TOPOLOGY DESIGN AND SCHEDULING IN STDMA BASED WIRELESS AD HOC NETWORKS

A THESIS

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MASTER OF SCIENCE

By

Sadettin Alp Ergin

September 2003

I certify that I have read this thesis and in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Sciences.

Assist. Prof. Dr. Ezhan Karaşan (Supervisor)

I certify that I have read this thesis and in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Sciences.

Assist. Prof. Dr. Nail Akar

I certify that I have read this thesis and in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Sciences.

Prof. Dr. Hayrettin Köymen

Approved for the Institute of Engineering and Sciences

Prof. Dr. Mehmet Baray
Director of Institue of Engineering and Sciences

ABSTRACT

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Sadettin Alp Ergin

M.S. in Electrical and Electronics Engineering

Supervisor: Assist. Prof. Dr. Ezhan Karaşan

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With current advances in technology, wireless networks are increasing in popularity. Wireless networks allow users the freedom to travel from one location to another without interruption of their communication activities. Ad hoc networks, a subset of wireless networks, allow the formation of a wireless network without the need for a base station. Since no fixed infrastructure is involved in the communication, the nodes of ad hoc networks can communicate with each other or can relay data to other nodes. With this flexibility, wireless ad hoc networks have the ability to form a network anywhere, at any time, as long as two or more wireless users are willing to communicate.

Managing ad hoc networks is a significantly more difficult task than managing wireline networks. The network requirements should be met by combined efforts of all the mobile nodes themselves. The nodes of ad hoc networks often operate under severe constraints, such as limited battery power, variable link quality and limited shared bandwidth. In this study, the topology design issue in ad hoc wireless networks is investigated. We employ hierarchical routing where the network topology is composed of clusters interconnected via a root node. Cluster-based topologies are suitable for military services, an important application area for ad hoc networks. The common power control technique (COMPOW) is used in this thesis where all nodes transmit at the same power level. Nodes employ the spatial TDMA (STDMA) scheme in order to access the channel. An important task is how to produce a minimum STDMA frame length, and this problem is known to be NP complete. We develop a heuristic algorithm for generating the minimum STDMA frame length. A new interference model for ad hoc networks is proposed which utilizes a hypergraph model. The relationship between the frame length, number of clusters and the transmit power level are investigated through numerical examples using a 15-node network.

Keywords: Ad hoc networks, topology design, STDMA, hierarchical routing, interference hypergraph model.

ÖZET

AD HOC KABLOSUZ AĞLARDA TOPOLOJİ TASARIMI VE ZAMAN ÇİZELGELEMESİ

Sadettin Alp Ergin
Elektrik ve Elektronik Mühendisliği Bölümü Yüksek Lisans
Tez Yöneticisi: Yrd. Doç. Dr. Ezhan Karaşan
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Teknolojideki son gelişmeler kalosuz ağların popülaritesini arttırdı. Kablosuz ağlar kullanıcıya bir yerden bir yere giderken kesintisiz komünikasyon sağlamaktadır. Kablosuz ağların bir alt kümesi olan ad hoc kablosuz ağlar, herhangi bir baz istasyona gerek duymaksızın bir şebeke kurulmasını sağlar. Haberleşmede sabit bir yardımcı tesis olmadığı için, ad hoc ağ istasyonları ya birbirleri ile haberleşir ya da gelen bilgiyi diğer istasyonlara yönlendirirler. Bu kolaylık sayesinde, ad hoc kablosuz ağların iki veya daha çok istasyon istediği müddetce her yerde ve her zaman bir ağ oluşturma kabiliyetleri mevcuttur.

Ad hoc ağların idaresi kablolu ağlara nazaran oldukça zor bir görevdir. Ağ ihtiyaçları bütün istasyonların gayretleri ile karşılanır. Bununla beraber ad hoc ağ istasyonları sınırlı batarya gücü, değişken link kalitesi ve sınırlı paylaşılan band genişliği gibi çok kuvvetli kısıtlamalar altında çalışırlar. Bu çalışmada, ad hoc kablosuz ağlarda topoloji tasarımı problemi araştırıldı. Grupların ana istasyon üzerinden birbirleri ile bağlantılarını sağladığı topolojide hiyerarşik

yönlendirme kullanıldı. Gruplandırma temelli topolojiler ad hoc ağlar için önemli bir uygulama alanı olan askeri operasyonlar için çok uygun olmaktadır. Uzaysal zaman bölümlemeli çoklu erişim metodu istasyonların kanala ulaşma metodu olarak seçildi. Tezde, bütün istasyonların aynı gönderme güç seviyesini kulllandığı ortak güç kontrol metodu kullanıldı. Bunlara ilaveten üstün çizgeler kullanılarak yeni bir girişim modeli sunuldu. Zaman uzunluğu, grup sayısı ve gönderme güç seviyeleri arasındaki ilişki 15 istasyonluk bir ağ kullanılarak bulunan sonuçlarla incelendi.
Anahtar Kelimeler: Ad hoc ağları, topoloji tasarımı, uzaysal zaman bölümlemeli çoklu erişim, hiyerarşik yönlendirme, üstün çizge girişim modeli.

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To My Wife Dilek Ergin

Chapter 1

Introduction

In the last ten years we are witnessing fast and enormous advancements in mobile wireless communications. People are beginning to depend on mobile wireless instruments. Cellular phones are already an integral part of our lives. Laptops, PDAs (Personal Digital Assistants), pagers, game consoles and other similar devices are following this trend. There were more than 200 million wireless telephone handsets purchased in 2002. Mobile data networks with the capability of connecting these devices to each other in wireless media have enjoyed a tremendous rise in popularity.

There are two distinct approaches for enabling wireless communication between two hosts. One method is to use the conventional cellular infrastructure and the second one is to use ad hoc networks. Cellular networks contain base stations and mobile users. Mobile nodes in cellular networks only communicate with the nearest base station, which is also the bridge of these networks. In contrast to cellular networks, an ad hoc network is a collection of wireless mobile nodes, dynamically formed without the support of any physical infrastructure or centralized administration. Ad hoc networks are also called as infrastructureless networks. Since no base station is needed, ad hoc networks can be deployed easily and rapidly. This factor makes the concept attractive for communications in situations where the instrastructure is not available. Ad hoc networks find applications in tactical military networks, sensor networks, disaster relief networks etc., where the deployment of a network needs to be done without any infrastructure.

This flexibility also brings some technical challenges. Specifically, the network should be dynamically self-organizing and self-configuring. All functions have to be executed in a distributed manner at each node due to the lack of a centralized controller. In addition, nodes powered by limited resources share a common wireless channel. Scarce resources, such as power and bandwidth, have to be managed wisely. When hosts are located closely together within the connectivity range of each other, no real routing protocol is necessary. However, if two hosts that want to communicate are out of their transmission ranges, they could communicate only if there are intermediate hosts between them. Therefore, nodes of ad hoc networks should behave as routers to maintain network connectivity.

In Chapter 2, we present detailed information about wireless ad hoc networks and their characteristics. In this chapter, applications of ad hoc networks are presented. Examples of potential practical uses of ad hoc networks are only limited by imagination. We may think of a group of people with laptop computers at a conference that may wish to exchange files and data without support of any additional infrastructure. We can also think of deploying ad hoc networks in home environment for communication between smart household appliances.

Ad hoc networks perfectly satisfy military needs like battlefield survivability, operation without pre-located base station and connectivity beyond the line of sight (LOS). For monitoring and measuring purposes, a large number of small computing devices could be spread over a hostile or unknown terrain to form a self-organized ad hoc network.

At the end of Chapter 2, a modification for the current field artillery battery fire direction system used in Turkish Army is proposed by changing communication into ad hoc manner. Current system traditionally uses one-hop communication. If destination is outside of the transmission range, connectivity is provided by intermediate repeater, which is pre-placed. Devices should be functioned with high power in order to make a connection. High power brings high power consumption and security problems. Modified system allows the artillery units to build short links instead of longer links and results in lower power consumption. Transmission at low power level also increases frequency reuse. Chance of detection of signals by the enemy and jamming can be significantly reduced. The communication in ad hoc manner ensures beyond line of sight (LOS) communication due to multihop packet routing.

