AN ABSTRACT OF THE THESIS OF

Jong-Hoon Youn for the degree of Doctor of Philosophy in Computer Science presented on May 31, 2002.

Title: Topology Independent Transmission Scheduling Algorithms in Mobile Ad Hoc Networks

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Abstract approved ______________________________________

Bella Bose

Due to the rapid growth of wireless technology, there has been a growing interest in the capabilities of ad hoc networks connecting mobile phones, PDAs and laptop computers. The distributed and self-configurable capabilities of ad hoc networks make them very attractive for some applications such as tactical communication for military, search and rescue mission, disaster recovery, conferences, lectures, etc.

In this thesis, we describe several new time scheduling algorithms for multihop packet radio networks; *MaxThrou*, *MinDelay*, *ECTS* (Energy Conserving Transmission Scheduling) *and LA-TSMA* (Location-Aided Time-Spread Multiple-Access). The *MaxThrou* and *MinDelay* algorithms focus on maximizing the system throughput and minimizing the delay bound by using constant weight codes. In these algorithms, each mobile host is assigned a word from an appropriate constant

weight code of length n, distance d and weight w. The host can send a message at the j^{th} slot provided the assigned code has a 1 in this j^{th} bit. The *MaxThrou* and *MinDelay* scheduling algorithms are better than the previously known algorithms in terms of the minimum throughput per node and/or the delay bound.

Since most of mobile hosts are operated using the scarce battery, and the battery life is not expected to increase significantly in the near future, energy efficiency is a critical issue in ad hoc networks. The *ECTS* algorithm conserves the power using strategies that allow the network interface to use the low power sleep mode instead of the idle mode, and also eliminates data collisions by introducing Request-To-Send (RTS) and Clear-To-Send (CTS) control slots. Simulation study shows that the ECTS algorithm outperforms previously known protocols.

Due to the increasing popularity of mobile networking systems, the scalability becomes a significant new challenge for ad hoc network protocols. To provide a scalable solution for mobile ad hoc networks, we introduce the LA-TSMA algorithm. Instead of assigning a globally unique TSV to each host as done in previous topology-transparent scheduling algorithms, the proposed algorithm assigns a locally unique TSV to each host. In LA-TSMA, a territory is divided into *zones,* and the mobile hosts located in different zones can be assigned the same TSV.

Topology Independent Transmission Scheduling Algorithms in Mobile Ad Hoc Networks

by

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A THESIS

Submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented May 31, 2002

Commencement June 2003

Doctor of Philosophy thesis of Jong-Hoon Youn presented on May 31, 2002

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Jong-Hoon Youn, Author

ACKNOWLEDGEMENTS

First of all, I would like to express sincere appreciation to my advisor, Dr. Bella Bose. I was fortunate to work with him. He has provided me constant encouragement, patiently guiding me throughout my research. I feel honored to have had Dr. Bella Bose as my advisor and I would like to thank him from my heart for believing in me throughout all these years.

I would like to thank each one of my committee members, Dr. Timothy Budd, Dr. Ben Lee, Dr. Toshimi Minoura and Dr. Cetin K. Koc, for their valuable comments and feedback.

My gratitude also extends to my former advisor at Kyonggi University, Dr. Seungjin Park, for his continuous support. He has provided me broad and deep advice throughout this study.

I am very grateful to my loving mother, my wife, In-Sook, and my daughters, Christina and Jamie for their constant support and love.

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1 INTRODUCTION

For the past several years, the advance of wireless communication technology has been remarkable, and numerous market studies indicate that the demand for wireless communication technology and devices will experience exponential growth in the coming years. Due to the rapid growth of wireless technology, there has been a growing interest in the capabilities of ad-hoc networks connecting mobile phones, PDAs and laptop computers.

A Mobile Ad hoc NETwork (MANET, *i.e.* multihop packet radio network) consists of a cluster of mobile hosts without fixed base station or any wired backbone infrastructure [22]. In MANETs, two mobile hosts can communicate directly with each other if they are located within their radio range. If the destination is located outside of the sender's radio range, packets are relayed via intermediate hosts located between the two hosts. Thus, each mobile host must act as a mobile router.

1.1 APPLICATIONS OF MOBILE AD HOC NETWORKS

Since MANETs have many advantages such as potential ease of deployment, dynamic network topology, distributed operation, etc., they are used in many practical applications including personal area networking, home area networking, search-and-rescue operations, disaster relief efforts and military networks. Some examples of the possible use of MANETs are listed below:

- *Emergency search and rescue*: To support emergency responses to natural disasters, rapid deployment of a dynamic network would be necessary. There are several reasons that we cannot rely on cellular networks for search and rescue operations. First, cellular networks rely on the fixed network infrastructures that may not be available because of power failure in natural disasters such as flood, earthquake and tornado. Second, cellular networks are available in urban and suburban areas only, but natural disasters can strike in any place. Third, the system capacity of conventional cellular networks is not sufficient to meet the demand in disaster situations. It is very difficult to make a cellular phone call during a minor emergency like a minor earthquake or flood. Since a MANET is a group of mobile hosts that cooperatively and spontaneously form a network without any fixed infrastructure or centralized administration, it is perfectly suited for disaster scenarios.
- *Military tactical operations*: Military operations are the main application of MANETs. In this scenarios, military units such as soldiers, tanks and

planes equipped with wireless network interfaces, are operating in a hostile environment. Thus, the network should be able to self-organize without any fixed infrastructures. Moreover, military units may fail because of enemy attack or lack of battery power, and new units may join the network. Therefore, the network must be able to reconfigure itself.

- *Wireless sensor networks*: With advances in hardware and wireless network technologies, it is expected that large-scale sensor networks will play a key role in monitoring, collecting and disseminating environmental information. For example, in forest fires, it is crucial to get the current environmental information such as the direction of wind, humidity and thermal gradients. Based on the collected environmental information, fire fighters can respond more quickly and effectively. We can find another example of wireless sensor networks in the military application. Lots of sensors that are dropped from several airborne platforms form a wireless ad hoc sensor network in a hostile territory, and then transmit the collected information back to the airborne platform.
- *Civil applications*: There is a wide range of applications for civil environments. In a classroom, an MANET can be formed between students' laptop computers and the workstation of the teacher for an interactive and effective lecture. Also, in a large metropolitan area, Taxicabs equipped with wireless network interface and Global Position

System (GPS) may form a MANET to study the traffic conditions and plan the route effectively.

1.2 TECHNICAL CHALLENGES AND RESEARCH ISSUES

The key characteristics of MANETs are highly dynamic and multihop topologies, limited channel bandwidth and scarce battery power.

- *Highly dynamic network topology*: Since hosts are free to move, the network topology may change arbitrarily and rapidly.
- *Limited channel bandwidth*: In general, wireless channel bandwidth is significantly lower than wired networks. Furthermore, the insufficient bandwidth decreased further due to the effects of multiple access, channel fading, noises, signal interference, etc.
- *Scarce battery power*: Some or all of the hosts in MANETs may have scarce energy due to short battery lifetimes.

These characteristics make the traditional protocols for wired networks unsuitable for MANETs, and demand specialized protocols. Thus, MANET is becoming a more and more interesting research topic, and there are many research projects performed by academic research groups, industries and government agencies worldwide. Some of the key research issues are listed below.

- *Routing*: Due to the extremely random and sporadic nature of MANETs, the issue of delivering packets between any pair of source and destination hosts becomes a very formidable challenge. Many protocols have been proposed to perform this task and they can be classified as either proactive or reactive schemes. Proactive schemes maintain consistent and up-to-date routing information while reactive schemes create and maintain a structure only when desired by the source host.
- *Multicasting*: Since the applications of MANETs are characterized by close collaboration of teams, and a lot of multimedia collaborative applications such as video and audio conferencing involve multiparty sessions, the multicast protocols for MANETs are becoming more and more important. In MANETs, multicasting is another challenge because the multicast tree is no longer static due to the dynamic network topology.
- *Security*: Since many applications of MANETs are in security sensitive settings such as military tactical operations, emergency rescue, policing, etc., security is an important issue. However, providing this security can be very difficult, because wireless networks are generally more vulnerable to physical security threats than wired networks. Furthermore, an MANET has other security problems because any malicious host may compromise the routing protocol functionality by disturbing the route discovery process. Thus, efficient message authentication and key distribution / management schemes are strongly required.

- *Quality of Service (QoS)*: Although a lot of research has been done on supporting QoS in the Internet and other network architectures, most of them are not suitable in the MANET environment because of the highly fluctuating nature of the quality of packet delivery, dynamic topology, unreliable wireless transmission and medium access contentions [11, 35, 46, 48]. In MANETs, supporting end-to-end QoS at different levels will be a challenging research problem, and require extensive investigation.
- *Internetworking with Internet*: In near future, a MANET can serves as an autonomous system or a multihop wireless extension to the Internet. Such MANETs will be designed with seamless connectivity to the global Internet infrastructure. Since Mobile IP protocol supports transparent host roaming within the Internet, it should be deeply investigated in order to give mobile hosts in MANETs the ability of accessing the Internet and other IP based networks.
- *Energy Efficiency*: Since most mobile hosts are operated using the scarce battery, and the battery life is not expected to increase significantly in the near future, energy efficiency is one of the most important design aspects of mobile networks. Especially, for wireless sensor network, the energy efficiency is the primary goal because it is usually very difficult to change or recharge batteries for randomly scattered wireless sensors. Most ongoing research is focusing on designing energy efficient Medium Access Control (MAC) and routing protocols that distributes information

while consuming minimal bandwidth and energy [16, 21, 40, 41, 49,55, 56, 57, 61, 67, 68].

1.3 OBJECTIVE

The rapid growth of the real-time and multimedia applications has created a need to have constant and predictable data delivery service. The goal of our research is to accomplish multimedia data transmission over MANETs with various Quality of Service (QoS) guarantees such as minimum throughput, bounded delay, low delay jitter, etc. Although the IEEE 802.11 Distributed Coordination Function (DCF) protocol is widely used as the MAC layer for MANETs, it doesn't provide real mechanisms for QoS, which is strongly desired in real-time multimedia applications. Thus, scheduling-based MAC protocols are potentially better suited for real-time multimedia traffic. In this thesis, we introduce new transmission-scheduling algorithms that guarantee minimum bandwidth and bounded maximum delay.

1.4 THESIS ORGANIZATION

The remainder of this thesis is organized as follows. In the following chapter, we review contention-based medium access control protocols, and introduce some preliminaries and the previously known topology-transparent algorithms.

In Chapter 3, we show that the topology-transparent transmission-scheduling problem is equivalent to the problem of constructing constant weight codes which satisfy certain properties. Then, we describe two proposed scheduling algorithms using the constant weight codes. Our simulation study shows that the proposed algorithms outperform the previously known algorithms in terms of mean system throughput. Chapter 4 describes the energy efficient scheduling algorithm, called Energy Conserving Transmission Scheduling (ECTS). The ECTS algorithm conserves the power using strategies that allow the network interface to use the low power sleep mode instead of the idle mode. Chapter 5 depicts the scalable scheduling algorithm, called Location-Aided Time-Spread Multiple-Access (LA-TSMA). The LA-TSMA algorithm not only provides a scalable MAC-layer solution for MANETs but also improves the system throughput significantly. Finally, Chapter 6 summarizes our work and gives some suggestions for future research directions.

