput is 1.0380 bps/Hz.

(2) For protocol interference model, the constraint is $d > (1+ \eta)*L$, $\eta = 0.9$, where L is length of the link, d is the distance for any other simultaneous transmissions. Under this model with real number airtime allocation, the resulting scheduling scheme gives a throughput of 1.3063 bps/Hz.

(3) In cross-layer TDMA link scheduling with real number airtime allocation, the end to end throughput is 1.3474 bps/Hz.

The cross-layer TDMA link scheduling increases the throughput by 3.15% compared with that of the protocol interference model and by 29.81% compared with that of the primary interference model. Although we observed that the scheduling scheme under protocol interference model performs quite close to optimal in this example, the transmission set $\{L_{23}, L_{45}\}$ could be allowed in the protocol interference model due to the greedy property of this mode, for example in the case when this network is a part of a large network. In this case, the transmission set $\{L_{23}, L_{45}\}$ will drag down the end-to-end throughput greatly. However, cross-layer TDMA link scheduling can always avoid this kind of inefficient transmissions

Example 5: Cross Topology (13 nodes)

In this example, a TDMA wireless network with cross topology is considered as in Fig. 12. The lengths of the links are like this: $d_{12} = d_{23} = d_{34} = d_{45} = d_{56} = d_{67} = d_{89} = d_{910} = d_{104} = d_{411} = d_{1112} = d_{1213} =$ 1m. There are two traffic flows: f_1 and f_2. f_1 is originated from A_1 as the source node and targeted to A_7 as the destination. f_2 is originated from A_8 as the source node and targeted to A_{13} as the destination. We calculate the total throughput of the network within one unit of airtime. We compare the throughput of our cross-layer TDMA link scheduling with that of the scheme under protocol interference model.

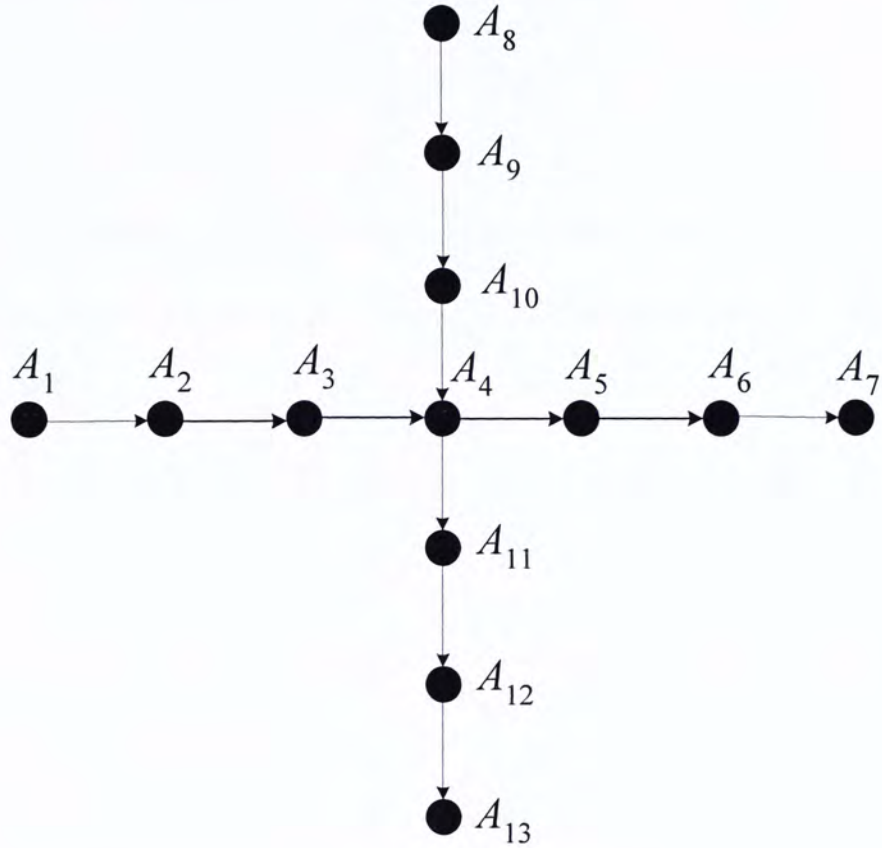


Fig. 12. Cross topology network

The simulation results are as follows:

(1) For protocol interference model, the constraint is $d > (1+\eta)*L$, $\eta = 0.9$, where L is length of the link, d is the distance for any other simultaneous transmissions. Under this model with real number airtime allocation, the resulting scheduling scheme gives a throughput of 1.0981 bps/Hz.