In Chapter 3, we discuss the topology design in wireless ad hoc networks. Topology is the set of communication links in the given network and has a significant importance on network performance. Unlike wireline networks, ad hoc network topology can be dynamically configured. Especially power control and routing are the main instruments to control the topology. In this thesis, we mainly consider the task of obtaining a connected topology. While obtaining the desired topology, we focus on spatial reuse of the wireless spectrum. One effective method of increasing the capacity of a wireless network is power control. By controlling the transmission power, a node can achieve its transmission quality while reducing the interference in the channel at same time. Although traditionally power control has been studied at the physical layer, in fact it has profound impacts and influences in all aspects of the network. In this thesis common power (COMPOW) algorithm is used for power control. This algorithm requires all nodes in the network use the same transmit power level P_c, which corresponds to the lowest power level for constructing a connected network topology.

The multihop characteristic of ad hoc networks allows reuse of the bandwidth. Different nodes can use the same frequency band simultaneously providing that they are sufficiently apart. One solution for channel utilization problem is the Spatial Time Division Multiple Access (STDMA) which is an access scheme for multihop radio networks [1]. It is an extension of TDMA where the capacity can be increased by letting several simultaneous transmissions. In this study, we address the problem of minimizing the STDMA frame length. The performance of the MAC scheme has a significant effect on the performance of the routing method. Hence, ad hoc routing and MAC protocols ought to be considered together. A unified approach to spatial TDMA slot assignments and routing are described in this study. The problem of assigning the transmission time slots to selected links is referred to as scheduling. The goal of combined scheduling and routing is primarily to minimize end-to-end delay.

In this thesis, the topology of the network is a two-layered structure and hierarchical routing is employed. Hierarchical routing is achieved by clustering formation. Military unit's location property leads us forming clustering model. Nodes in the same cluster can establish unidirectional links with each other. Clusterhead nodes have the responsibility of routing packets that are sent to the nodes outside of the cluster. The connectivity among the clusters is provided by the root node. Throughout our study, mobility is not considered. Model definitions and assumptions are given in Chapter 3.

Chapter 4 describes clustering and scheduling algorithms. In the development of the algorithm, a hierarchical routing is achieved by forming clustering since it is suitable for military networks. Partitioning the nodes into groups, called as clustering, provides the spatial reuse of the common channel. Such a partitioning of the links is achieved by using proximity-based clustering algorithm. If the nodes are separated enough from each other they can make conflict-free communication at the same time slot.

The problems of link scheduling and routing in wireless ad hoc networks are investigated in this thesis. The end-to-end delay is minimized by scheduling established transmission links. As we schedule the links, we eliminate possible collisions and reuse the frequency efficiently. The interference model which is used widely in the literature is binary, i.e., constraints always concern couples of transmitters. However, real-world interference is additive, i.e., the number of interfering stations should be taken into account for conflict-free communication. A more accurate interference model is proposed by a hypergraph modeling in this thesis. In our model, the set of vertices V corresponds to a possible transmission links. Each hyperedge E is a group of links, all of which cannot be established simultaneously. In order to find maximum number of simultaneous transmission links, we take advantage of the property of the maximal independent set. Using maximal independent set of the interference hypergraph model, clusters are formed. After clustering, clusterhead nodes are determined by the root node.

The last step of the algorithm is to assign time slots to selected links. Our main interest is to obtain minimum schedule STDMA length as well as to form the desired connected topology. But the minimum-length-scheduling problem is NP complete [2]. A greedy heuristic is proposed to obtain the minimum frame length. Link scheduling is performed by traffic requirements and routing information at each node. As achieving hierarchical routing, link scheduling is performed such that a connected topology is generated. Connected topology implies that each node can reach to all other nodes within an STDMA frame. In connected topologies, end-to-end delay is limited by the frame length. End-to-end delay can be minimized by minimizing the frame length. At the end of the algorithm, connected topology is constructed by minimum STDMA length frame. A combined scheduling and routing scheme is developed by executing the same algorithm. The relationship between frame length, number of clusters and transmit power are investigated through numerical examples using a 15-node network. At the end of this chapter, a distributed algorithm is given for collecting all pairs gain and adjacency matrices by the root node. After collecting this information, scheduling algorithm is executed at the root node, and link scheduling list is distributed to all other nodes by the root node. Finally, Chapter 5 concludes the thesis.

Chapter 2

Wireless Ad Hoc Networks

In this chapter, we introduce wireless ad hoc networks. Later features, problems and applications of wireless ad hoc networks are discussed. At the end of this chapter, we present field artillery battery fire direction system in ad hoc manner as a military application.

2.1 Wireless Ad Hoc Networks and Characteristics

With the advances in mobile computing, people are beginning to depend on mobile wireless instruments. The variety of information services to access via light, hand-held, cordless devices such as portable computers, mobile phones and Personal Digital Assistants (PDAs) have changed wireless communication systems into an indispensable part of any state of the communication networks. Cellular phones are already an integral part of our life. Laptops, PDAs, pagers, game consoles and other similar devices are following this trend. Some of the advantages of mobile wireless networks are

Allowed user mobility

Rapid access to services, regardless of person's placement

No need for cabling

Low costs

Deployment of wireless solutions takes significantly less time compared to wired solutions. Due to these advantages, such wireless networks could be more suitable for military and emergency applications, and surveillance of critical signals and data gathering.

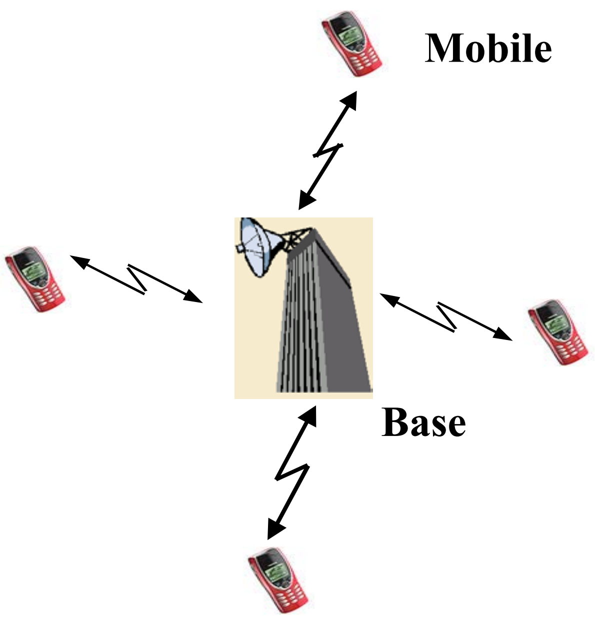


Figure 2.1: Example of infrastructured wireless networks
(Cellular networks).

Various sensors are already used in industry and military. Many people carry numerous portable devices for their professional and private use. With all these communication devices available in the field, a requirement to connect them easily and efficiently has arisen. There are currently two variations of mobile wireless networks. Cellular networks are the first example of wireless services. In these networks, as shown in Figure 2.1, base station and mobile hosts are grouped into a cellular structure.

The developments in wireless networking have primarily been driven by the success of the dominant cellular architecture model. In cellular networks, the base station that is not mobile has the responsibility of maintaining the communication. A mobile host connects to, and communicates with, the nearest base station that is within its transmission range. When it goes out of communication range of one base station, it connects to a new base station and starts transmitting through it. Base stations are also bridges of these networks.

The second type of mobile wireless network, sometimes referred to as ad hoc, or peer-to-peer, or multi-hop networks, consists entirely of wireless and often mobile nodes that may communicate either directly or via multiple hop paths that require the support of intermediate nodes to achieve connectivity. In contrast with the cellular architecture, wireless ad hoc networks do not require centralized access points or pre-existing infrastructure as shown in Figure 2.2. Absence of an infrastructure is the main difference between ad hoc and cellular networks. That is the why ad hoc networks are also called the infrastructureless networks.