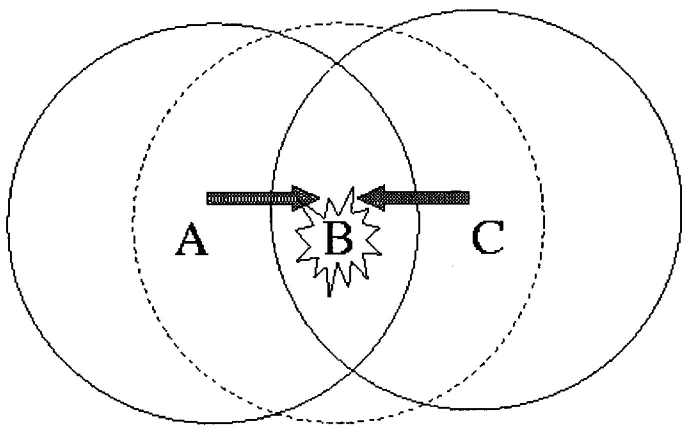
2 A REVIEW OF EARLY MAC PROTOCOLS

Since the wireless medium is a broadcast medium, multiple simultaneous transmissions can result in collision. A medium access control (MAC) protocol defines rules that allow the hosts to share the medium in an efficient and fair manner. Therefore, MAC protocol is a key issue that determines the performance of a packet radio network. Wireless MAC protocols have been studied extensively since the 1970s, and many MAC protocols have been developed for wireless communication networks [6, 12, 13, 14, 15, 18, 20, 26, 28, 30, 34, 38, 58, 60, 65, 69, 70, 71, 72]. In this chapter, we review some MAC protocols in the literature.

2.1 CONTENTION-BASED WIRELESS MAC PROTOCOLS

The first MAC protocol used in multihop packet radio networks was the Carrier Sense Multiple Access (CSMA) protocol. In CSMA, the sender first senses the radio channel, and only transmits the packet if the channel is idle. If the channel is busy, the sender must wait until the channel is idle. Although the CSMA protocol senses the channel before transmission, a packet sent by a host *S*, can collide at the receiver with another packet sent by a different host *H*, which is outside the range of *S*; the host *H* is referred to as the hidden terminal of *S* [30]. As shown in Figure 2.1, *A* can communicate with *B*, and *B* can communicate with *C*. However, *C* is located out of *A*'s transmission range. Thus, while *A* is transmitting its packets to B, *C* may sense the channel idle.

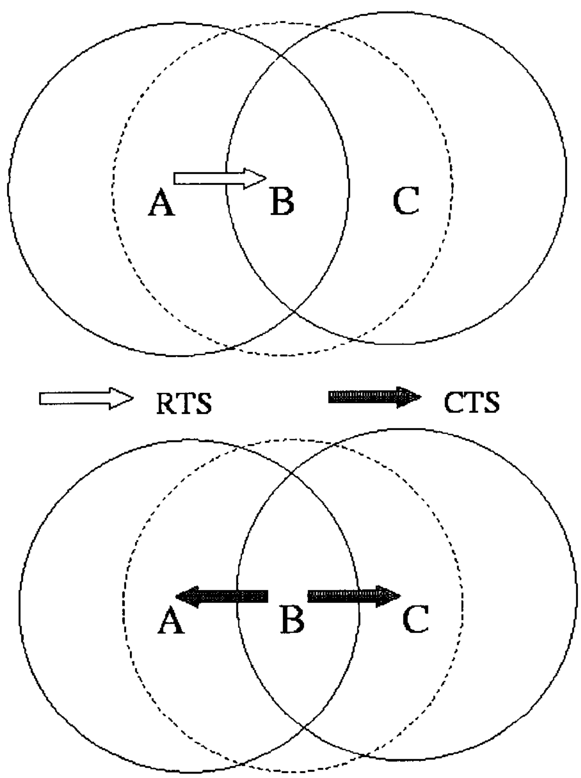
Figure 2.1: Hidden Terminal Problem



To solve the hidden terminal problem, the Multiple Access with Collision Avoidance (MACA) protocol was proposed by Karn [28]. In MACA, a mobile host first transmits a Request To Send (RTS) control message whenever it wants to transmit a packet. When the receiver receives an RTS message, it responds with a Clear To Send (CTS) control message. A CTS message informs other adjacent hosts that they are not allowed to send. On receiving the CTS message, the sender begins transmitting the data packet. This back-and-forth exchange is necessary to avoid the 'hidden terminal' problem. Since the protocol described above informs the host C that the host B is busy, the host C can hold its packet.

The RTS / CTS mechanism is shown in Figure 2.2. Several modifications of MACA have been proposed in [6, 18, 20].

Figure 2.2: The RTS / CTS Mechanism



The IEEE 802.11 Distributed Coordination Function (DCF) protocol [20] based on the RTS / CTS mechanism of the previous MAC protocol is a widely used MAC protocol for MANETs. In IEEE 802.11 DCF, whenever a sender needs to transmit a packet, it first randomly chooses a back-off interval in the range [0, k]. If the channel is idle, the sender countdowns the back-off interval.

Otherwise, the countdown is suspended. When the back-off interval reaches 0, the sender sends an RTS packet that contains information on the length of the packet. If the receiving host hears the RTS clearly, it responds with a CTS packet. After this exchange, the sender transmits its data packet. If the packet is received successfully, the receiving host transmits an acknowledgment (ACK) packet. Although the IEEE 802.11 DCF protocol is widely used as the MAC layer for MANETs, it doesn't provide real mechanisms for QoS because of its contention-based nature.

2.2 SCHEDULING-BASED WIRELESS MAC PROTOCOLS

Another class of MAC protocols used in multihop wireless networks is a time-division multiple-access (TDMA) protocol. In TDMA, the frequency band is split into a number of channels, which are stacked into short time units, so that a single frequency can support multiple, simultaneous data channels. The design of time scheduling in multihop mobile radio networks has been an active research topic. Most previous research has focused on designing a fair collision-free scheduling algorithm which maximizes the system throughput. In [15], it is proved that the problem of scheduling the time slots with optimal throughput is NP-Complete. Also, the optimal scheduling algorithms mostly require complete topology information. Therefore, we need to develop a scheduling algorithm that guarantees higher system throughput without any topology information.

An interesting scheduling algorithm called Galois Radio Network Design (GRAND), which does not require any topology information, has been proposed in [12]. This algorithm is topology transparent, and guarantees that each host has at least one collision-free slot in each frame. Some variations of this scheduling scheme are introduced in [13, 14], and the attempt to improve the minimum throughput per host of the algorithm has been made in [26]. We briefly explain these topology-transparent algorithms in the next subchapter.

2.3 PRELIMINARIES

A MANET (*i.e.* multihop packet radio network) can be represented as an undirected graph G=(V, E), where V is a set of vertices denoting the mobile hosts in the radio network, and E is a set of edges between vertices. For any two vertices $u, v \in V$, $(u, v) \in E$ if and only if they can hear each other's transmission. In this case, the vertices u and v are called *adjacent*. The degree of a host v, $d(v)$, is defined as the number of hosts which are adjacent to it. Each host uses an omnidirectional antenna for communication, and the network works in half-duplex mode, which means that a host cannot transmit and receive simultaneously. We assume that all hosts in the network are synchronized. Synchronization can be achieved by using a Global Positioning System (GPS) card up to 100 ns resolution [27, 44], or a global time synchronization protocol such as Network Time Protocol (NTP) [42].

Assume there are N mobile hosts in the network, i.e. $|V| = N$, and the maximum degree in the network is $D_{max} = max\ d(v)$, where $v \in V$. In some mobile environments, it might be difficult to find the maximum degree of a network in advance. However, a topology control technique [52, 66] can be used to maintain the bounded degree of the mobile network.

Each host in V has a transmission scheduling vector (TSV) which is defined as follows.

Definition 1: A TSV is a binary vector of length n. The TSV of a host $A \in V$, denoted by TSV_A, is $a_1\ a_2\ a_3\ a_4\ \ldots\ a_{n-2}\ a_{n-1}\ a_n$, where

$a_i = 1$ if host A has a permission to transmit in the i^{th} slot, and

$a_i = 0$ otherwise, for $1 \leq i \leq n$.

The problem of transmission scheduling is equivalent to finding a schedule, S, which is a set of transmission scheduling vectors (TSVs) satisfying the conditions described below.

Given N and D_{max}, for any given TSV and any other D_{max} of TSVs $\{TSV_1, TSV_2, TSV_3, \ldots, TSV_{Dmax}\}$, there exists a position j, for $1 \leq j \leq n$, such that TSV has 1 in this position, and all other TSV_i, for $1 \leq i \leq D_{max}$, have 0 in this same position. To give each host in the network an equal chance to access the channel, it is assumed that each host uses the same number of transmission slots.

Thus, the transmission scheduling problem can be formalized as follows.

Problem 1: Find a set of TSVs, S, which satisfies the following properties.

1. S has at least N number of TSVs; $|S| \geq N$.

   (This is because each host must have a unique TSV.)

2. There are exactly q 1's in a TSV.

   (Each host has an equal chance to access the channel.)

3. For any two TSVs, TSV_i and TSV_j in S, there are at most k positions in which both TSV_i and TSV_j are 1's. In other words, there must be at least $2(q-k)$ positions in which TSV_i and TSV_j differ.

4. $q > D_{max} \cdot k$.

   (The properties 3 and 4 guarantee that there is at least one collision free slot in each frame.)

2.4 TOPOLOGY-TRANSPARENT TRANSMISSION SCHEDULING ALGORITHMS

Chlamtac and Farago solve the transmission scheduling problem by designing a topology-transparent transmission scheduling method called the 'Galois Radio Network Design (GRAND)' algorithm [12]. The GRAND algorithm assumes that the number of mobile hosts (N) and the maximum degree

(D_{max}) are known in advance. This algorithm constructs TSVs of length q^2, where q is a prime or a prime power.

Definition 2: Let F be a field. If $a_m, a_{m-1}, \ldots, a_1, a_0 \in F$, then any expression of the form $a_m x^m + a_{m-1} x^{m-1} + \ldots + a_1 x + a_0$ is called a polynomial over F. If n is the largest integer such that $a_n \neq 0$, then the polynomial $f(x) = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0$ has degree n.

The constructed schedules satisfy the properties specified in *Problem 1.* In this algorithm, a distinct polynomial of degree at most k over GF(q) is assigned to each mobile host. Since the number of polynomials over GF(q) of degree at most k is q^{k+1}, the number of mobile hosts (N) should be less than or equal to q^{k+1}. Using the uniquely assigned polynomial, each mobile host calculates its transmission scheduling vector as follows.