(2) In cross-layer TDMA link scheduling with real number airtime allocation, the

end to end throughput is 1.4669 bps/Hz.

The throughput of cross-layer TDMA link scheduling is increased by 33.59% compared with the scheduling scheme under protocol interference model. Obviously, in this example, scheduling scheme under primary interference model performs even worse than that under protocol interference model. Therefore, we conclude that our cross-layer TDMA link scheduling improves the throughput dramatically compared the scheduling schemes under protocol interference model as well as the primary interference model.

7.2 Complexity Analysis and Comparisons for BTSR+LP and LP

In Chapter 5, we have proposed the BTSR algorithm in order to reduce the computational complexity for our cross-layer TDMA link scheduling. We perform the BTSR algorithm before solving the formulated LP problem. Numerically analysis shows that BTSR algorithm reduces the problem size by 47.37% compared with the original LP problem. Simulations for different examples also shows that BTSR algorithm as well as its revised version can efficiently reduce the total complexity of the link scheduling while keep the optimal throughput same as the original LP formulation.

7.2.1 Complexity of LP Problem

To compare the total complexity of performing link scheduling we first analysis the complexity of solving the LP problem. We solve the LP problem using traditional LP tools such as GLPK (GNU Linear Programming Kit) which is intended for solving large scale linear programming problems by means of the simplex method. The simplex algorithm has polynomial smoothed complexity[††]. Simplex algorithm is the classic example of algorithm that performs well in practice but takes exponential time in the worst case. The average number of pivot steps required by simplex method is polynomial.

The number of links in the network is denoted by m and N is the number of possible transmission sets, as large as 2^m. According to [22], the average case for solving the LP problem is listed as follows:

Number of pivot steps	$O(N + m)$
In each step	(Nm-m) multiplications (Nm-m) summation (N-m) comparison
N	$O(2^m)$

Table 5 Complexity for LP problem

Therefore, the total operations needed for the average case is $O(mN^2) = O(m4^m)$.

[††]Smoothed analysis is a hybrid of worst-case and average-case analyses that inherits advantages of b oth. The smoothed complexity of an algorithm is the maximum over its inputs of the expected running

time of the algorithm under slight random perturbations of that input, measured as a function of both t he input length and the magnitude of the perturbations. If an algorithm has low smoothed complexity, then it should perform well on most inputs in every neighborhood of inputs.

7.2.2 Problem Size Reduced by BTSR

In the simulations, we generate n wireless nodes distributed in a line as the example in Fig. 6. We assume that the distance between two neighboring nodes is 1m, i.e., $d_{12} = d_{23} = d_{34} = ... = d_{nn+1}$ =1m. Each node transmits with power P = 10mW, $P/\sigma^2 = 20dB$, $\Gamma = 1$, $\alpha = 2$. We fix total airtime used to be 1 unit and maximize the end-to-end throughput. It is equivalent to the original LP problem that minimizing that total airtime used and satisfying the end-to-end traffic requirement.

Fig. 13 shows the problem sizes of the original LP problem and performing BTSR before LP formulation for different sizes of the chain networks accordingly, i.e., the chain n nodes. Table 6 lists the problem sizes for some of the examples as well as the percentages of problem sizes reduced by BTSR. In average of our simulated examples, the problem size reduced by BTSR is 47.37%. Specifically, for the chain network we also discovered that BTSR reduces the problem size for the LP problem from $O(1.618^{n-1})$ to $O(n^2)$.