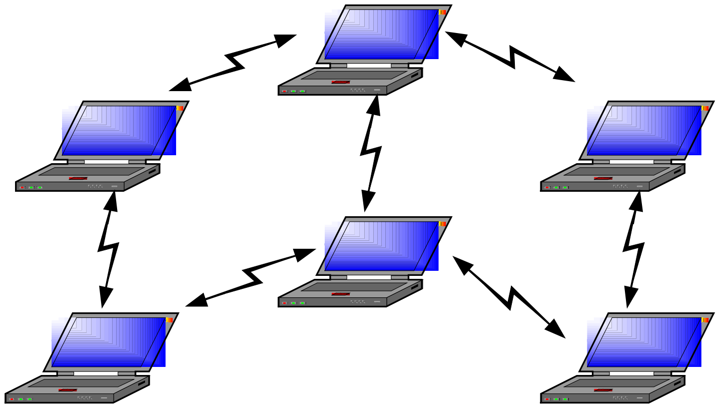


Figure 2.2: Example of wireless ad hoc network.

Ease and speed of deployment make the operation of ad hoc networks attractive for many applications. We can communicate anywhere and at anytime in ad hoc networks. Since there is no base station, each node in an ad hoc network can communicate with other nodes or can relay data to other nodes. Nodes of these networks function as routers that discover and maintain routes to other nodes. So ad hoc networks have the multihop property. To achieve connectivity, we need multiple hop paths that require the support of intermediate nodes. Due to lack of infrastructure of ad hoc networks, all network functions have to be achieved by the participating users. For instance, when a node wants to send data to some other nodes which are outside its transmission range, other intermediate users in the network have to relay the packet to the destination. That is why it is also called as multihop wireless network. Figure 2.3.b illustrates one example of ad hoc networks. In this example, Node-1 needs relaying of Node-2 in order to communicate with the other nodes.

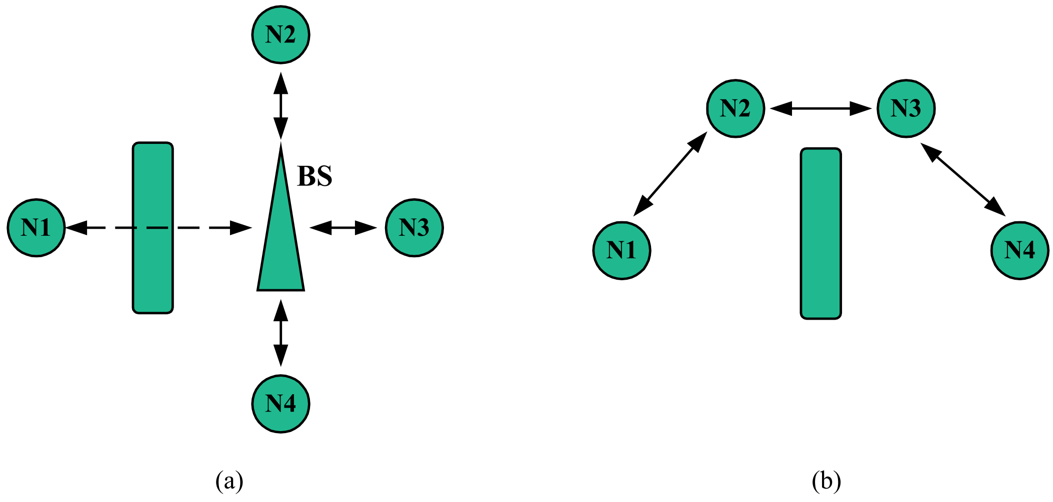


Figure 2.3: Examples of the two paradigms of wireless networks.

Ad hoc network nodes can communicate without knowing where the other nodes are and do not need a clear line of sight. In the cellular network of Figure 2.3.a, nodes 2-3-4 exchange information by routing through the base station. Node-1 cannot communicate with any other nodes, because of an obstacle that blocks the line of sight to the base station. In the ad hoc network of Figure 2.3.b any two nodes can communicate if a path exists between them. Nodes 1 and 4 can use nodes 2 and 3 as relays to communicate with each other.

Ad hoc networks are autonomous systems. Beside they can operate in isolation, they can also have gateways for communicating with other networks as illustrated in Figure 2.4.

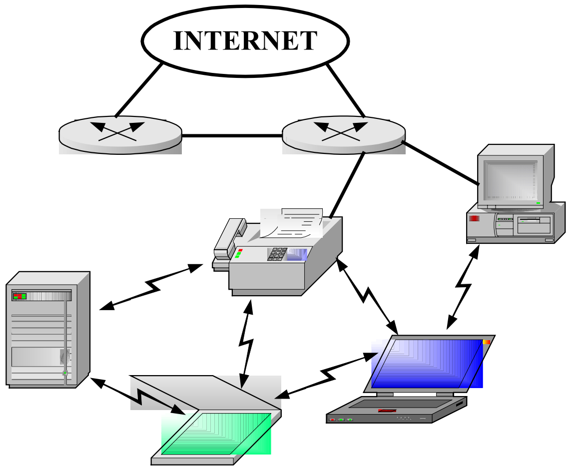


Figure 2.4: Ad hoc networks connected to fixed networks.

Below we discuss some typical operational characteristics of ad hoc networks:

1) Dynamic Topologies: Ad hoc networks are generally highly dynamic in nature. That means nodes can move within the network or they can disappear or appear dynamically. In Figure 2.5, Node-1 moved and topology changed. New neighbors of Node-1 are Node-4 and Node-5. So the link between Node-1 and Node-2 cannot be used anymore. Such movements of nodes result in unpredictable changing in the network topology. In fixed networks, there is no strong limitation on routing updates. When wireless networks are considered, new routing mechanisms are clearly needed.

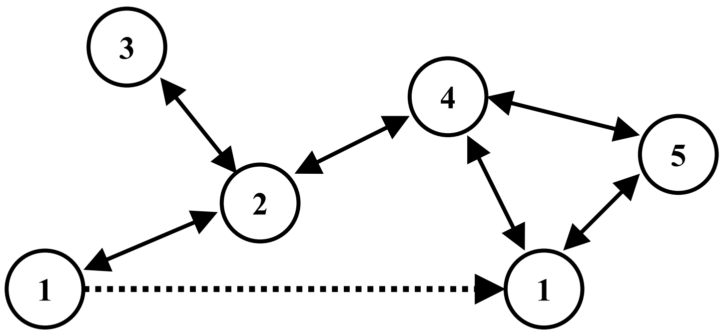


Figure 2.5: Dynamic topology of wireless ad hoc networks.

2) Bandwidth-limited and variable capacity links: In wireless networks, channel bandwidth is usually limited and has lower capacity than wired networks. The effects of multiple access, fading, noise and interference conditions should be taken into account in link layer protocols.

3) Energy-constrained operation: Some or all of the hosts may have limited resources in terms of power. Since they rely on batteries for their energy, continuous operation of mobile terminals is an important issue. Therefore energy conservation is critical task in network topology design.

4) Distributed operation: Since there is no background network for the central control of the network operations, the control and management of the network should be distributed among the mobile nodes. The nodes involved in wireless ad hoc networks should collaborate with other nodes, and each node should act as a router as needed to implement functions such as security and routing. These functions must be designed so that they can operate efficiently in distributed manner.

2.2 Challenges in Wireless Ad Hoc Networks

In coming years, information technology will be mainly based on wireless area. In future applications, wireless mobile and access will become more ad hoc and reconfigurable. The ad hoc architecture has many benefits such as self-organization and adaptability to highly variable mobile characteristics such as transmission power and conditions, traffic distribution variations and load balancing. However, such benefits come with some challenges which mainly reside in the unpredictable network topology due to node movements and shared wireless medium. The solutions for conventional networks are usually not sufficient to provide efficient ad hoc operations. The most important of these challenges are summarized below.

2.2.1 Wireless Medium Unreliability and Security

Unlike wired networks where an adversary must damage the network wires or pass through several lines of defense at firewalls and gateways, attacks on a wireless ad-hoc network can come from all directions and target at any node. Damages can include leaking secret information, message contamination, and node impersonation. All these mean that a wireless ad-hoc network will not have a clear line of defense, and every node must be prepared for encounters with an adversary directly or indirectly.

Furthermore, the wireless nature of communication and lack of any security infrastructure raise several reliability problems. Contrary to fixed-cable networks, wireless ad hoc networks are highly unreliable. Wireless signals are subject to significant attenuation and distortion, which are generally of random nature.