Assume $p_i(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \ldots + a_{k-2} x^{k-2} + a_{k-1} x^{k-1}$ is the assigned polynomial to the host i. Let the elements in GF(q) be $\alpha_0, \alpha_1, \alpha_2, \ldots, \alpha_{q-2}, \alpha_{q-1}$.

$$\text{TSV}_i = [\phi(p_i(\alpha_0))\ \phi(p_i(\alpha_1))\ \phi(p_i(\alpha_2)) \ldots \phi(p_i(\alpha_{q-1}))\ ],$$

where $p_i(t) = (a_0 + a_1 t + a_2 t^2 + \ldots + a_{k-2} t^{k-2} + a_{k-1} t^{k-1})$ for $t \in$ GF(q),

and ϕ is a function which maps a q-ary number to a binary vector of length q:

$\phi(\alpha_0) = 1000 \ldots 00$

$\phi(\alpha_1) = 0100 \ldots 00$

$\phi(\alpha_2) = 0010 \ldots 00$

...

...

...

$\phi(\alpha_{q-1}) = 0000 \ldots 01$

While calculating $p_i(t)$, note that the multiplication and addition operations must be done in GF(q).

Theorem 1. If $f(x)$ is a non-zero polynomial of degree n over any field F, then the equation $f(x) = 0$ has at most n distinct solutions over F.

Proof: (By induction on the degree of the polynomial)

If $n = 0$, $f(x)$ is a constant polynomial. Since $f(x)$ is a non-zero polynomial, it has no solution. Assume $f(x)$ is a polynomial of degree $n > 0$. If $f(x)$ has no roots, then the theorem has been proved. Suppose $r \in F$ is a root of $f(x)$, then there is a polynomial $q(x)$ over F such that $f(x) = q(x) \cdot (x - r)$, where the degree of $q(x)$ is n-1. If s is another root of $f(x)$ that is distinct from r, then $f(s) = q(s) \cdot (s - r) = 0$. Since s is distinct from r, $q(s) = 0$. Thus, all the roots of $f(x)$ that are distinct from r are roots of $q(x)$. Since $q(x)$ has degree n-1, by inductive hypothesis, $q(x)$ has at most n-1 roots that are distinct from r. Thus, $f(x)$ has at most n distinct roots. ♦

Note that the maximum number of collisions for any two hosts is exactly the same as the degree of their difference polynomial. Let us assume that the polynomial $p_A(x)$ and $p_B(x)$ are assigned to hosts A and B respectively. Since the polynomial $p_A(x)$ and $p_B(x)$ are used to calculate their schedules, collision can happen if $p_A(x)$ and $p_B(x)$ have the same value. Therefore, we can find the collision slots by solving the equation '$p_A(x) - p_B(x) = 0$'. Since the degree of each assigned polynomial is at most k, the degree of the difference polynomial of any pair of hosts is also at most k. By *Theorem 1*, the maximum number of slots in which any pair of hosts can collide with each other is at most k. Furthermore, if $q > D_{max} \cdot k$, each host has at least one collision free slot in each frame. Since $q > D_{max} \cdot k$, the GRAND algorithm guarantees at least one collision-free slot in each frame.

Later, Ju and Li have given an improved topology-transparent scheduling algorithm that increases the minimum throughput per host of the GRAND algorithm [26]. In their scheduling algorithm, the length of TSV (i.e. the length of frame) is restricted to p^2, where p is a prime. Their analysis shows that the best value of k (the degree of the polynomial) is 1 unless the network size is extremely large. More precisely, the best value of k is 1 if $D_{max} > 0.1464\ N^{1/2}$. It is also shown that for a given k, the minimum throughput per host is maximized when $p = 2k \cdot D_{max}$, provided $N^{1/(k+1)} \leq 2k\ D_{max}$, and $p = N^{1/(k+1)}$, otherwise.

Example 1: Assume there are 35 mobile hosts in the network, and the maximum degree in the network is 5. First, the GRAND algorithm selects proper q and k values. Since q^{k+1} should be greater than or equal to 35, and q should be greater than $5k$, the selected q and k are 7 and 1 respectively. Then, a distinct polynomial over GF(7) of degree at most 1 is assigned to each mobile host. This polynomial is used to construct a TSV of length 49. Assume the polynomial $p_A(x) = 2x + 3$, $p_B(x) = 2x + 5$ and $p_C(x) = 5x + 3$ are assigned to hosts A, B and C respectively. Then the hosts A, B and C calculate their TSVs as follows.

$$\text{A: } TSV_A = [\phi(p_A(0))\ \phi(p_A(1))\ \phi(p_A(2))\ \phi(p_A(3))\ \phi(p_A(4))\ \phi(p_A(5))\ \phi(p_A(6))]$$

$$= [\phi(2\cdot0+3)\ \phi(2\cdot1+3)\ \phi(2\cdot2+3)\ \phi(2\cdot3+3)\ \phi(2\cdot4+3)\ \phi(2\cdot5+3)\ \phi(2\cdot6+3)]$$

$$= [\ \phi(\underline{3})\quad \phi(5)\quad \phi(0)\quad \phi(2)\quad \phi(4)\quad \phi(6)\quad \phi(1)]$$

$$= [\underline{0001000}\ 0000010\ 1000000\ 0010000\ 0000100\ 0000001\ 0100000]$$

$$\text{B: } TSV_B = [\phi(p_B(0))\ \phi(p_B(1))\ \phi(p_B(2))\ \phi(p_B(3))\ \phi(p_B(4))\ \phi(p_B(5))\ \phi(p_B(6))]$$

$$= [\phi(2\cdot0+5)\ \phi(2\cdot1+5)\ \phi(2\cdot2+5)\ \phi(2\cdot3+5)\ \phi(2\cdot4+5)\ \phi(2\cdot5+5)\ \phi(2\cdot6+5)]$$

$$= [\ \phi(5)\quad \phi(0)\quad \phi(2)\quad \phi(\underline{4})\quad \phi(6)\quad \phi(1)\quad \phi(3)]$$

$$= [0000010\ 1000000\ 0010000\ \underline{0000100}\ 0000001\ 0100000\ 0001000]$$

$$\text{C: } TSV_C = [\phi(p_C(0))\ \phi(p_C(1))\ \phi(p_C(2))\ \phi(p_C(3))\ \phi(p_C(4))\ \phi(p_C(5))\ \phi(p_C(6))]$$

$$= [\phi(5\cdot0+3)\ \phi(5\cdot1+3)\ \phi(5\cdot2+3)\ \phi(5\cdot3+3)\ \phi(5\cdot4+3)\ \phi(5\cdot5+3)\ \phi(5\cdot6+3)]$$

$$= [\ \phi(\underline{3})\quad \phi(1)\quad \phi(6)\quad \phi(\underline{4})\quad \phi(2)\quad \phi(0)\quad \phi(5)]$$

$$= [\underline{0001000}\ 0100000\ 0000001\ \underline{0000100}\ 0010000\ 1000000\ 0000010]$$

The transmissions between the host A and B cannot collide with each other. This is because the degree of $p_A(x) - p_B(x)$ is 0 (*i.e.*= $2x + 3 - (2x + 5) = 5$ and deg (5) = 0). Thus, the transmission slots used by the host A and B are disjointed. Since the degree of $(p_B - p_C) = (2x+5 - 5x-3) = ((-3)x+2) = 4x+2$ is 1, there is exactly one position at which both TSV_B and TSV_C have value 1. This is because $4x+2$ has only one root in GF(7). When $x = 3$, $4x+2 = 14 = 0$, and so $\phi(p_A(3)) = \phi(p_B(3))$. Thus, there is a collision in the fourth subframe. Similarly, there is exactly one position at which both TSV_A and TSV_C have value 1. This is because when $x = 0$, $2x+3 = 5x+3 = 3$, and so $\phi(p_A(0)) = \phi(p_B(0))$

Ju and Li's improved algorithm uses a different frame length. Since $5 > 0.1464 \cdot 35^{1/2}$, the best value of k is 1. Since $35^{1/2} \leq 2 \cdot 5$, the minimum throughput per host is maximized when $p = 2k \cdot D_{max} = 10$. However, p should be a prime, and so $p = 11$. After this, the GRAND algorithm is used to construct TSVs of length 121. ♦

3 TRANSMISSION SCHEDULING ALGORITHMS USING CONSTANT WEIGHT CODES

Since our approach uses constant weight codes to design an efficient scheduling algorithm, let us redefine *Problem 1* using coding theory concepts. Some definitions are given below.

Definition 3: The *weight* of a binary vector $X = (x_1, x_2, \dots, x_n)$ where $x_i \in \{0,1\}$, denoted by $\omega(X)$, is the number of 1's in X.

Definition 4: The *Hamming distance* between two vectors X and Y, denoted by $H_d(X, Y)$, is the number of positions at which X and Y differ.

Definition 5: An *(n, d, w) constant weight binary code* is a set of binary vectors of length n, Hamming distance at least d apart, and weight w.

Definition 6: *A(n, d, w)* denotes the maximum number of binary vectors of length n, Hamming distance at least d apart, and constant weight w.

From the above definitions, it can be seen that the problem of transmission scheduling is equivalent to the problem of constructing a constant weight code that satisfies the properties mentioned in *Problem 2* below.

Problem 2: Construct a (n, $2(w-k)$, w) binary constant weight code C such that

1. $A(n, d, w) \geq N$.

   (Since each host must have a distinct vector, there must be at least N codewords.)

2. $\omega(X) = w$, where $X \in C$.

   (Each host has an equal chance to access the channel.)

3. For X, $Y \in C$, $H_d(X, Y) \geq d = 2(w - k)$, where k is an non-negative integer.

   (k is similar to the degree of polynomials in the GRAND algorithm.)

4. $w > D_{max} \cdot k$.

   (The properties 3 and 4 guarantee that there is at least one collision free slot in each frame)

The proposed algorithms are based on the constant weight code which satisfies the properties mentioned in *Problem 2*. The new algorithms have similar properties to that of the previously known topology-transparent algorithms such as the GRAND and Ju and Li's algorithms: topology independence, guaranteed minimum throughput, bounded maximum delay, etc. In the previous topology-transparent algorithms, the length of the frame should be q^2, where q is a prime or a prime power. In our algorithms, the length of the frame (n) depends on the number of mobile hosts in the network. The only restriction on the length of the frame is that the selected constant weight code should have at least N codewords; *i. e.* $A(n, d, w) \geq N$ (the number of mobile hosts).

3.1 MAXIMIZING THE MINIMUM THROUGHPUT PER HOST

Before describing the new algorithm, let us define the minimum throughput per host (T_{min}).

Definition 7: The minimum throughput per host (T_{min}) is defined as the ratio of the number of guaranteed collision-free slots in a single frame to the length of the frame.

$$T_{min} = \frac{\text{the number of guaranteed collision-free slots}}{\text{the length of the frame}} = \frac{(w - D_{max} \cdot k)}{n}$$

We can improve the minimum throughput per host (T_{min}) by decreasing the length of the frame (n) while preserving the number of guaranteed collision-free slots. The proposed algorithm tries to maximize the minimum throughput per host by choosing proper constant weight codes. The algorithm is described below; the first and second steps of our algorithm are based on Ju and Li's analysis in [26].

Scheduling algorithm (***MaxThrou***)

(*Input*: the number of mobile hosts (N),

the maximum degree in the network (D_{max}),

Output: The transmission scheduling vectors.)