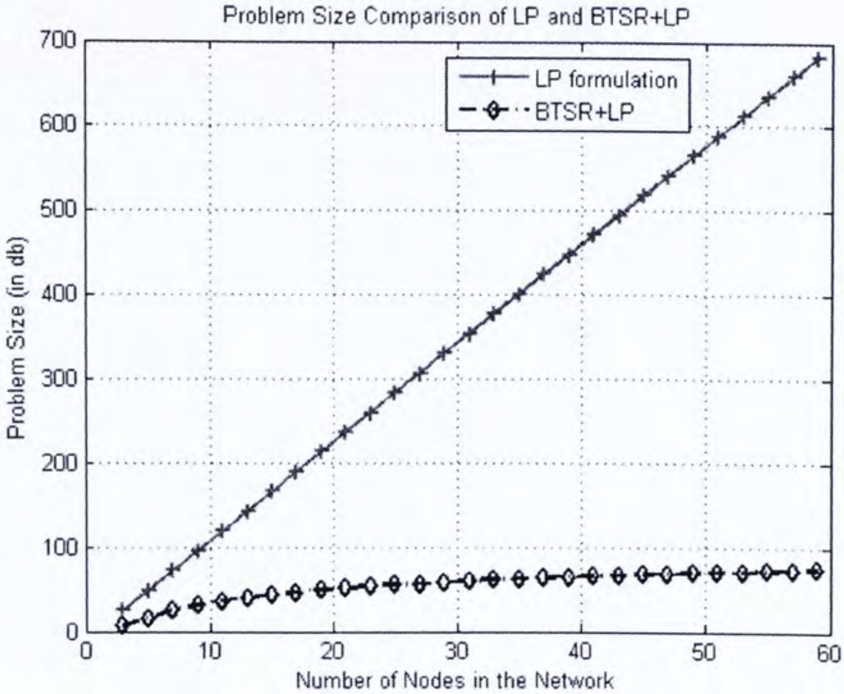


Fig. 13. Problem size comparison of LP and BTSR+LP

Size of the network	LP formulation (Problem size)	BTSR + LP formulation (Problem size)	Problem size reduced (%)
$n = 3$	2	2	0.0
$n = 5$	7	5	28.6
$n = 7$	20	12	40.0
$n = 9$	54	23	57.4
$n = 11$	143	38	73.4
$n = 13$	376	57	84.8
$n = \infty$	$F(n)$	$G(n)$	

Table 6 Problem size reduced by BTSR

7.2.3 Revised BTSR Algorithm

In Line 5 of the pseudo code for BTSR algorithm, we should compare S_0 with the optimal air time allocation to S_1, S_2,..., S_k which itself is an LP problem. In order to reduce the complexity of BTSR itself, we also propose a revised version of BTSR algorithm which only tests for transmission sets with small number of links in practice. If the set S_k is a bad transmission set, then we remove S_k as well as all the other sets S_w where $S_k \subseteq S_w$.

Pseudo code of BTSR:

Algorithm 1 BTSR Algorithm before LP formulation
Input: A wireless as hoc network with communication graph $G = (V, E)$, where $V = \{A_i\}$, $E = \{L_{ij}\}$.
Output: Transmission sets $S_1, S_2, \ldots, S_{N'}$ without "bad" ones.

Generate all the possible transmission sets $S_1, S_2, \ldots, S_N$ and their corresponding rate matrices $\mathbf{R}_1, \mathbf{R}_2, \ldots, \mathbf{R}_N$ according to G;
Let $\Phi = \{ S_1, S_2, \ldots, S_N \}$;
for $i = 1$ to N **do**
  if $\forall S_{j_1}, S_{j_2}, \ldots, S_{j_k} \in \Phi$ **and** $\bigcup_{u=1}^{k} S_{j_u} = S_i$
    and $\sum_{u=1}^{k} x_{j_u} \mathbf{R}_{j_u} = \mathbf{R}_i$ **and** $\sum_{u=1}^{k} x_{j_u} < 1$ **then**
      $\Phi = \Phi - \{S_i\}$;
  end
end for
return Φ