Achieving security within ad hoc networking is challenging due to following reasons [3]:

- *Dynamic topologies and membership* : A network topology of ad hoc network is very dynamic as mobility of nodes or membership of nodes is random and rapid. This emphasizes the need for secure solutions to be dynamic.
- *Vulnerable wireless link* : Passive/Active link attacks like eavesdropping, spoofing, denial of service, masquerading, impersonation are possible.

- *Roaming in dangerous environment* : Any malicious node or misbehaving node can create hostile attack or deprive all other nodes from providing any service.

Therefore security challenges must be considered when designing a wireless system. And sufficient levels of security should be provided especially military and banking applications.

2.2.2 Routing in Wireless Ad Hoc Networks

Since the transmission range of nodes of wireless ad hoc networks is limited, a routing protocol is needed to enable them to be connected to each other. Conventional routing protocols are not appropriate for ad hoc mobile networks due to temporal nature of the wireless links. So the issue of routing packets between any node pairs becomes a challenging task. Routing is one actively researched area for mobile ad hoc networks. Moreover, the network topology changes arbitrarily as the nodes move and information is subject to becoming obsolete both in time (information may be outdated at some nodes but current at others) and in space (a node may only know the network topology in its neighborhood and not far away from itself). In Figure 2.6, Node-1 reaches Node-3 via intermediate Node-2. After changing the location of Node-1, a new path (Node-1→Node-4→Node3) is established between Node-1 and Node-3. Routing algorithm should be updated according to this new path. In Figure 2.7, the current path between Node-5 and Node-2 is Node-5 → Node-4 → Node-2. But failure of link Node-5 → Node-4 makes the current path obsolete. A new path needs to be configured, and the routing algorithm computes the new path Node-5→Node-6→Node-4→Node-2.

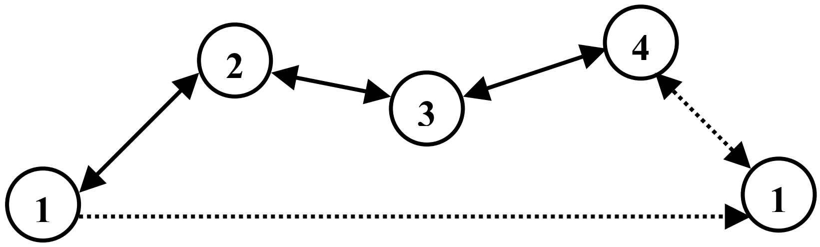


Figure 2.6: The effect of node movements on routing algorithm.

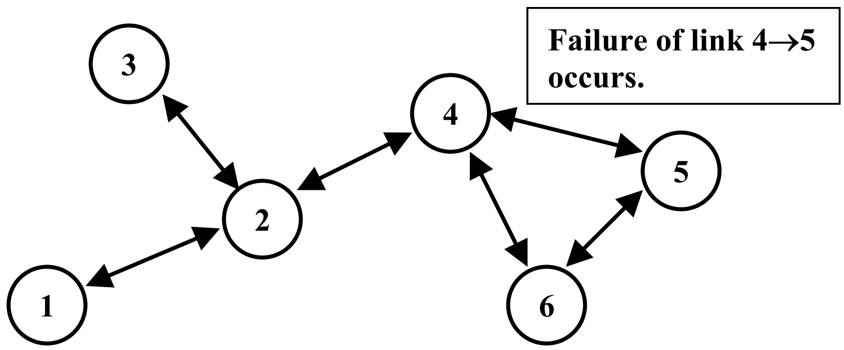


Figure 2.7: The effect of link failures on routing algorithm.

Ad hoc routing protocols should comply with frequent topology changes, less accurate information and link failures. Because of these unique requirements, routing in these networks is very different from the others. The Mobile Ad-Hoc Networks (MANET) working group of the Internet Engineering Task Force (IETF) has been actively evaluating and standardizing routing, including multicasting, protocols. Ad hoc routing protocols can be classified as table-driven routing protocols and on-demand routing protocols. Since gathering fresh information about the entire network is often costly and impractical, many routing protocols are reactive (on-demand) protocols. They collect routing information only when needed and to destinations they require routes to, and do not maintain unused routes. This way the routing overhead is greatly reduced compared to pro-active protocols which maintain optimal routes to all destinations at all time. This is important for a protocol to be adaptive. AODV [4], DSR [5] and TORA [6] are representatives of on-demand routing protocols presented at the MANET working group.

Another type of routing protocols is Table-Driven routing protocols also called as pro-active routing protocols. These protocols require each node to maintain one or more tables to store routing information, and they respond to changes in network in order to maintain a consistent network view. Some of them are Destination-Sequenced Distance-Vector Routing (DSDV) [7], Clusterhead Gateway Switch Routing (CGSR) [8], and Wireless Routing Protocol (WRP) [9].

These two types of ad hoc routing protocols have advantages and drawbacks. In order to provide quality-of-service, routing protocols need not only to find a route but also to deal with the typical limitations of ad hoc networks, such as high power consumption, low bandwidth and high error rates. In the literature, there are some studies that consider efficient minimum energy routing schemes. In [10], they achieve energy efficient routing by establishing routes that ensure that all nodes equally deplete their battery power. Subbarao [11] conducts an initial investigation of energy routing and develops a minimum power routing scheme using table-driven protocol approach. Singh et al. [12] introduce power aware cost metrics for routes and design routing policies that minimize energy consumption.

2.2.3 Bandwidth and Capacity Management in Wireless Ad Hoc Networks

Bandwidth-guaranteed service in ad hoc networks is a challenging task due to several factors such as the absence of central control, the dynamic network topology, the hidden terminal problem and the multihop routing property. In addition to these factors, communication is node-based because of the broadcast nature of the wireless medium. Every transmission by a node can be received by other nodes that are located within its transmission range. Mobile nodes of the network share the wireless channel for communication. This causes situations where two or more stations may want to use the same shared medium at the same time. Such conflicts result in garbling and eventual loss of data due to collisions. Therefore, nodes must negotiate with each other to manage the bandwidth. Nodes require efficient medium access mechanism to schedule their transmission so that the goals of minimizing interference and efficient utilization of the bandwidth are satisfied.

Medium access control protocols define rules for orderly access to the shared medium and play a crucial role in the efficient and fair sharing of scarce wireless bandwidth. Designing of wireless MAC protocols is the another heavily researched area for mobile ad hoc networks. Moreover, routing and power control schemes can also increase the capacity of wireless network. Quality of Service (QoS) routing requires not only to find a route connecting the source to the destination, but the route can satisfy the end-to-end QoS requirement, often given in terms of bandwidth and delay.

2.2.4 Power Management in Wireless Ad Hoc Networks

Ad hoc network is a collection of mobile nodes which are generally battery driven devices. Due to infrastructureless operation, nodes of ad hoc networks must relay the data to maintain connectivity. This results in extra energy consumption in the nodes. Therefore power is one of the critical resources, and it is needed to be managed wisely. The power control is to select the transmitting power level for each communication link in the wireless network. Selecting the power level has significant effects on network topology.

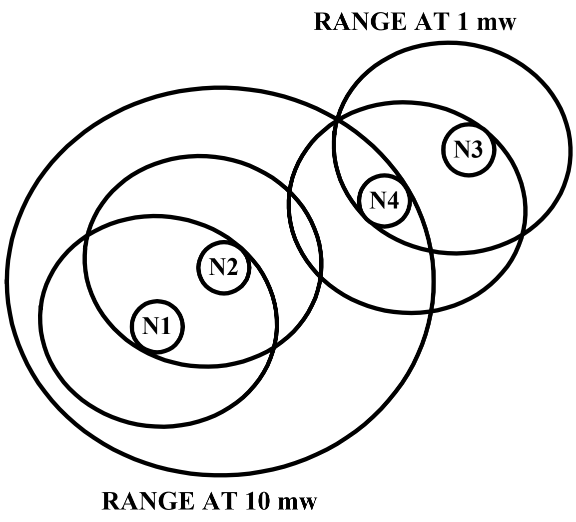


Figure 2.8: Power control for energy savings.

- ***Power control provides energy saving.***

In Figure 2.8, transmission between Node 2 and Node 1 is at 10mW. But Node 1 is in the 1mW transmission range of Node 2. There is a waste of energy for Node 2. With adjusting power level, Node 2 can save on battery power.