1. Set k to 1 if $D_{max} > 0.1464\ N^{1/2}$; Set k to 2, otherwise.
2. Set w to $2k \cdot D_{max}$ if $N^{1/(k+1)} \leq 2k\ D_{max}$; Set w to $N^{1/(k+1)}$, otherwise.
3. Set d to $2 \cdot (w - k)$.
4. By looking up the table of constants weight codes in [50], select the smallest n such that $A(n, d, w) \geq N$.
5. Calculate $T_{min} = (w - D_{max} \cdot k) / n$.
6. Using the method denoted in [50], construct a (n, d, w) binary constant weight code.
7. Assign a unique codeword to each host.

3.2 MINIMIZING THE NODEAL DELAY BOUND

In this subchapter, we focus on designing a transmission scheduling which minimizes the nodal delay bound without sacrificing minimum / average system throughput. The nodal delay is the amount of time between when a packet is ready and when it is transmitted. To reduce the nodal delay, the proposed algorithm chooses a constant weight code such that n is as small as possible while maintaining at least one collision-free slot.

Scheduling algorithm (*MinDelay*)

(*Input*: the number of mobile hosts (N),

the maximum degree in the network (D_{max}),

Output: The transmission scheduling vectors.)

1. Set w to $D_{max} + 1$.
2. Set d to $2 \cdot (w - 1)$.
3. By looking up the table of constants weight codes in [50], select the smallest n such that $A(n, d, w) \geq N$.
4. Using the method denoted in [50], construct a (n, d, w) binary constant weight code.
5. Assign a unique constant weight code to each host.

The fundamental difference between the proposed algorithm and the GRAND algorithm is the length of the frame. In the GRAND algorithm, the frame length should be q^2, where q is a prime or a prime power. But our algorithm can flexibly select the frame length based on the number of mobile hosts (N). Thus, the proposed algorithm can minimize the frame length while preserving the number of collision-free slots. This minimization of the frame length results in the improved minimum throughput per host.

Example 2: Assume there are 12 mobile hosts in the network, and the maximum degree in the network is 3.

The *MaxThrou* scheduling algorithm performs the following steps.

1. Since $D_{max} > 0.1464\ N^{1/2}$, set k to 1.
2. Since $N^{1/(k+1)} = 12^{1/2} \leq 2\ D_{max}$, $w = 2k \cdot D_{max} = 2 \cdot 1 \cdot 3 = 6$.
3. $d = 2 \cdot (w - k) = 2 \cdot (6 - 1) = 10$
4. By looking up A(n, 10, 6) table in [50], select the smallest n such that A(n, 10, 6) $\geq$ 12. Since A(26, 10, 6) = 13, n = 26 (see Table 3.1).

Table 3.1: A(n, 10, 6)

N	A(n, 10, 6)
...	...
24	9
25	10
26	13
27	14
28	16
29	20
...	...

5. Calculate the $T_{min} = (w - D_{max} \cdot k) / n = (6 - 3 \cdot 1) / 26 = 3 / 26 = 0.115$.

6. Using the method denoted in [50], construct a constant weight code of length 26, distance 10 and weight 6;

0 : 00000000110010000010100001
1 : 00000001100100000101000010
2 : 00000011001000001010000100
3 : 00000110010000010100001000
4 : 00001100100000101000010000
5 : 00011001000001010000100000
6 : 00110010000000100001000001
7 : 01100100000001000010000010
8 : 11001000000000000100000101
9 : 10010000000010001000001010
10 : 00100000000110010000010100
11 : 01000000001100100000101000
12 : 10000000011001000001010000

7. Assign a unique codeword to each mobile host. Since there are 13 codewords, we can randomly select any 12 of them.

Sometimes, the selected constant weight code may not maximize the minimum throughput per host. For example, if we use a (34, 12, 7) constant weight code, then the T_{min} is equal to 0.118; since A(34, 12, 7) = 12, we can also use this code. This code is slightly better than the (26, 10, 6) code in terms of the minimum throughput. Thus, we might want to check the minimum throughputs of other constant weight codes whose weights are close to the current code weight. To do this, we may increase or decrease the weight by 1, and perform the Step 3 to Step 5 of the proposed algorithm until T_{min} is not improved.

The steps of the *MinDelay* scheduling algorithm is shown below.

1. $w = D_{max} + 1 = 3 + 1 = 4$.
2. $d = 2 \cdot (w - 1) = 2 \cdot (4 - 1) = 6$.
3. By looking up the table in [50], select the smallest n such that $A(n, 6, 4) \geq 12$. Since $A(13, 6, 4)=13$, $n = 13$ (see Table 3.2).

Table 3.2: $A(n, 6, 4)$

N	$A(n, 10, 6)$
...	...
10	5
11	6
12	9
13	13
14	14
15	15
...	...

4. Using the method denoted in [50], construct a constant weight code of length 13, distance 6 and weight 4;

   0 : 0000010110001

1 : 0000101100010

2 : 0001011000100

3 : 0010110001000

4 : 0101100010000

5 : 1011000100000

6 : 0110001000001

7 : 1100010000010

8 : 1000100000101

9 : 0001000001011

10 : 0010000010110

11 : 0100000101100

12 : 1000001011000

5. Assign a unique codeword to each mobile host.

The GRAND algorithm selects proper q and k values. Since q^{k+1} should be greater than or equal to 12, and q should be greater than $3k$, the selected q and k are 4 and 1 respectively. Then, each host constructs its TSV as shown in *Example 1*. The length of the constructed TSVs is 16.

0: 1000100010001000

1: 0100010001000100

2: 0010001000100010

3: 0001000100010001

4: 1000010000100001

5: 0100100000010010

6: 0010000110000100

7: 0001001001001000

8: 1000001000010100

9: 0100000100101000

10: 0010100001000001

11: 0001010010000010

12: 1000000101000010

13: 0100001000011000

14: 0010010000011000

15: 0001100000100100

Ju and Li's algorithm selects different q and k values. Since $3 > 0.1464 \cdot 12^{½}$, the best value of k is 1. Since $15^{½} \leq 2 \cdot 3$, the minimum throughput per host is maximized when $p = 2k \cdot D_{max} = 6$. However, p should be a prime, and so $p = 7$. Then, 49 TSVs with length 49 are constructed using the GRAND algorithm. ♦

Example 3: In this example, we compare the minimum throughput of the *MaxThrou* algorithm to that of previously known algorithms (the conventional TDMA, Chlamtac and Farago's GRAND algorithm [12], and Ju and Li's algorithm [26]). Assume there are 12 mobile hosts in the network, and the maximum degree in the network is 3.

- For the conventional TDMA, unique collision-free slots are assigned to each mobile. Thus, the minimum throughput (T_{min}) is 1/12 = 0.083.
- For the GRAND algorithm, there are 16 slots in each frame, and every host has at least one collision-free slot. Thus, the minimum throughput (T_{min}) is 1/16 = 0.062.
- For the Ju and Li's algorithm, there are 49 slots in each frame, and every host has at least 4 collision-free slots. Thus, the minimum throughput (T_{min}) is 4/49 = 0.082.

- In the *MaxThrou* scheduling algorithm, there are 26 slots (or 34 slots) in each frame, and every host has at least 3 (or 4) collision-free slots. Thus, the minimum throughput using the proposed algorithm is 3/26 (or 4/34) = 0.115(or 0.118). ♦

3.3 THEORETICAL BOUNDS

In the previous example, the minimum throughput (T_{min}) of our algorithms is much better than that of the previously known algorithms. Now we'll show that our algorithm is better than the GRAND algorithm in almost all cases. Since Ju and Li's analysis shows that the best value of k is mostly 1 unless the network size is extremely large, the proper value of k is usually 1 except for some extremely sparse and large networks. Furthermore, except using the different parameters p and k, Ju and Li's algorithm is exactly same as the GRAND algorithm. Thus, we only consider the GRAND algorithm with $k = 1$ for the comparison.

We first describe some properties of A(n, d, w), and then construct a new class of efficient (n, d, w) codes. The upper and lower bounds on A(n, d, w) have been extensively studied for almost 40 years by coding theory researchers[1, 8, 25, 50]. Although none of them found the general answer for these bounds, various upper and lower bounds have been known so far. The following theorem is due to S. M. Johnson.

Theorem 2 (Johnson's bound [25]):

$A(n, d, w) \leq \lfloor (n/(n-w)) \cdot A(n-1, d, w) \rfloor$

Proof:

Let C be an optimal (n, d, w) constant weight code. From C, we construct $(n-1, d, w)$ constant weight codes C_i for $1 \leq i \leq n$. To construct C_i, first select the codewords that have a 0 in the i^{th} column, and then delete this column from the selected codewords. If this column is eliminated, a code C_i is obtained with length n-1, distance d, and weight w. Since $|C_i|$ is equal to the number of 0's in the i^{th} column, $|C_1| + |C_2| + \ldots + |C_{n-1}| + |C_n|$ is equal to the total number of 0's in C. The total number of 0's in C is $(n-w) \cdot A(n, d, w)$. Since $|C_i| \leq A(n-1, d, w)$,

$$(n-w) \cdot A(n, d, w) = |C_1| + |C_2| + \ldots + |C_{n-1}| + |C_n| \leq n \cdot A(n-1, d, w).$$

Thus, $A(n, d, w) \leq \lfloor (n/(n-w)) \cdot A(n-1, d, w) \rfloor$ ♦

From Johnson's upper bound we can get a lower bound of $A(n-1, d, w)$.

$$A(n-1, d, w) \geq \lceil ((n-w)/n) \cdot A(n, d, w) \rceil \quad (1)$$

Let S be the set of TSVs obtained by the GRAND algorithm. A TSV in S can be divided into q subframes, and has exactly one transmission slot in each subframe. Thus, we can add the following q additional TSVs (TSV_1, TSV_2, TSV_3, … , TSV_q) to S without changing the properties of S.

$$TSV_1 = (111\ldots1 \quad 000\ldots0 \quad 000\ldots0 \quad \ldots \quad 000\ldots0)$$

$$TSV_2 = (000\ldots0 \quad 111\ldots1 \quad 000\ldots0 \quad \ldots \quad 000\ldots0)$$

$$TSV_3 = (000\ldots0 \quad 000\ldots0 \quad 111\ldots1 \quad \ldots \quad 000\ldots0)$$

•

•

$$TSV_q = (000\ldots0 \quad 000\ldots0 \quad 000\ldots0 \quad \ldots \quad 111\ldots1)$$

This set S of the scheduling vectors forms a $(q^2, 2(q-1), q)$ binary constant weight code, and the number of codewords is $q^2 + q$, where q is a prime or a prime power. Thus, $A(q^2, 2(q-1), q) \geq q^2 + q$.