For example, in the 7-node chain network, instead of considering all the 2^6-1=63 transmission sets, we remove all the sets with conflicts first. Then 20 transmission sets are left. We test for $S_k = \{L_{12}, L_{34}\}$. To deliver the same amount of traffic as set $\{L_{12}, L_{34}\}$ can transmit within one unit of airtime, we can activate set $\{L_{12}\}$ for 0.1491 units of airtime and $\{L_{34}\}$ for 0.4822 units. That is, the amount of airtime needed is reduced to 0.6313 units as opposed to 1 unit if L_{12} and L_{34} are activated at different time instead of simultaneously. In this case, we call the set $S_k = \{L_{12}, L_{34}\}$ as a "bad" transmission set and remove it, as it can obviously be replaced by other better transmission schemes. Then all sets which is a superset of S_k can also be removed, e.g., $\{L_{12}, L_{34}, L_{56}\}$, $\{L_{12}, L_{34}, L_{67}\}$. Similar for sets $\{L_{23}, L_{45}\}$, $\{L_{23}, L_{45}, L_{67}\}$, $\{L_{34}, L_{56}\}$, $\{L_{45}, L_{67}\}$, $\{L_{12}, L_{45}, L_{67}\}$, they can also be removed by the BTSR algorithm. Finally, only 12 transmission sets are remained. We solve the simplified LP problem with 12 unknown variables which are corresponding to the remained 12 transmission sets, the optimal throughout keeps the same as that of the original LP problem.

7.2.4 The Complexity Issues

***Lemma 1*:** The revised BTSR algorithm reduces the total complexity for the cross-layer TDMA link scheduling from $O(m4^m)$ to $O(m^2 2^m)$ in average and from $O(e^{2^m})$ to $O(e^{m^2})$ for the worst case, where m is the number of links.

Proof: The revised BTSR algorithm does operations only for the transmission sets with size of 2, i.e., containing two links. Each iteration is to solve an equation with two variables (constant time) and to check for the supersets of the removable set (at most N operations, where N is the number of possible transmission sets, as large as 2^m). There are m*(m+1) such iterations. Therefore, the total complexity for revised BTSR is $m^2 * (N + c) = m^2 * (2^m + c) = O(m^2 2^m)$.

As we explained in Section 7.2.1, for LP problem, the average number of pivot steps required by simplex method is polynomial and it takes exponential time in the worst case. Specifically, the total number of operations needed for the average case is

$O(m4^m)$. Therefore, the total complexities for the link scheduling using LP formulation and using LP formulation with revised BTSR (BTSR+LP) can be calculated. The results are listed in Table 7.

Link Scheduling Methodology	Average Case	Worst Case
LP	$O(mN^2) = O(m4^m)$	$O(e^N) = O(e^{2^m})$
BTSR+LP	$O(m^2 2^m + m^5) = O(m^2 2^m)$	$O(m^2 2^m + e^{m^2}) = O(e^{m^2})$

Table 7 Complexity comparison

For average, applying BTSR reduces the complexity from $O(m4^m)$ to $O(m^2 2^m)$. For the worst case, BTSR reduces the complexity from $O(e^{2^m})$ to $O(e^{m^2})$. The complexity reduced by BTSR is the order of $2^m/m$ for the average case and $e^{2^m - m^2}$ for the worst case. □

7.3 Performance and Complexity Issues for RDSA

Example 6: Hierarchical topology (19 nodes)

In this example, a TDMA wireless ad hoc network of size19 with chain topology is considered. We call it hierarchical topology because this long chain forms three short chains in RDSA. In this example 19 nodes $A_1, A_2, ..., A_{19}$ spread in a line, with power for nodes $P_1 = P_2 = ... = P_{19}$, $P_1/\sigma^2 = 20dB$, $\Gamma = 1$, $\alpha = 2$, and $d_{12} = d_{23} = d_{34}$

$= \ldots = d_{1819}$ =1m. There is one flow from source node A_1 to destination node A_{19} with a traffic requirement 1 bits/Hz. Then the optimal scheduling solution can be calculated by our BTSR algorithm and LP formulation. We compare this optimal result with the suboptimal one obtained by RDSA.