When all other nodes are considered, choosing convenient power level can extend network life. Thus energy conservation is a key requirement in the design of ad hoc networks. Especially in sensor networks with power-aware design, the node's energy consumption displays a graceful scalability in energy consumption at all levels of the system, including the signal processing algorithms, operating system, and even the integrated circuits themselves. Sensor systems must utilize the minimal possible energy while operating over a wide range of operating scenarios. Throughout its lifetime, a node may be called upon to be a data gatherer, a signal processor, and a relay station. Its lifetime, however, must be on the order of months to years, since battery replacement for thousands of nodes is not an option.

- ***Power control extends capacity of the network.***

Simultaneous transmissions cause interference with other nodes. Bandwidth re-use is desired goal of the wireless network designer. Power control helps dealing with long term fading effects and interference. When power level is managed, a transmitter will use the optimal power level that is required to communicate. Optimal power level results in minimizing interference to other nodes in the vicinity. In Figure 2.8, Node-3 wants to send data to Node-4 at 1mW. This communication can be established successfully provided that the transmission between Node-2 and Node-1 is established at 1mW. Otherwise, using 10mW does not allow communications over both links due to interference by Node-2 to Node-4. Therefore, power control can enhance the network capacity.

Power control can be managed in several layers. In the physical layer, power control impacts the link quality. Ongoing transmission link can be broken for a while unless power control is not used. However, power control also has direct effects on the network layer. The recent interest in ad hoc networks has led to a number of routing schemes that use the limited resources available at nodes more efficiently [11]. These schemes typically try to find the minimum energy path to optimize energy usage at a node. Using lowest energy paths may be optimal from the point of view of network lifetime and long-term connectivity. As shown in Figure 2.9, although the above path is shorter than the below path, it is selected when energy metric is considered as a cost function for routing policy. There is an inter-relation between transmission power control and routing, and power control should be managed in conjunction with routing.

As terminals are powered by a limited battery source, energy constraints play a major role in management of wireless ad hoc networks. Although traditionally power control has been studied at the physical layer, it has been recognized that power control should be performed at every aspect of the network. In the next chapter, different power control algorithms in the literature will be presented.

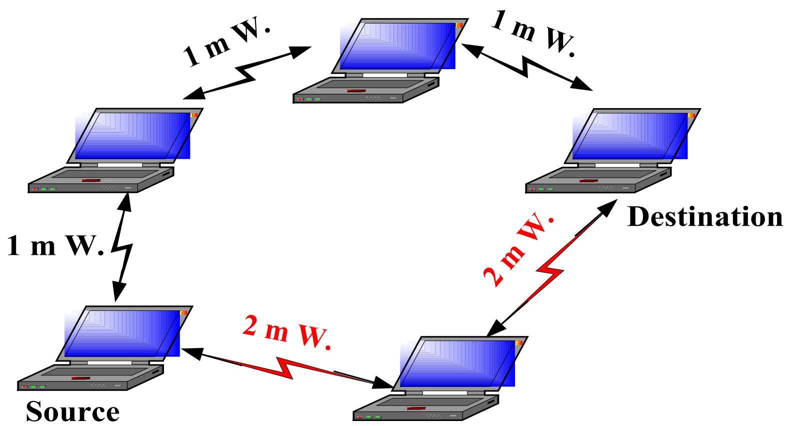


Figure 2.9: Power control effects routing policy.

2.3 Typical Applications of Wireless Ad Hoc Networks

With the current technology and increasing popularity of notebook computers and hand-held devices, interest of people in ad hoc networks has greatly peaked. As stated in the previous section, wireless communication systems have advantages compared to wireline systems. The most important ones of these advantages are mobility and cost savings. Mobility lifts the requirement for a fixed point of connection to the network. Users are able to move while using their appliances. Wireless networks are also beneficial in reducing network costs. Therefore, ad hoc networks have been the focus of many recent research and development efforts. Recent advances in technology allow us to form small ad hoc networks on campuses, during conferences, and even in our own homes. They are good for applications in home networks where devices can communicate directly to exchange information, such as image, alarms, and configuration updates.

Furthermore, the feature for easily deployable ad hoc networks in rescue missions and in situations located in rough terrain are becoming extremely common. Applications of ad-hoc networks range from military tactical operations to civil rapid deployment such as emergency search-and-rescue missions, data collection/sensor networks, and instantaneous classroom/meeting room applications. It is clear that decentralized and self-organized network structure is an operative advantage or even a necessity for military applications. Many projects in ad hoc networks have been mainly considered for military applications. Many countries in all over the world have been focusing on providing their soldiers with up-to-date technology for wireless communication, navigation and information interchange. Major motivation for wireless ad hoc networks is the military requirement for battlefield survivability. To survive under battlefield conditions, warfighters and their mobile platforms must be able to move about freely without any of the restrictions. Therefore, for battlefield survivability we need mobile wireless communication systems, which are coordinated in a distributed manner. Soldiers who need to communicate with each other are deployed over an unfamiliar terrain where no fixed network infrastructure exists or has failed. The lack of centralized control stations, a main feature of ad hoc networks, ensure avoiding single points of failure. Here are the some examples of military applications.

- Infantry and Tank unit collaborations
- Special forces operations
- Sensor networks
- Reconnaissance operations
- Search and Rescue operations
- Unexpected attack in enemy terrain
- Deep valley and mountain operations
- Guard unit in defense

Since ad hoc networks can self-configure and self-organize, they are an optimal solution for many networking applications. Sensor networks, which consist of a large amount of disposable sensors, are scattered to collect background data in the events like earthquakes, nuclear disasters, airplane disasters, etc. The sensors coordinate to establish a communications network and then send the data back to the master-site for more intensive analysis. We are familiar with the communication problems due to breaking down the base stations especially in earthquakes. Ad hoc networks are the exact solution to deal with these communication problems. Examples include rescue operations in remote areas, or when local coverage must be deployed quickly at a remote construction site.

In the commercial sector, as the capacity of mobile computing increases, the need for networking is also expected to rise. Ad hoc networks could serve as wireless public access in urban areas, with fast deployment and extended coverage. In office Local Area Networks (LAN), different office equipments (intelligent devices like PCs, notebooks, mobile phones, PDAs etc.) that want to communicate with each other can form a temporary network without cabling. When laptop users go outside their office environment, the need for collaborative computing is very important. With the presence of ad hoc structure, one can collaborate and share information via a network that updates instantly to meet the requirements of business organization. The Bluetooth system is the most promising technology in the context of personal area networks. The Bluetooth short-range radio device is expected to cost less than $5 within three years and to be incorporated into millions of wireless communications devices. Therefore, wireless data communications devices will connect many of intelligent machines when some technological problems are solved.

2.4 An Example Military Application: Field Artillery Battery Fire Direction System (FABFDS)

Wireless networking technology will play a key role in future battlefield communications. Like many armies, Turkish Armed Forces have a great effort to introduce a new war fighting capability. The key to this capability is communications technology that requires a minimal amount of fixed infrastructure; delivers secure voice, video and data in real time at broadband data rates; is small and highly portable and is inexpensive enough to be standard issue for every soldier. Future mobile military networks as shown in Figure 2.10 cannot be based on fixed infrastructures. Fixed nodes are more vulnerable to enemy attacks. Highly mobile military forces require networks that are equally mobile. And military communication must continue in operation even when some nodes are destroyed or some links are jammed.

Many network companies and its strategic partners in the defense market are working towards enabling all the communication devices on the battlefield into a wireless mesh that will instantly form, heal, and update the network as users come and go. That is, they will associate in an ad hoc manner. Moreover, the devices will continuously and automatically optimize the connections between everyone in the network. This means that users can join and leave the network at will, while the network maintains its overall integrity. Unlike cell-based solutions, ad hoc network solution is portable, requiring no infrastructure and it scales as the number of devices increases, network coverage and service levels improve when user density increases.