By (1),

$$\begin{aligned} A(q^2-1, 2(q-1), q) &\geq \lceil ((q^2-q)/q^2) \cdot A(q^2, 2(q-1), q) \rceil \\ &\geq \lceil ((q^2-q)/q^2) \cdot (q^2+q) \rceil \\ &= \lceil ((q^2-q) \cdot (q^2+q))/q^2 \rceil \\ &= \lceil q^2((q-1) \cdot (q+1))/q^2 \rceil \\ &= (q-1) \cdot (q+1) \\ &= q^2 - 1 \end{aligned}$$

Therefore, if the number of mobile hosts is less than q^2, then we can reduce the frame size by at least 1. Since the frame size is reduced while preserving other properties, it is easy to see that the minimum throughput per host (T_{min}) of the proposed algorithm is better than that of the GRAND algorithm.

Regarding the delay bound, the same argument can be applied. In the GRAND algorithm, the frame size should be q^2, and there is at least one collision-free slot. In the *MinDelay* algorithm, the frame size is n, and at least one collision-free slot is guaranteed. Therefore, in the worst case, the nodal delay of the GRAND algorithm is q^2, and that of the *MinDelay* algorithm is n. Note that $n < q^2$ if the number of mobile hosts is less than q^2. In other words, the nodal delay bound of the proposed algorithm is less than that of the GRAND algorithm, if the number of mobile hosts is less than q^2.

3.4 AVERAGE SYSTEM THROUGHPUT

In the previous subchapter, we showed that the proposed algorithms outperform the previously known algorithms in the worst situations. However, in designing a realistic network system, the system designer should consider not only the guaranteed minimum system throughput but also the average system throughput. Thus, we discuss the average system throughput in this and next subchapters.

Let us consider the network topology shown in Figure 3.1 (pp. 36); there are 12 mobile hosts in the network, and the maximum degree of the network is 3. This network topology is already discussed in *Example 2*, and the corresponding TSVs constructed in *Example 2* are used for each scheduling algorithm.

Since each host has two or three neighbors, there will be one or two collisions in each frame for the low or moderate data traffic load. Similarly, there will be two or three collisions for the heavy data traffic load. As the traffic load increases, the number of collisions will also increase. The maximum number of collisions can be up to two or three depending on the number of neighbors.

We estimate the system throughputs before the simulation. These estimations are shown in Table 3.3. According to our estimation, we expect that the system throughput will be MinDelay > MaxThrou > GRAND > Ju and Li's > TDMA for the moderate data traffic load, and MaxThrou > MinDelay > GRAND > Ju and Li's > TDMA for the heavy data traffic load.

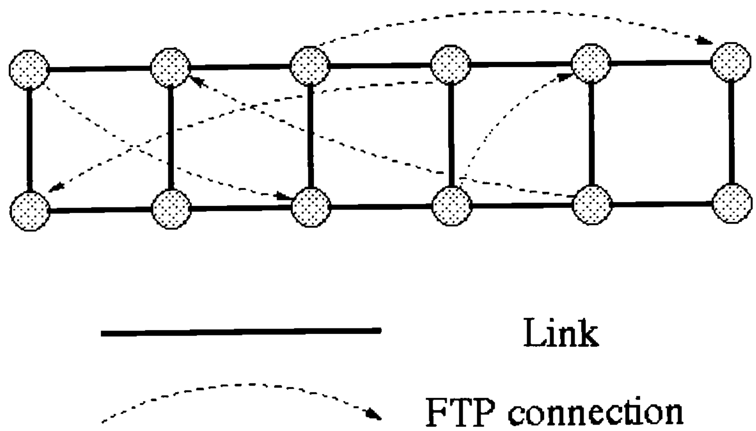
Table 3.3: Estimated Throughput per Hosts

Scheduling algorithm	Moderate load (50%: 1 collision, 50%: 2 collisions)	Heavy load (50%: 2 collisions, 50%: 3 collisions)
TDMA	(1/12 + 1/12)/2 = 0.083	(1/12 + 1/12)/2 = 0.083
GRAND	(3/16 + 2/16)/2 = 0.156	(2/16 + 1/16)/2 = 0.094
Ju and Li's	(6/49 + 5/49)/2 = 0.112	(5/49 + 4/49)/2 = 0.092
MaxThrou	(5/26 + 4/26)/2 = 0.173	(4/26 + 3/26)/2 = 0.135
MinDelay	(3/13 + 2/13)/2 = 0.193	(2/13 + 1/13)/2 = 0.115

3.5 SIMULATION STUDY

In order to compare the average system throughput of the proposed algorithms to that of previously known algorithms, the GloMoSim library [64] is used for the simulation. The GlomoSim library is a scalable network simulation environment for large MANETs based on the parallel discrete-event simulation language PARSEC [3]. Since the implementation of the GRAND algorithm is freely available in the library, this implementation is used without any modification.

Figure 3.1: Simulated Network Topology



3.5.1 Simulation Model

In this simulation, we consider the network topology as shown in Figure 3.1; there are 12 hosts in the network and the maximum degree is 3. A unique TSV generated by the different scheduling algorithms as shown in Example 2, is randomly assigned to each host. The transmit and receive characteristics of the radio model are similar to Lucent's WaveLAN network interface. We assume that the radio propagation range for each mobile is 200 *m*, and the channel capacity is *2Mbits/sec*.

The source sends 512-byte data packets during the simulation. To evaluate the relation between the data traffic load and the system throughput, we increase the number of connections up to 5; the source and destination pairs used in the simulation are also shown in Figure 3.1. Each simulation is run for 600 seconds of simulation time to measure the average system throughput.

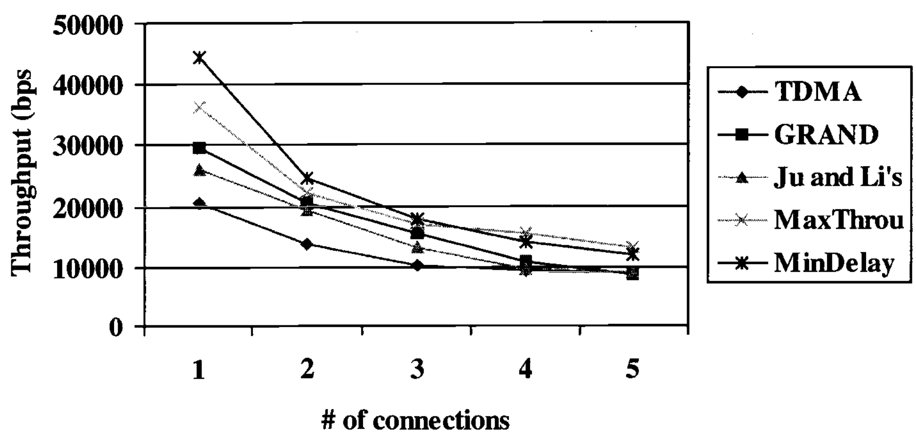
3.5.2 Simulation Results

We run each simulation 10 times and measure the mean system throughput of the mobile network. Table 3.4 and Figure 3.2 display the mean system throughput as a function of the offered traffic load. The simulation results are very similar to our expectation for the moderate data load (up to 3 FTP connections). Although Ju and Li's algorithm is better than the GRAND algorithm in terms of minimum system throughput, the mean system throughput of their algorithm was poor. This is because their algorithm has a low channel utilization rate. For example, in the simulated case, Ju and Li's algorithm uses only 7 slots among 49 slots (14%) while the GRAND algorithm uses 4 slots among 16 slots (25%).

Table 3.4: Simulation Results (Mean System Throughputs: bps)

Algorithm	Data Traffic load (The number of FTP connections)				
	1	2	3	4	5
TDMA	20504	13694	10287	9462	9140
GRAND	29391	20489	15416	10923	8796
Ju and Li's	25899	19201	13194	9676	9117
MaxThrou	36123	22180	16942	15359	13093
MinDelay	44344	24504	17842	14090	11861

Figure 3.2: Mean System Throughput as a Function of Traffic Load



However, Ju and Li's algorithm outperforms the GRAND algorithm when the system is heavily loaded (5 FTP applications). This is because, in the heavy load situation, the average system throughput is very close to the worst system throughput (*i.e.* minimum system throughput). Based on the simulation results, we conclude that MaxThrou and MinDelay algorithms outperform the previously known algorithms in terms of mean system throughput.

3.6 CONCLUSION

In this chapter, we showed that the topology-transparent transmission scheduling problem is equivalent to the problem of constructing constant weight codes which satisfy certain properties. Constructing constant weight codes and finding the upper and lower bounds on constant weight codes are extensively studied for almost four decades. Thus, we can use the previously known results to find the proper scheduling for the given networks.

Further, we have given some improved constant weight codes; when these codes are used for transmission scheduling, we get better minimum throughput per host while at the same time preserving other properties such as topology independence, guaranteed minimum throughput, bounded maximum delay, etc. In the simulation study, we measure the average system throughput of the transmission scheduling algorithms. The simulation results show the proposed algorithms outperform the previously known algorithms in terms of mean system throughput.

4 ENERGY EFFICIENT TRANSMISSION SCHEDULING

Since most mobile hosts in MANETs are operated using the scarce battery, and the battery life is not expected to increase significantly in the near future, energy efficiency is a critical issue [10, 17, 49, 57, 58, 59, 63]. Although there has been extensive research on the energy efficiency of wireless communications, most of the previous methods assume that there are base stations that have virtually unlimited energy [19, 48, 54, 60]. However, in MANETs, there are no base stations, and so these methods are not applicable. In this chapter, we briefly describe power conservation principles observed in the previous studies [17, 19, 60, 63], and elaborate on the proposed energy conserving MAC layer protocol.

4.1 POWER CONSERVATION PRINCIPLES

We assume that a network interface has four modes: transmit, receive, idle and sleep. In the transmit or receive mode, the network interface is transmitting or receiving a message from its neighbor. In the idle mode, the network interface is ready but neither receiving nor transmitting. In the sleep mode, the network interface minimizes the power consumption but cannot communicate.

Now we consider the energy consumption of each mode. The sleep mode has extremely low power consumption, followed by idle, receive and transmit modes in that order. For example, Feeney and Nilson measure the energy consumption of Lucent's WaveLAN network interface card in a MANET environment in [17], and their experimental results are shown in Table 4.1. Note that, in MANETs, a receiver should keep listening to the channel to receive a message from its neighbors, and so the network interface is idling instead of sleeping. Thus, significant energy is consumed even though there is no traffic in the network.

Further, it is observed that the mode transition between the transmit and the receive also consumes significant power and time [19, 60]. The transition from the sleep mode to the transmit or receive mode is even worse. For example, it takes about 250 μs for the WaveLAN interface to change from the sleep mode to the receive or transmit mode [19]. These mode transitions significantly impact on the energy consumption of network interface. Thus, especially for low power mobile hosts the number of mode transitions should be minimized as far as possible.

Table 4.1: Measured WaveLAN Network Interface Characteristics (2Mbps)

Modes	Energy Consumption
Transmit Mode	280 mA
Receive Mode	204 mA
Idle Mode	178 mA
Sleep Mode	14 mA
Power Supply	4.74 V

TDMA protocols might be an appropriate choice for the energy efficient MAC protocols. This is because a host *A* can change from the idle mode to the sleep mode if there is no message destined to *A* at the beginning of the slot. Then, the host *A* wakes up before the beginning of the next slot, and listens to the channel again. Although this straightforward solution can significantly reduce the idling power consumption, it causes the mode transition overhead; there is a mode transition from sleep to receive in every slot if *A* does not communicate in that slot.