In RDSA, the whole network is partitioned into three sub network which are $\{A_1, A_2, \ldots, A_7\}$, $\{A_7, A_8, \ldots, A_{13}\}$, $\{A_{13}, A_{14}, \ldots, A_{19}\}$. Total airtime is minimized for transmit 1 bps/Hz data from source to destination. Optimal scheduling is found within each cluster shown in Table 8.

Airtime	Links activated
S_0: 0.0768	L_{23}
S_1: 0.15002	L_{34}
S_2: 0.15002	L_{45}
S_3: 0.2277	L_{12}, L_{56}
S_4: 0.1524	L_{23}, L_{67}
S_5: 0.0692	L_{12}, L_{67}

Table 8 Optimal scheduling for the 7-node sub network

In simulation, we use our RDSA algorithm to schedule the 19-node chain network. In simulation, we set $\delta = 3.85$ in RDSA. The repetition time R in RDSA is set to be 3. In RDSA, one of the suboptimal link scheduling is shown in Table 9.

Sub Chain 1	Sub Chain 2	Sub Chain 3
S_3	S_2	S_0
S_1	S_1	S_1
S_0	S_0	S_3
S_2	S_5	S_2
	S_4	
S_4	S_3	S_4
S_5		S_5

Table 9 One suboptimal scheduling obtained by RDSA

We run RDSA for 5 times. In average, the total airtime cost is 0.9732 and the average throughput is 0.3716bps/Hz. We also calculate optimal scheduling using cross-layer TDMA link scheduling. The optimal throughput is 0.4034bps/Hz.The average throughput obtained by RDSA is 92.12% of the optimal throughput.

Example 7: 9-node network

In this example, a TDMA wireless ad hoc network with9 nodes is considered as shown in Fig. 14. Lengths of the links are $d_{12} = d_{23} = d_{13} = d_{34} = d_{45} = d_{56} = d_{67} = d_{78} = d_{79} = d_{89} =$ 1m. There are two traffic flows in this example, i.e., f_1 and f_2. f_1 is originated from A_1 as the source node and targeted to A_8 as the destination. f_2 is originated from A_2 as the source node and targeted to A_9 as the destination. The target is to compare the throughput of RDSA with that of optimal one (obtained cross-layer TDMA link scheduling).