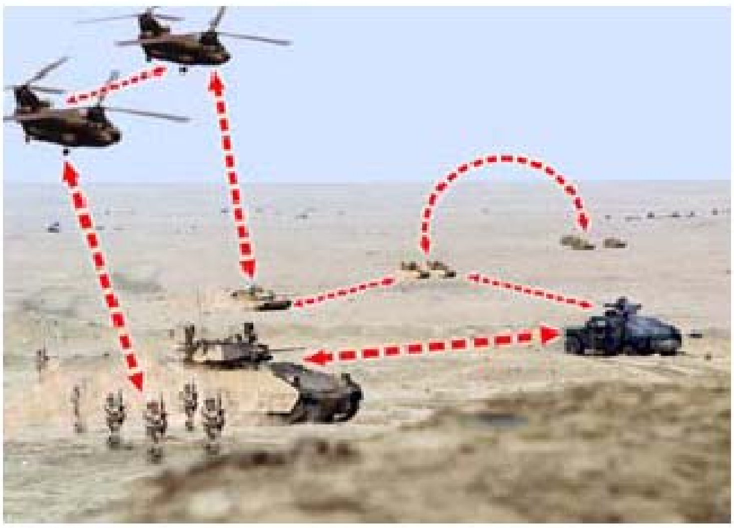


Figure 2.10: A picture of modern battlefield communication.

Field artillery, coastal artillery and mortar units support ground force combat with heavy indirect fire. In modern warfare this means that fire must be directed quickly at targets already located. Traditional registration fire would reveal our intentions to the enemy and hence give time to take cover. The Field Artillery Battery Fire Direction System is designed to provide the functions of: fast and accurate ballistic computations for a wide range of artillery weapons, fire support coordination, message transfer in digital format and ammunition accounting at the battery level. Description of this system is presented by ASELSAN (Turkish Telecommunication Company) as BAİKS 2000 for Turkish army. In this system one hop communication is used. Units in the system can reach each other in one hop. This communication requires devices, which use high power. The communication in high power brings high power consumption and security problems. This also causes high interference and more collision.

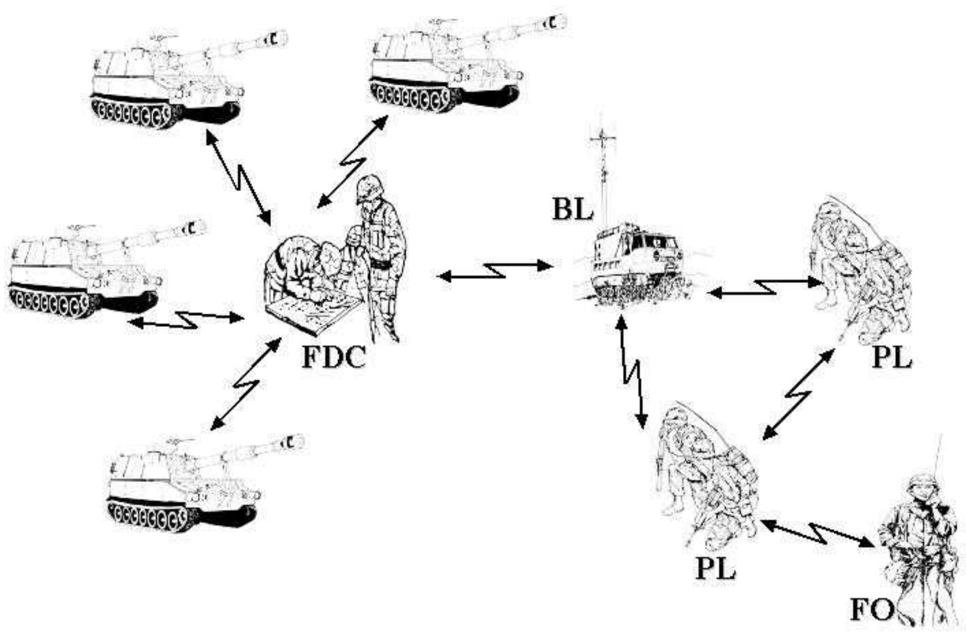


Figure 2.11: Field artillery battery fire direction system.

Instead, a system based on ad hoc communication can be built. The system consists of a battery fire control computer, a communications control unit, forward observer’s target acquisition device and fire support officer's digital message device and gun display units. The system units are linked by digital communications using tactical radios with ad hoc operation capability as shown in Figure 2.11. The system can also be linked to a tactical fire control system. Digital message encryption as well as automatic acknowledgement, error detection and correction capabilities provide safe and reliable communications in battlefield environment.

In recent years, the methods used by forward observers to determine even distant targets have improved considerably. The coordinates of the observation post and the direction of the target can be determined much more accurately. When laser technology is used, the distance to targets can be determined to the accuracy of a few meters. Target acquisition devices represent the latest development, having observation optics, a program to determine your own location, direction and distance measurement and the calculation of target coordinates all in the same device. This device also includes ad hoc capable radio and externally display unit for keeping digital map data and forming needed messages. Forward observer equipped with this target acquisition, after finding self-location, points his location in digital map on the display unit and send this data to platoon leader and fire direction center. This data is to be sent by above network units in ad hoc manner. Using the same procedure other messages e.g. fire mission message, can be sent to related units.

The battery fire control computer receives target information and calls for fire in digital format either from the forward observers or from the battalion computer. The battery computer computes the firing data for each gun (up to 8 guns) and transfers the firing commands to the gun display units. The battery fire control computer and the communication control unit can be mounted in a vehicle or dismounted in a stationary command post.

Company Fire Support Officer's Computer (FSOC) provides the Company Fire Support Team Headquarters with the capabilities for fire support planning, coordination and execution in a digitally automated environment, as well as data communications with the other fire support elements.

Gun Commander's Digital Message Unit (GCDMU) enables gun commander to digitally communicate with the platoon leader and the battery/platoon Fire Direction Center. It receives and displays firing data and sends firing data (azimuth, elevation and fuze setting) digitally to automatic gun laying, automatic loader and automatic fuze setting systems. It also receives gun position and pointing data directly from on-board navigation/positioning systems and sends it to the fire direction center.

The digital message devices and the gun display units are easy-to-use lightweight handheld units. These devices differ only in their custom keyboards and software thus leading to savings in logistics and maintenance. The handheld message units are powered by internal rechargeable batteries.

In ad hoc structured system, transmit power can be reduced significantly. Instead of establishing longer communication links, by using power control we can build short links to communicate. For example in Figure 2.11, Forward Observer sends a fire mission message to Fire Direction Center. This message is sent to the destination by assisting platoon and battalion leader instead direct link between Forward Observer and Fire Direction Center. While this communication is occurring, Fire Direction Center can also receive gun location information from any of gun commander. All messages can be exchanged at low power levels by routing via intermediate nodes. This results in many advantages. With low power devices, we extend our network life, which is very important in battlefield. Transmission at low power levels increases spectrum reuse possibility. Low power level also results in security. Chance of detection of signals by the enemy can be significantly reduced. Because of multihop packet routing communication beyond line of sight (LOS) is possible at high frequencies. The units, which are not within LOS of each other, can easily exchange messages in ad hoc networks. Moreover, efficient routing algorithms provide us reusing the frequency and more bandwidth to communicate.

So far, ad hoc networks are discussed with characteristics and challenges. In the next chapter, topology design issue will be discussed. Power control and routing schemes need to be considered carefully in order to achieve an optimal topology. Combined Medium Access Control (MAC) scheme and routing algorithm will be described for obtaining the desired topology.

Chapter 3

STDMA-based Topology Design by Using Power Control

In this chapter, we discuss the topology design in wireless ad hoc networks. The topology of an ad hoc network has a significant impact on its performance. There are two approaches to topology management in ad hoc networks: topology control using power control and hierarchical topology organization. We use both of them in order to have better performance. Power control impacts and influences many aspects of the network. We discuss types of power control algorithms in this chapter. In ad hoc networks, the communication channel is shared among independent stations. MAC mechanisms regulate the access to the shared channel for maximum channel utilization. We also discuss MAC protocols in the literature. Especially we focus on Spatial Reuse TDMA (STDMA) which is an extension of TDMA where the capacity is increased by letting several radio terminals share the same time slot without any collision. At the end of this chapter, we give model definitions, assumptions and performance measures. Scheduling and routing based on STDMA is also presented in this chapter.