Since the GRAND algorithm is a variation of TDMA schemes, and the average system throughput of the GRAND algorithm is usually much higher than that of the conventional TDMA, it may use for the energy efficient scheduling in mobile ad hoc environment. However, the GRAND algorithm has several fundamental drawbacks as an energy efficient MAC protocol.

- The sender does not know whether the receiver gets the message correctly or not. Since the transmission may collide at the destination, and the sender cannot detect the collision in wireless environments, the sender may keep sending its message after the collision. It results in significant power waste of the sender.

- Transition overhead from the sleep to the receive mode causes a major power waste. Since the transition overhead from sleep to receive is extremely expensive, an energy efficient MAC protocol should reduce not only idling power consumption but also the overhead caused by the mode transition.

- There is no consideration given for low-power mobile hosts. For example, there may be hosts which have lower power capacity than some other hosts. The power consumption of a host depends on its TSV. However, TSVs are assigned arbitrarily to these hosts.

4.2 AN ENERGY CONSERVING TRANSMISSION SCHEDULING (ECTS)

In designing a new MAC protocol, we focus on eliminating the data collisions, reducing the idling power consumption and minimizing the mode transitions, especially from the sleep mode to the transmit or receive modes. The proposed algorithm increases the energy efficiency while preserving other desired properties of the GRAND algorithm such as topology transparency, guaranteed minimum throughput, and bounded maximum delay. The following two features are added to the GRAND algorithm to improve energy efficiency.

1. The additional q TSVs which are shown in *Chapter 3.3* are added for low power hosts.
2. By introducing Request-To-Send (RTS) and Clear-To-Send (CTS) control slots, data collisions can be detected at the beginning of each subframe, and thus, the energy consumption caused by collisions is reduced.
3. An acknowledgement (ACK) control message is added to eliminate unnecessary retransmissions.

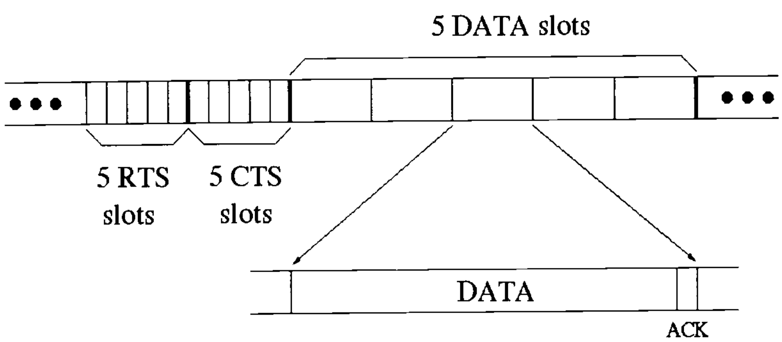
Since the extra TSVs have consecutive q 1's in a subframe, the hosts using one of these TSVs can minimize the number of transitions between transmit and receive modes. By assigning these extra TSVs to the low power hosts, these hosts transmit their data in more efficient manner. Since there are q additional TSVs, our protocol can support up to q low power hosts.

Next, we describe the second improvement. To eliminate the data collision in the GRAND algorithm, we use Request-To-Send (RTS) and Clear-To-Send (CTS) control messages [28]. There are $2 \cdot q$ control slots at the beginning of each subframe; q consecutive RTS slots are followed by q consecutive CTS slots. Let us assume a mobile host A has a permission to send data at the j^{th} slot of the i^{th} subframe. If A doesn't have data to send, then it listens to all the RTS slots of that subframe. If A clearly receives an RTS message from its neighbor at the k^{th} RTS slot for $1 \leq k \leq q$, then it replies a CTS message to the sender at the k^{th} CTS slot. If A has data to send, it sends an RTS control message to the corresponding neighbor at the j^{th} RTS slot. A should listen all other RTS slots, and send CTS messages if necessary. If A receives the CTS message clearly from the destination at the j^{th} CTS slot, then it transmits its data in the j^{th} data slot.

The format of a subframe is depicted in Figure 4.1. An acknowledge (ACK) control slot follows a data slot. The receiver sends an ACK control message to the source host using this control slot, if it successfully received a unicast packet.

For the broadcast message, the receiver doesn't send an acknowledgement message. All messages are preceded by 2 synchronization bytes.

Figure 4.1: The Format of a Subframe for q=5.



Note that only RTS control messages can be collided. There is no collision in CTS, data and ACK slots. The hidden terminals can be detected in the RTS control slots. If there is a hidden terminal that sends an RTS message at the same RTS slot, then these RTS messages collide each other, and the receiver will not send a CTS message. Thus, all data collisions can be detected at the beginning of each subframe, and so the host can eliminate the data collisions. Furthermore, the host can reduce the unnecessary mode transitions from the sleep mode to the receive or transmit mode; the host sleeps during the whole subframe if there is no communication demand. Since the receiver determines the data transmission of the sender, the ECTS algorithm also relieves the exposed terminal problem.

4.3 SIMULATION STUDY

In order to evaluate the energy efficiency of the ECTS algorithm, we measure the energy consumption of the ECTS protocol, the GRAND algorithm [12] and IEEE 802.11 [20]. The GloMoSim library [64] is used to compare the energy efficiency of three MAC protocols. The GlomoSim library is a scalable network simulation environment for large MANETs based on the parallel discrete-event simulation language PARSEC [3]. Since the implementations of the GRAND algorithm and the distributed coordination function (DCF) of IEEE 802.11 are freely available in the library, these implementations are used with minor modifications in the energy consumption model. In the simulation, we measure the energy consumption only. This is because other properties, such as the delay and system throughput, are very similar to that of the GRAND algorithm.

4.3.1 Simulation Model

Hosts are randomly placed within a 1000 $m \times 1000$ m area. Host mobility is based on the random waypoint model. In this mobility model, each host randomly selects its destination, and chooses a speed from a uniform distribution between 0 and 20 meters per second. Then, it moves in the direction of the destination in the chosen speed. When the host reaches its destination, it stays there for 30 seconds. After a pause period, the host selects another destination, and moves towards the destination. This process is repeated until the end of the simulation.

The characteristics of radio model are similar to Lucent's WaveLAN network interface. We assume that radio propagation range is 300 m, and the channel capacity is 2Mbits/sec.

The source and destination pairs are randomly spread in the area. The source sends data once a second, and the size of data packet is 512 bytes. To evaluate the relation between the load and the power consumption, we increase data rate up to 4 packets/second while keeping the number of connections constant. Each simulation is run for 600 seconds of simulation time to measure the energy consumption.

To calculate the energy consumption of the mobile hosts, the values in Table 4.1 (pp. 41) are used. We assume that the transition between the receive and transmit modes takes 5 μs, the transition from the sleep mode to the transmit or receive mode takes 250 μs, and the energy consumption of the transition is as much as that of the idle mode. Ad hoc On-demand Distance Vector (AODV) routing protocol [47] is used as a network layer protocol in the simulation.

4.3.2 Simulation Results

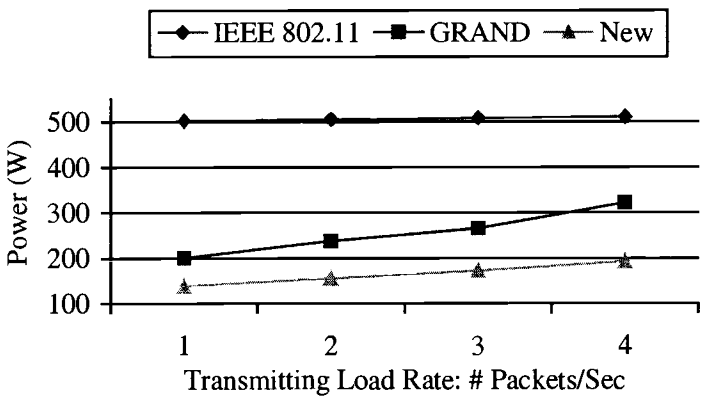
We run each simulation 10 times and measure the energy consumption of network interface. According to the simulation results, the network interface using the IEEE 802.11 protocol consumes about 70 – 90 % of its power in the idle mode.

Figure 4.2 displays the averaged power consumption per host as a function of the offered traffic load. The energy consumption of a network interface that uses the proposed protocol is very low. As an example, for *N*=30 and the transmission load rate = 4 packets/second, the power consumption of IEEE 802.11 is 511.3 W, that of the GRAND is 321.5 W, and that of our protocol is 192.7 W.

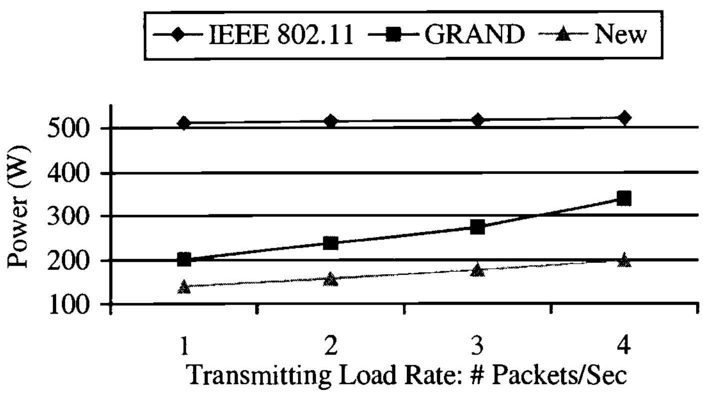
As the transmitting load rate increases, the energy consumption also increases for all simulated cases. The additional power consumption of IEEE 802.11 is very small. This is because power consumption increases only if it is actually receiving or transmitting a message. These additional costs are relatively small. In the GRAND algorithm, the additional power consumption grows faster as the transmitting load rate goes higher. The most dominant additional cost comes from the data collisions. In the GRAND, as the transmitting load rate increases, the probability of data collision also increases, and these data collisions result in the retransmissions. The energy consumption of a network interface that uses the ECTS protocol is very low but grows faster than that of the IEEE 802.11. This is because there is an additional power consumption caused by the mode transition from sleep to receive or transmit. As the transmitting load rate increases, the number of mode transitions from sleep to receive or transmit becomes large.

Based on the simulations, we can conclude that the ECTS protocol is very efficient in terms of power conservation.

Figure 4.2: The Average Power Consumption per Host



(a) The number of mobile hosts (N) = 30



(b) The number of mobile hosts (N) = 90

4.4 CONCLUSION

In this chapter, we describe a scheduling algorithm for low-power MAC protocol for MANETs. The proposed algorithm, called ECTS algorithm, is based on the GRAND algorithm. The goals of the ECTS algorithm are to conserve scarce battery power while preserving other desired properties of the GRAND algorithm, such as topology transparency, guaranteed minimum throughput and bounded maximum delay. The ECTS algorithm conserves the power using strategies that allow the network interface to use the low power sleep mode instead of the idle mode. To relieve the unnecessary battery consumption, the ECTS protocol eliminates data collisions using CTS and RTS control slots, and significantly reduces the number of mode transitions from sleep to receive or transmit. In the simulation study, we have compared the energy efficiency of our protocol with that of IEEE 802.11 and the GRAND algorithms. Simulation results show that our protocol is very efficient in terms of power conservation.