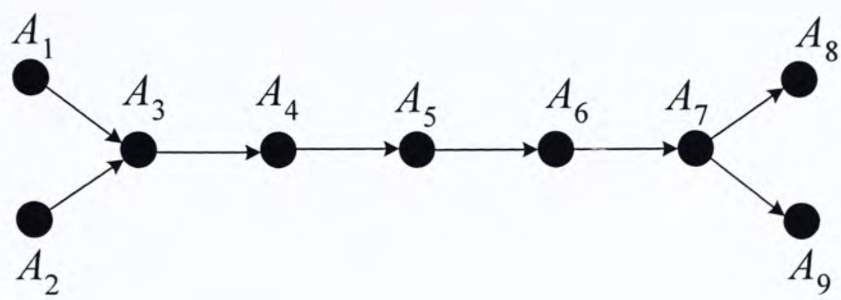


Fig. 14. 9-node network

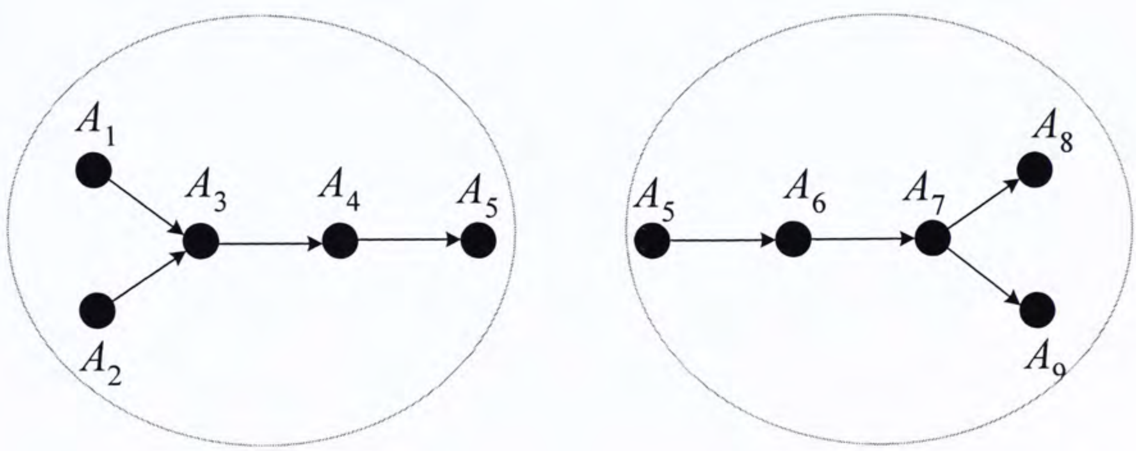


Fig. 15. Two clusters formed in RDSA

In RDSA, the whole network is partitioned into two clusters as shown in Fig.15. We set δ = 3.85. The repetition time R in RDSA is set to be 3. We run RDSA for 5 times. In average, the suboptimal throughput is 1.1472bps/Hz. We also calculate optimal scheduling using cross-layer TDMA link scheduling. The optimal throughput is 1.1848bps/Hz. The average throughput obtained by RDSA is 96.82% of the optimal throughput.

In summary, RDSA can achieve a suboptimal throughput which is 94.47% of the optimal one. However, it reduces the computational complexity from exponential to near linear.

Chapter 8 Conclusion and Future Work

8.1 Conclusions

In this thesis, we develop a cross-layer TDMA link scheduling scheme to maximize the end-to-end throughput of wireless ad hoc networks. Unlike existing works, the effect of link scheduling on per-link data rate is explicitly taken into consideration in the proposed scheme. In particular, we formulate the scheduling problem into a LP problem based on the rate matrices with each entry being a function of SINR. With this formulation, the cross-layer link scheduling problem can be solved in polynomial time. To relieve the system from computational complexity, we propose a BTSR algorithm to reduce the size of the LP problem. Furthermore, to handle large-scale wireless networks, we present a suboptimal TDMA scheduling solution – a decentralized scheduling algorithm RDSA, with dramatically lowered computational complexity compared with the original LP formulation. Numerical results for the illustrated examples show that the proposed cross-layer link scheduling schemes yield a dramatic throughput improvement compared with the existing schemes that are based on a simplistic PHY-layer interference model. Our simulations also prove that BTSR algorithm can reduce the size of the LP problem, resulting in a much lower complexity, while keeping the throughput the same as the optimal one. They also show that RDSA can achieve a close-to-optimal solution with a dramatically lowered computational complexity.

8.2 Future Work

Our work presented in this thesis can be further optimized or extended in many ways. In the following paragraphs, we give out examples of some potential directions for future research.

(1) Semi-distributed algorithm for clustering-based TDMA scheduling

In this thesis, we proposed a fully-distributed clustering-based TDMA scheduling algorithm, namely RDSA, to divide the whole large optimization problem into multiple smaller sub-problems to obtain near-optimal solutions for general wireless ad hoc networks. However, it would be more interesting if we could develop semi-distributed algorithm for practical systems, e.g. MIMO networks [23], WIMAX networks [24]. Then, semi-distributed clustering-based TDMA scheduling algorithm with high performance and low complexity for these wireless systems can be developed by using maximum matching and randomized algorithms.

(2) Power control and link scheduling with topology control

In this thesis, our frame work and presented algorithms achieve the optimal throughput via link scheduling design, namely airtime allocation. On top of that, we can further improve the throughput by allocating different transmitting power to each link, i.e., doing power control together with link scheduling. Furthermore, we can consider link scheduling and power control in a wireless network with dynamic topology. The absence of a central infrastructure implies that an ad hoc network does not have a fixed topology, which makes topology control an active research area [25-28]. Since communication capabilities of the nodes in ad hoc networks are limited by their power consumption, topology control plus power control will be a promising and challenging way to further improve the throughput of ad hoc networks.