3.1 Topology Design with Power Control

The topology of a multihop wireless network is the set of communication links between node pairs used explicitly or implicitly by a routing mechanism [13]. Unlike wireline networks, ad hoc wireless network topology can be controlled. It is a challenging problem and popular research area of ad hoc networks. Topology information needs to be considered by network manager. It helps the manager to monitor topology control decisions within the network such as connectivity, transmission power and channel bandwidth. Network topology describes the connectivity and reachability map of the network. In this study, we are mainly concerned with the task of obtaining a connected topology for communication. We use delay, network connectivity, load balancing, and power consumption and frequency reuse as performance metrics in order to evaluate wireless network topology. Desired topology must ensure good performance over these metrics. Undesired topology shown in Figure 3.1 which is too dense results in less network life and less throughput by wasting the resources unwisely. On the other hand, a very sparsely connected topology causes the problem of network connectivity and large delays. There are two approaches to topology management in ad hoc networks: topology design with using power control and hierarchical topology organization.

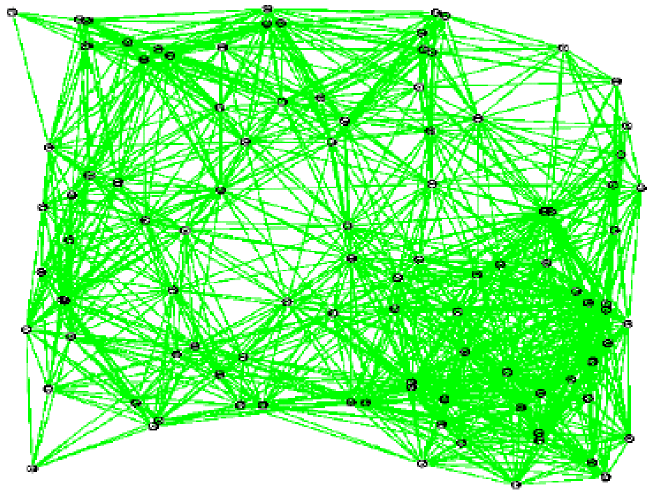


Figure 3.1: Undesired topology picture.

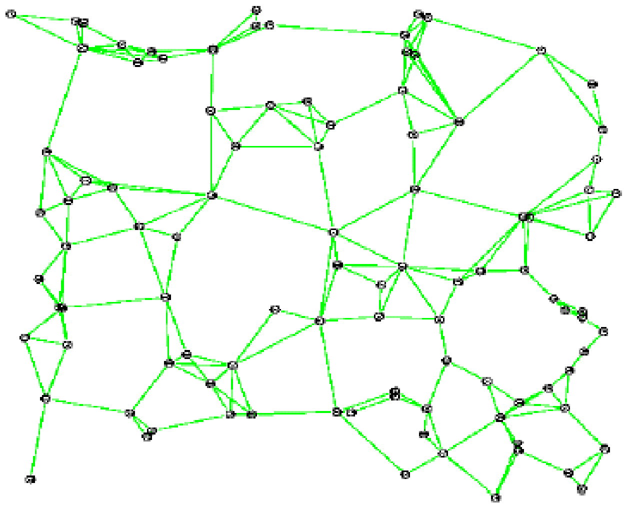


Figure 3.2: Desired topology picture.

Since routing and transmission power is the controllable parameters of the wireless network, we can exactly use power control algorithms in order to design a more balanced topology as shown in Figure 3.2. Power control shows available links. As seen in the previous chapter, ad hoc networks have the advantage of saving energy. Throughput and interference are highly related in wireless networks. By power control we can obtain more spatial reuse and higher capacity of the network that are the goals of network designer. Without power control, simultaneous transmission links can not be established due to interferences.

Work on power control can be classified into three classes. In the first class of algorithms, power control is exercised such that some connectivity features are satisfied. In common power (COMPOW) [14] protocol, transmit power used by all nodes would converge to a common power level. This level is the minimum power level so that the network connectivity is ensured. In Figure 3.3, each node of the network uses the same transmit power level P that is the lowest power level for constructing connected topology. In this thesis, we use COMPOW scheme in concerning network connectivity.

In [13], the authors propose that each node adjusts its transmit power to meet a global topological property. The number of one-hop neighbors is bounded in order to determine transmit power level. As seen in Figure 3.4, each node selects different power levels to maintain a connected topology. Nodes can adjust their transmit power levels in response to topological changes.

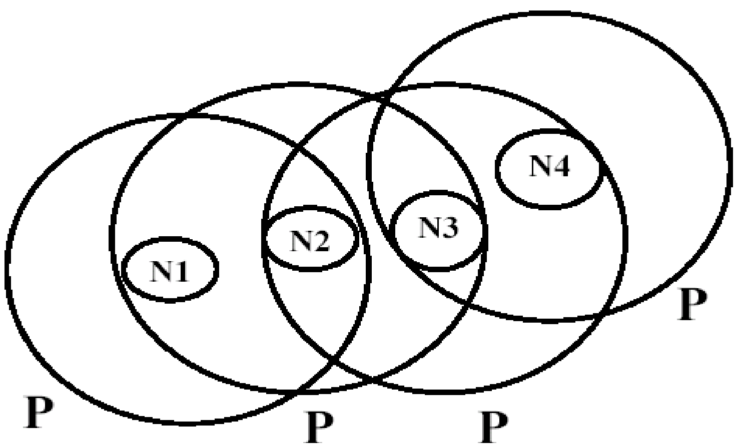


Figure 3.3: Common power algorithm (COMPOW) scheme.

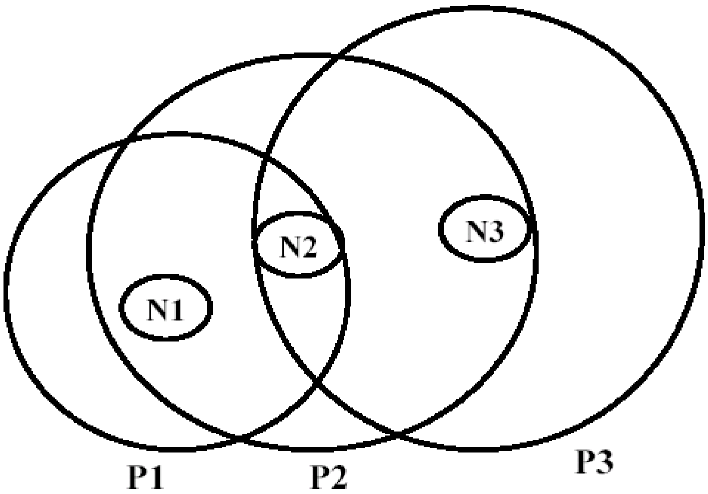


Figure 3.4: Adaptive power per node scheme.

The objective of [15] is to find the impact of using different transmit powers on the average power consumption, and the percentage of packets successfully reaching their destinations. In [16], a simple distributed algorithm is introduced where each node makes local decisions about its transmission power and these local decisions collectively guarantee global connectivity. Adaptive power per link approach is presented in [17]. Instead of every node using same transmit power, a node uses only the power level that is required to communicate with a desired receiver. In Figure 3.5, Node-2 uses two different power levels. Lower power level is for closer receiver Node-1, and the higher power level is for Node-3 which is further. The goal here is to minimize the energy cost of communication between any given pair of neighboring nodes if such communication is possible.

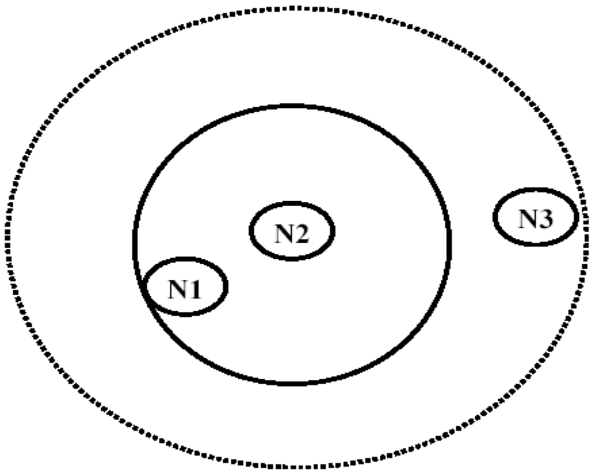


Figure 3.5: Adaptive power per link scheme.