5 LOCATION-AIDED SCALABLE TRANSMISSION SCHEDULING

Due to the increasing popularity of mobile networking systems, the scalability becomes a significant new challenge for MANET protocols [16, 21, 23, 45]. Thus, we proposed a scalable transmission scheduling algorithm in this chapter. Before the description of the proposed algorithm, let us discuss the problems in the previously known scheduling algorithms. The topology transparent scheduling algorithms described in [12, 13, 14, 26, 69, 70] have the following disadvantages. First, the number of mobile hosts in the networks should be known in advance. This is because the length of the TSV depends on the number of mobile hosts. Second, there is no consideration for spatial reuse. Although two mobile hosts are geographically separated enough, they must still be assigned two distinct TSVs. Note that, if several mobile hosts can share the same TSV, then we can reduce the number of required TSVs. This reduction results in shortening the length of TSVs while preserving the number of collision-free slots [70]; thus, higher system throughput can be achieved.

A set of TSVs constructed using the GRAND algorithm has an interesting property. We can divide a set of constructed TSVs into q^k collision-free subsets which contain exactly q TSVs. This is because there are q polynomials which have same coefficients but different constant terms. For example, the set of TSVs constructed in *Example 2* can be divided into 4 collision-free subsets, and each subset has exactly 4 TSVs.

0:	1000100010001000	Collision-Free Set 1
1:	0100010001000100	
2:	0010001000100010	
3:	0001000100010001	
4:	1000010000100001	Collision-Free Set 2
5:	0100100000010010	
6:	0010000110000100	
7:	0001001001001000	
8:	1000001000010100	Collision-Free Set 3
9:	0100000100101000	
10:	0010100001000001	
11:	0001010010000010	
12:	1000000101000010	Collision-Free Set 4
13:	0100001000011000	
14:	0010010000011000	
15:	0001100000100100	

If we can assign these collision-free TSVs to the nodes that are neighboring each other, then the number of collisions will be dropped considerably. The major throughput gain of the proposed algorithm comes from assigning these collision-free TSVs to neighboring nodes using their location information obtained from Global Position System (GPS) [27, 44].

5.1 LOCATION-AIDED TIME-SPREAD MULTIPLE-ACCESS (LA-TSNA)

First, a Location-Aided TSMA algorithm (LA-TSMA) is introduced in this chapter. In LA-TSMA, a territory is divided into *zones,* and the mobile hosts located in different zones can be assigned the same TSV. Each zone is divided into several *regions* again, and the number of region depends on user's mobility patterns. The region is at least as big as $2r \times 2r$, where r is the radio propagation range. The number of zones is decided according to the size of the territory and the number of regions in a zone. An example of zones and regions is shown in Figure 5.1; thick and solid lines indicate the boundaries of the zones, and thin and solid lines depict the boundaries of the regions. Note that the mobile hosts A, B, C and D in Figure 5.1 may use the same TSV since they are located in different zones. The difference between GRAND and LA-TSMA is summarized in Table 5.1.

Figure 5.1: Zone and Region.

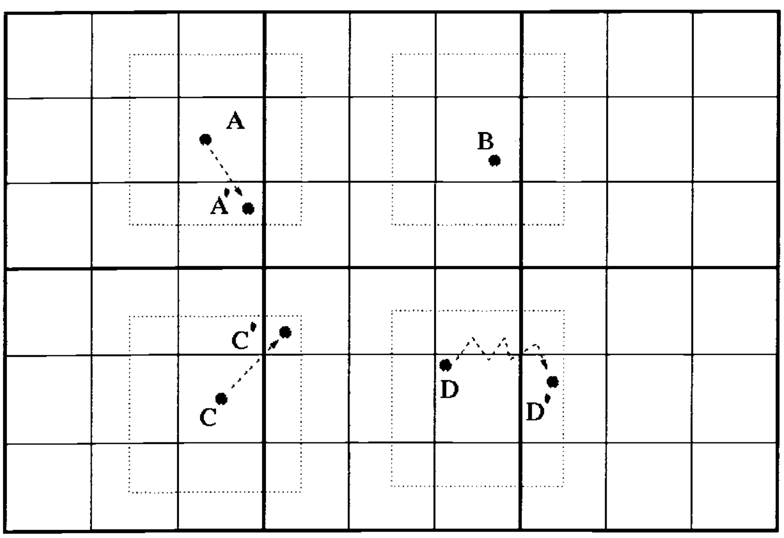


Table 5.1: GRAND vs. LA-TSMA.

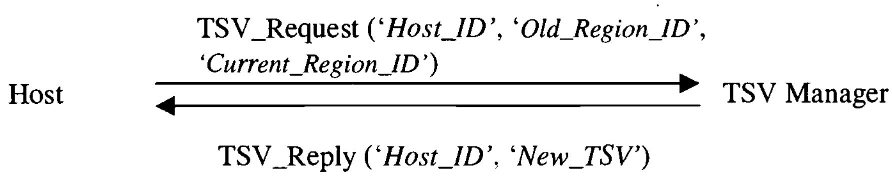
	GRAND	LA-TSMA
TSV assignment	Globally unique and permanent	Locally unique and temporary
Taking advantage of Collision-free sets	No	Yes
Need for GPS	No	Yes

Definition 8 (Effective Scope): Suppose *A* and *B* are any two hosts having the same TSV but inhabiting in different zones. The *effective scope* of *A* is the range in which *A* can move without interfering with *B*.

For example, the hosts *A* and *C* in Figure 5.1 can share the same TSV after *A* moves to A' and *C* moves to C'. Since each region is at least as big as $2r \times 2r$, where r is the radio propagation range, any pair of hosts that are located in different dotted regions can't interfere with each other. Dotted rectangles in Figure 5.1 show the effective scope (*Definition 8*) of the host A, B, C and D respectively.

For all inhabited zones, a TSV manager is elected. A TSV manager is responsible for assigning a locally unique TSV to the mobile host, and maintaining the list of hosts that reside in the zone. As shown in Figure 5.2, when a host moved out of its effective scope, it broadcasts a TSV-Request message, which contains '*Host_ID*', '*Old_Region_ID*' and '*Current_Region_ID*'. When the TSV-manager receives the TSV-Request message, it updates the list of current hosts based on '*Old_Region_ID*' and '*Current_Region_ID*', and then replies with a TSV-Reply message if the TSV requester currently resides in the same zone. A TSV-Reply message contains a requested '*Host_ID*' and a '*New_TSV*'. A '*New_TSV*'' is selected according to '*Current_Region_ID*'.

Figure 5.2: TSV_Request and TSV_Reply Messages



A TSV-manager should have a disjoint set of TSVs for each region. A set of TSVs assigned to a region should have the following properties:

1. They should have at least R elements in the set, where R is the maximum number of mobile hosts that can reside in a region.
2. If $q < R$, where q is the number used in constructing TSVs in the GRAND algorithm, the number of possible collisions between any pair of TSVs in a set should be minimized. This property will considerably

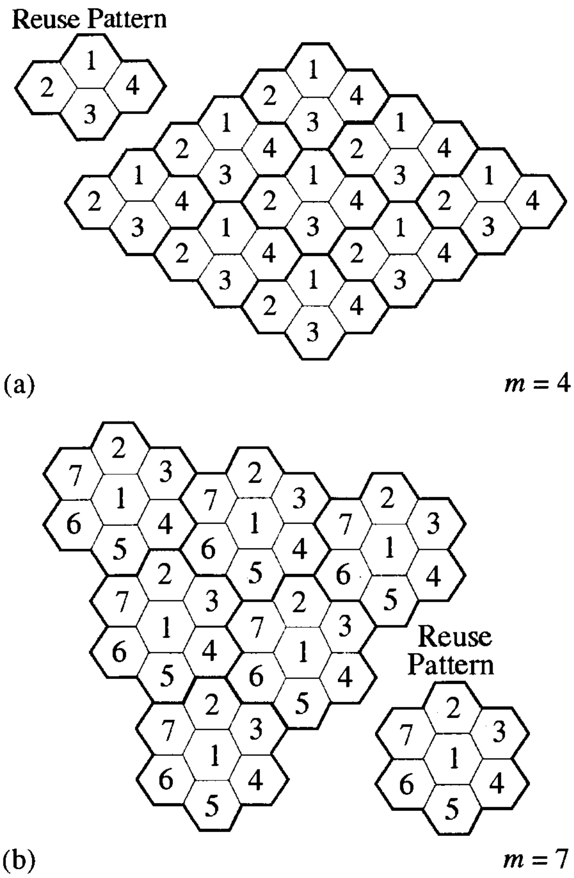
increase the system throughput. (Note that, if $q \geq R$, a set of collision-free TSVs can be assigned to each region.)

Since every host in a zone should use a unique TSV, the LA-TSMA needs only $m \times$ R TSVs, where m is the number of regions in a zone. In general, $m \times$ R is much smaller than the number of mobile hosts (N). Note that the LA-TSMA algorithm does not need to know the number of mobile hosts in advance, it only needs to know the maximum number of mobile hosts (R) in a region.

Assume there is a mobile host H that resides on a region boundary, and the effective scope of H is equal to the region boundary. Suppose H moves the region boundary back and forth very frequently, H sends too many TSV-Request messages and wastes most of the time slots for sending TSV-Request messages and receiving TSV-Reply messages. For the host H, the TSV-manager can assign two TSVs according to the regions where H travels. The host H should use a proper TSV according to the region where it resides.

Also, we can adjust the effective scope of a mobile by selecting an appropriate number of regions (m). If the majority of the hosts do not travel far from the registered region, and if the number of regions is large enough, then they can communicate with the neighboring hosts without acquiring another TSV. Thus, while selecting the number of regions (m), we have to consider user's mobility pattern carefully; the effective scope should be big enough to cover user's general mobility patterns. For the dynamic mobile networks, m should be large enough.

Figure 5.3: Examples of Reuse Patterns



A hexagonal pattern can be used for designing region patterns. Figure 5.3 shows some possible hexagonal patterns. In a hexagonal pattern, only the following values are possible for m [62]:

$$\text{the number of regions } (m) = i^2 + j^2 + (i \times j), \qquad \text{for } i, j = 0, 1, 2, 3, 4 \ldots$$

$$= 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, \ldots$$

Since we can considerably reduce the number of TSV-Request and TSV-Reply messages by adjusting the number of regions (*i.e.* effective scope) based on user's general mobility patterns, the overhead caused by TSV-Request and TSV-Reply messages won't be significant.

To select a TSV-manager among the hosts in the zone, lowest ID clustering algorithm [7] or any other sophisticated clustering algorithm [2, 5, 33, 36, 39] can be used. Since the TSV-manager can act like a cluster head, some cluster-based routing protocols [2, 5, 24, 33, 36, 39] or location-based routing protocols [4, 9, 31, 32] can be used to minimize the overhead caused by TSV-Request and TSV-Reply messages. To provide differentiated services, a high priority/mobility host may use a globally unique TSV. The high priority host can use the globally unique TSV regardless of its location.