(3) Graph theoretical approach

Many published algorithms used for link scheduling in wireless networks, e.g. [29-31], are based on finding maximal independent sets in an underlying graph. Such algorithms are developed under protocol interference model and do not consider the aggregated effect of interference. However, we propose to model the PHY-layer interference by probability in the random graph. To be specific, the amount of effect for co-channel interference from one link to another is measured by a probability. In this way, the link scheduling problem is transformed into a classical graph problem, e.g., vertex coloring problem, maximal independent set problem, etc.. We can then utilize all those existing elegant algorithms and properties in graph theory to solve our scheduling problem. Therefore, it is of interest to model and further investigate the scheduling problem in the wireless ad hoc networks through graph theory approach.

(4) Link scheduling in wireless networks with MPR (multiple packet reception) capability

Most previous works on link scheduling including this thesis are based on the traditional single-packet-reception model. However, with advanced physical-layer reception techniques, e.g., multi-user detection in CDMA [32] or MIMO networks [23], it is possible for the receiver to resolve multiple simultaneously transmitted packets. Thus more than one packet can be transmitted simultaneously and decoded successfully without collisions. With MPR [33] capability, collision occurs only when the number of simultaneously transmitted packets exceeds the maximum number of the simultaneous packets that the receiver can resolve. It is expected that, with MPR capability in the physical layer, the MAC layer will behave differently from what is commonly believed. Therefore, a challenging yet promising path with MPR capability is now waiting to be fully exploited, for greater improvements on link scheduling.

Bibliography

[1] M. Kodialam and T. Nandagopal, "Characterizing the Achievable Rates in Multihop Wireless Networks," *Proc. ACM Mobicom*, San Diego, CA, USA, September 2003.

[2] M. J. Post, P. E. Sarachik, and A. S. Kershenbaum, "A Biased Greedy Algorithm for Scheduling Multihop Radio Networks," *Proc. Annual Conference on Information Sciences and Systems (CISS)*, pp. 564-572, March 1985.

[3] J. Silvester, "Perfect Scheduling in Multihop Broadcast Networks," *Proc. International Conference on Computer Communications (ICC)*, London, England, Sepmteber 1982.

[4] M. Post, A. Kershenbaum, and P. Sarachik, "A Distributed Evolutionary Algorithm for Reorganizing Network Communications," *Proc. MILCOM*, Boston, MA, October 1985.

[5] D. Baker and A. Ephremides, "The architectural organization of a packet radio network via a distributed algorithm," *IEEE Transactions on Communications*, vol. 29, pp.1694–1701, 1981.

[6] U. K. N. Johansson and L. Tassiulas, "A distributed scheduling algorithm for a Bluetooth scatternet," *Proc. International Teletraffic Congress (ITC)*, Salvador da Bahia, Brazil, September 2001.

[7] T. Salonidis, L. Tassiulas, "Distributed dynamic scheduling for end-to-end rate guarantees in wireless ad hoc networks," *Proc. ACM MobiHoc*, Urbana-Champaign, IL, USA, May 2005.

[8] S. Toumpis and A. J. Goldsmith, "Capacity regions for wireless ad hoc networks," *IEEE Transactions on Wireless Communications*, vol. 2, no. 4, pp. 736-748, July 2003.

[9] R. L. Cruz and A. V. Santhanam, "Optimal routing, link scheduling and power control in multi-hop wireless networks," *Proc. IEEE INFOCOM'03*, March 2003.

[10] X. Lin and N. Shroff, "Joint rate control and scheduling in multihop wireless networks," *Proc. 43rd IEEE Conference on Decision and Control*, Paradise Island, Bahamas, December 2004.

[11] X. Lin and N. Shroff, "The impact of imperfect scheduling on cross-layer rate control in wireless networks," *Proc. IEEE INFOCOM'05*, Miami, Florida, March 2005.

[12] T. Elbatt and A. Ephremides, "Joint scheduling and power control for wireless ad hoc networks," *IEEE Transactions on Wireless Communication*, January 2004.