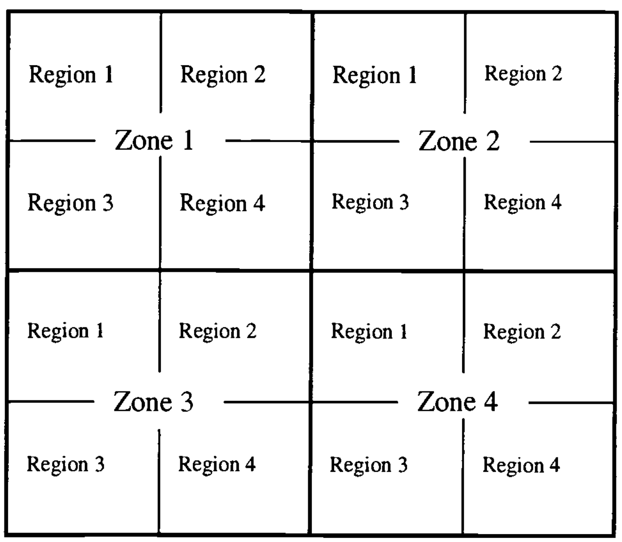
5.2 SIMULATION STUDY

In order to compare the average system throughput of the proposed algorithms to that of the GRAND algorithm, simulation studies are conducted using the GloMoSim library [64]. The GlomoSim library is a scalable network simulation environment for large MANETs based on the parallel discrete-event simulation language PARSEC [3]. Since the implementation of the GRAND algorithm is freely available in the library, this implementation is used for the simulation without any modification.

5.2.1 Simulation Model

In the simulation, a 1600 $m \times 1600$ m territory is divided into 4 zones, and each zone is divided into 4 regions as shown in Figure 5.4. There are 100 mobile hosts, and the 25 mobile hosts are randomly placed in each zone. Host mobility is based on a random waypoint model. Each host randomly selects its destination, and chooses a speed from a uniform distribution between 0 and 20 meters per second. Then, it moves in the direction of the destination in the chosen speed. When the host reaches its destination, it stays there for 100 seconds. After a pause period, the host selects another destination, and moves towards the destination. This process is repeated until the end of the simulation.

Figure 5.4: Simulated Reuse Pattern



The characteristics of the radio model are similar to Lucent's WaveLAN network interface. We assume that radio propagation range for each mobile is 200 *m*, and the channel capacity is *2Mbits/sec*. A pair of source and destination hosts is randomly selected in each zone. The source sends 1460 byte data packets during the simulation. To evaluate the relation between the mobility and the system throughput, we simulate different mobility patterns.

- 0% global host: All hosts move in their region boundary.
- 30% global host: 70 hosts move in their region boundary, and 30 hosts roam globally.
- 50% global host: 50 hosts move in their region boundary, and 50 hosts roam globally.
- 70% global host: 30 hosts move in their region boundary, and 70 hosts roam globally.
- 100% global host: All hosts move globally.

We assume that the maximum degree (D_{max}) is 8. Thus, in the GRAND algorithm, the selected values of q and k are 11 and 1 respectively. The GRAND algorithm constructs 121 TSVs, and then randomly assigns a unique TSV to each host. For the LA-TSMA, q and k are 9 and 1 respectively. 81 TSVs are generated for the simulation, and they are divided into 9 collision-free sets. Since there are only 4 regions, each region has two unique collision-free sets (total 18 TSVs) for the transmission scheduling and one collision-free set (9

TSVs) is reserved for the high priority/mobility hosts; i.e. we assume that the maximum number of mobile hosts in a region (R) is 18. The Lowest ID clustering algorithm described in [24] is used to select a TSV-manager among the hosts in the zone, and a TSV is assigned to each host based on the region where the host resides. Each simulation is run for 600 seconds of simulation time to measure the average system throughput.

5.2.2 Simulation Results

Figure 5.5 and Table 5.2 show the average system throughput as a function of the percentage of hosts that roam globally. At 0% global hosts, there is no additional overhead caused by TSV-Request/TSV-Reply messages, and the system throughput of LA-TSMA is almost 67% better than of that of the GRAND algorithm. This is because the TSVs assigned to the hosts that reside in the same region are collision-free.

As the % of global host increases, the overhead caused by TSV-Request/TSV-Reply messages and a network-layer protocol increases, and so the throughput decreases. For the cases of 70% and 100% of global host, the system throughput of LA-TSMA drops significantly. It is due to the collisions caused by the hosts in the same region. As the mobility increases, there are some regions that have more than 9 hosts. Since it is assigned q = 9 for LA-TSMA, the number of collision-free TSVs is also 9. Thus, if there are more than 9 hosts in a region, the transmissions from two hosts in the same region can collide with each other.

Figure 5.5: Average System Throughput.

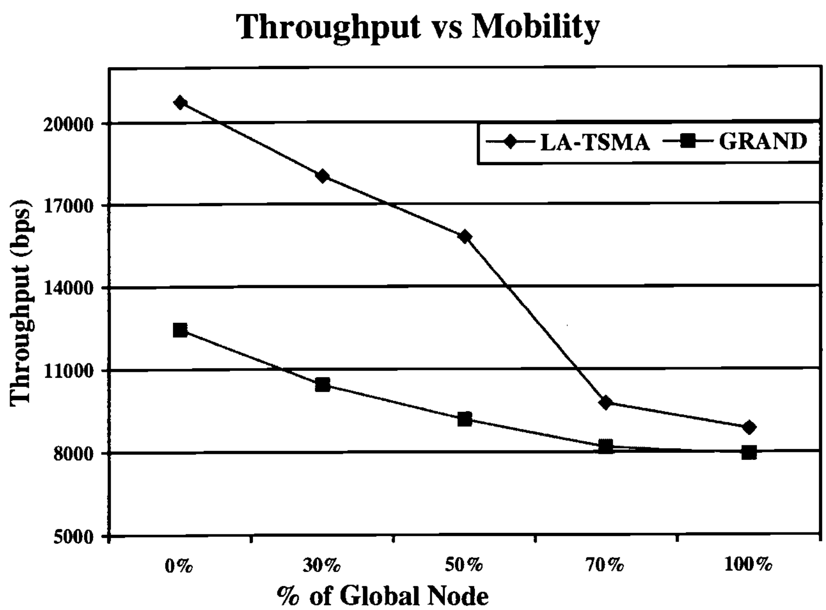


Table 5.2: Simulation Results (mean system throughputs: bps)

Algorithm	Global hosts				
	0 %	30 %	50 %	70%	100 %
LA-TSMA	20752	18026	15809	9774	8864
GRAND	12433	10441	9175	8178	7946

For all cases, the system throughput of LA-TSMA is higher than that of the GRAND algorithm. Based on the simulation results, we conclude that LA-TSMA outperforms the GRAND algorithm.

5.3 CONCLUSION

In this chapter, we've proposed a scalable transmission scheduling algorithm, called LA-TSMA, for MANETs. Although there were several protocols that use the location information in mobile ad-hoc networks [4, 9, 30, 31, 43], they mostly focused on broadcasting overhead reduction and routing algorithms. As we know, the proposed algorithm is the first approach to utilize the location information for the transmission scheduling. Since, in the mobile environment, it is extremely expensive to maintain the whole network topology information, the LA-TSMA uses location information instead. To attain higher system throughput, the proposed algorithm assigns a locally unique TSV to each host instead of assigning a globally unique TSV to each host as done in previous topology-transparent scheduling algorithms [12, 13, 14, 26, 69, 70]. The proposed algorithm has the following advantages.

- LA-TSMA reduces the number of collisions by assigning collision-free TSVs to neighboring nodes using only location information.
- LA-TSMA does not need to know the number of mobile hosts in advance.
- LA-TSMA is scalable.

- The length of TSVs can be significantly reduced.
- LA-TSMA can significantly improve the system throughput and the delay bound.
- LA-TSMA can provide differentiated services.
- LA-TSMA can be combined with previously known location-aided approaches without modifications.

LA-TSMA is our first step towards a scalable solution for MANETs. To realize our scheme, we need to design a routing algorithm that is apt to the proposed scheduling algorithm, and perform additional simulation studies in various environments.

6 CONCLUSION AND FUTURE WORK

In this thesis, we have shown that the topology-transparent transmission scheduling problem is equivalent to the problem of constructing constant weight codes which satisfy certain properties. Constructing constants weight codes and finding the upper and lower bounds on constant weight codes are extensively studied for almost four decades. Thus, we can use the previously known results to find the proper scheduling for the given networks.

Based on coding theory concepts, we have designed the MaxThrou and MinDelay scheduling algorithms. The *MaxThrou* algorithm aims at maximizing the guaranteed minimum system throughput, and the *MinDelay* algorithms tries to minimize the delay. Using these algorithms, we get better minimum system throughput and/or delay bound while at the same time preserving other properties such as topology independence, guaranteed minimum throughput, bounded maximum delay, and fair transmission policy.

To use the scarce battery efficiently, the Energy Conserving Transmission Scheduling (ECTS) algorithm is proposed. The ECTS algorithm conserves the power using strategies that allow the network interface to use the low power sleep mode instead of the idle mode. To relieve the unnecessary battery consumption, the ECTS protocol eliminates data collisions using CTR and RTS control slots, and significantly reduces the number of transitions from the sleep mode to the receive or transmit mode.

To provide a scalable solution for MANETs, another scheduling algorithm called LA-TSMA, is also introduced. Instead of assigning a globally unique TSV to each host as done in the previous scheduling algorithms, the proposed algorithm assigns a locally unique TSV to each host. The proposed algorithm has the following advantages.

- The number of mobile hosts is not a parameter of LA-TSMA.
- LA-TSMA is scalable.
- The length of TSVs can be significantly reduced.
- LA-TSMA can improve the system throughput and the delay bound significantly.
- LA-TSMA can provide differentiated services.
- LA-TSMA can be combined with previously known location-aided approaches without modifications.

Future Research

Since the area of mobile ad hoc networking is relatively new, there are many unexplored areas. As a follow-up to this thesis research, we would like to explore the following area further.

One of our future research interests is to develop scalable solutions for dynamically configuring ad hoc wireless networks. Since maintenance of hosts' approximate locations may be easier than maintenance of end-to-end routes, location-based routing protocols are likely going to be more scalable. Several studies show that location-based routing can significantly reduce the overhead caused by control messages compared with route-based methods [4, 35]. The proposed scheme in *Chapter 5* is the first step towards a scalable solution, and it is highly desired to combine the proposed scheduling algorithm with a new routing algorithm that is apt to the proposed scheduling algorithm.

Advances in wireless communications technologies and the emergence of ubiquitous applications have recently generated a lot of interest in supporting multimedia applications with Quality of Service (QoS) guarantees in next generation mobile environments. QoS is more difficult to guarantee in MANET than in most other types of networks because of the highly fluctuating nature of the quality of packet delivery, dynamic topology and unreliable wireless transmission. Therefore, we believe that wireless QoS will be a challenging area to be in for both the research community and the telecommunications industry.

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