[13] E. Arikan, "Some complexity results about packet radio networks," *IEEE Transactions on Information Theory*, vol. IT-30, pp. 681–685, July 1984.

[14] I. Holyer, "The NP-completeness of edge coloring," *Proc. SIAM Journal of Computing*, vol. 10, pp. 718–720, 1981.

[15] A. Neishaboori and G. Kesidis, "Routing and uplink-downlink scheduling in ad hoc CDMA networks," *Proc. IEEE ICC'06*, June 2006.

[16] P. Gupta and P. Kumar, "Capacity of wireless networks," Journal version in *IEEE Transactions on Information Theory*, vol. IT-46, no.2, pp.388-404, 2000.

[17] J. Gronkvist and A. Hansson, "Comparison between graph-based and interference-based STDMA scheduling," *Proc. ACM MobiHoc*, 2001.

[18] A. Behzad and I. Rubin, "On the performance of graph-based scheduling algorithms for packet radio networks," *Proc. IEEE GlobeCom'03*, 2003.

[19] M. Alicherry, R. Bhatia, and L. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," *Proc. ACM MobiCom '05*, pages 58–72, 2005.

[20] T. S. Rapport, *Wireless Communications - Principles and Practice*. IEEE Press, 1996.

[21] D. Qiao S. Choi A. Soomro K. Shin, "Energy-efficient PCF operation of IEEE 802.11a wireless lan," *Proc. IEEE INFOCOM'02,* 2002.

[22] G. Sierksma, *Linear and Integer Programming: Theory and Practice*. New York, Marcel Dekker, second edition, 2002.

[23] S. Talwar, M. Viberg, and A. Paulraj, "Blind separation of synchronous co-channel digital signals using an antenna array, Part I: Algorithms," *IEEE Trans. Signal Processing*, vol. 44, no. 5, pp. 1184-1197, May 1996.

[24] A. Ghosh, D.R. Wolter, J.G. Andrews, R. Chen, "Broadband wireless access with WiMax/802.16: current performance benchmarks and future potential," *IEEE Communications Magazine*, 2005.

[25] R Ramanathan, R Rosales-Hain, "Topology control of multihop wireless networks using transmit power adjustment," *Proc. IEEE INFOCOM'00*, March 2000.

[26] R. Wattenhofer, L. Li, P. Bahl, Y-M Wang, "Distributed topology control for power efficient operation inmultihop wireless ad hoc networks," *Proc. IEEE INFOCOM'01*, April 2001.

[27] B. Ryu, Z. Zhang, Z. Huang, " Impact of Topology Control on End to End Performance for Directional MANETs," *Proc. MILCOM 2006*, October 2006.

[28] C-C Shen, C. Srisathapornphat, R. Liu; Z. Huang, C. Jaikaeo, E.L. Lloyd, "CLTC: a cluster-based topology control for ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 3, issue 1, pp. 18-32, Jan-Feb 2004.

[29] B Hajek, G Sasaki, "Link scheduling in polynomial time," *IEEE Transactions on Information Theory*, vol. 34, issue 5, part 1, pp. 910-917, Sept. 1988.

[30] M Kodialam, T Nandagopal, "Characterizing Achievable Rates in Multi-Hop Wireless Mesh Networks With Orthogonal Channels," I*EEE ACM Transactions on Networking*, vol. 13, issue 4, pp. 868-880, Aug. 2005.

[31] X. Meng, K. Tan, Q. Zhang, "Joint Routing and Channel Assignment in Multi-Radio Wireless Mesh Networks," *Proc. IEEE ICC'06*, June 2006.

[32] P. B. Rapajic and D. K. Borah, "Adaptive MMSE maximum likelihood CDMA multiuser detection," *IEEE J. Select. Areas Commun.*, vol. 17, no. 12, pp. 2110-2122, Dec. 1999.

[33] L. Tong, Q. Zhao, and G. Mergen, "Multipacket reception in random access wireless networks: From signal processing to optimal medium access control," *IEEE Commun. Mag.*, vol. 39, no. 11, pp. 108-112, Nov. 2001.