To minimize power, long edges should be excluded and short ones should be included whenever possible, while optimizing the hop-diameter and maintaining network connectivity. This leads to approaches using the Voronio diagram and nearest neighbor graphs with directional information [18], [19]. Theoretical graph formulation is used in these approaches. Li et al. [20] proposed that network connectivity is minimally maintained as long as the decreased power level keeps at least one neighbor remaining connected at every 2Π/3 to 5Π/6 angular separation. In [21], it is shown that the relative neighborhood graph can be a good candidate for topology control due to its good graph properties in terms of throughput, interference, delay, power and connectivity.

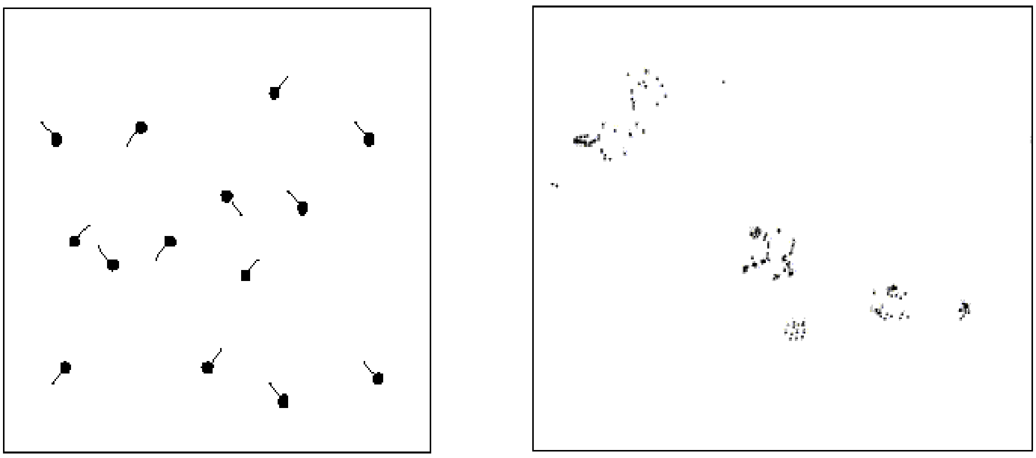
The next class of algorithms focuses on impact of power control over routing algorithms. Most schemes in this class are interested in power aware routing. With using power consumption metric instead of hop count, shortest path is calculated in [12]. In [22], two protocols, Geographic Adaptive Fidelity (GAF) and Cluster-based Energy Conservation (CEC) are proposed. GAF determines redundant nodes and controls node duty cycle to extend network operational lifetime while maintaining network connectivity, independent of the involvement of ad hoc routing protocols. GAF can substantially conserve energy (40% to 60% less energy than an unmodified ad hoc routing protocol), allowing network operational lifetime to increase in proportion to node density. CEC eliminates the dependency of GAF on global location information and its assumption about radio range. CEC measures local connectivity with low overhead and is thus able to dynamically adapt to a changing network. The other examples of this class are presented in [11], [23] and [24]. In this thesis, power aware routing is not considered.

The third class of algorithms points at modifying the MAC layer. In [25], the PCMA power controlled medium access protocol is introduced within the collision-avoidance multiple access frameworks. They have demonstrated that PCMA allows for a greater number of simultaneous senders than 802.11 by adapting the transmission ranges to be the minimum value required satisfying successful reception at the intended destination. In [26], a Power Control MAC protocol (PCM), which periodically increases the transmit power during data transmission is proposed. In [27], sensor-MAC (S-MAC), a new MAC protocol which reduces energy consumption is presented. S-MAC achieves good scalability and collision avoidance by utilizing a combined scheduling and contention scheme. The other class of MAC protocols is based on reservation and scheduling, for example TDMA-based protocol. In [28], they present a novel approach for an energy-aware management for sensor networks. A gateway node, which is a network manager, monitors latency throughout the cluster and energy usage at every sensor node. The gateway configures the topology to extend the network life. They also present new techniques for slot assignment. In this thesis, we work on Spatial TDMA (STDMA) which is an extension of TDMA (Time Division Multiple Access). We want to minimize end-to-end delay by scheduling established transmission links. As we schedule the links, we eliminate the possible collisions and reuse the frequency efficiently. The details of STDMA are presented in the next section.

So far, the relation between power control and topology management is discussed. When we focus on military applications, network topology also depends on different properties. Military forces tend to exhibit group of mobility as shown in Figure 3.6.

On the left, a typical ad hoc network where nodes are free to move without any limitation. On the right, a military ad hoc network where groups of nodes are clustered as they carry out a particular mission is depicted. Military forces have this behavior since:

- Military forces have well-defined chain of command. Although communications may not strictly follow that chain of command, a chain of command will always exist, and in general, the nodes are physically placed according to that model. This location impacts on ad hoc network topologies.



Pure MANET **vs** **Military MANET**

Figure 3.6: Examples of mobility models.

- Military deployments are mission based, so units are expected to cooperate with each other and operate within reasonable bounds of doctrine. This mission-based feature can also lead to a certain amount of predictability in a unit's movement and distance among the units.
- Military deployments are bounded in that they execute in a fixed area for a predetermined period of time. Node's movement is not random.

These points are important because they directly affect on forming topology. In this thesis, we consider these characteristics of military application for designing the desired topology. We focus on common power control (COMPOW) and hierarchical topology management. Hierarchical topology management entrusts a selected subset of the nodes in the network to impose a backbone topology and to carry out essential forwarding and control functionalities. It is required that the selected subset of nodes be minimum as well as connected. The hierarchical approach in communication networks is often referred to as clustering. In the clustering approach, a set of clusterheads is selected, and gateways are also chosen to connect clusterheads, so that the union of gateways and clusterheads forms the topology. In [29], the *Cluster-based Topology Control* (CLTC) framework is proposed for a hybrid approach to control topology using transmission power adjustment. They employ a clustering algorithm by minimizing the maximum power used by any node and minimizing the total power used by all of the nodes in the network. Our clustering algorithm is presented in Chapter 4.

In mobile ad hoc networks, the network topology changes frequently, and communications control protocols usually require large amount of topology information exchanges in order to maintain entity reachability and network connectivity. Topology information in order to provide the minimum and sufficient connectivity information is usually referred to as topology control or topology management. Topology control in ad hoc networks can improve the efficiency of the routing control protocols and provide useful information for efficient channel access. Many topology control algorithms based on power adjustment have been proposed, where topology control is defined as the problem of assigning transmission powers to the nodes so that the resulting topology satisfies certain connectivity properties and some function of the transmission powers is optimized.

3.2 Spatial Time Division Multiple Access (STDMA) for Multihop Networks

In ad hoc networks, mobile stations may contend simultaneously for medium access. Therefore, transmissions of packets from distinct mobile terminals are more prone to overlap, resulting in packet collisions and waste of energy. The coordination for accessing the shared channel is performed by channel access algorithms. The problem of medium access control becomes a challenging task for wireless ad hoc networks due to nonexistence of a centralized authority. The medium access regulation procedures have to be enforced in a distributed and collaborative manner by mobile stations in the ad hoc network. The MAC layer also has to provide efficient and fair access to the wireless medium for all devices and to ensure reliable data transmission. Current research in ad hoc networks has focused on two central themes: (i) routing protocols and (ii) efficient *Medium Access Control* (MAC) protocols to access the shared medium. Both are significant problems in ad hoc networks. In addition to making routing decisions, each node needs to determine the neighboring node selected by the routing protocol. This decision is governed by the MAC protocol. Routing and access procedures are strongly inter-related. Current MAC protocols for ad hoc networks could be classified in three groups, depending on their channel access policy: contention protocols, allocation protocols, and a combination of both the hybrid protocols.

Contention protocols use similar protocols like ALOHA or CSMA, with the exception of slotted ALOHA. The majority of contention protocols are based on asynchronous communication models. Collision avoidance is an important feature of these protocols. It has been shown that contention protocols are simple, but their performances tend to degrade as the traffic load increases where the number of collisions rises. In overload situations, a contention protocol can become unstable as the channel utilization drops. This can result in exponential increase of packet delay and the network service breakdown, since few, if any, packets can be successfully exchanged. Nowadays, the contention protocols are well known and used by the most projects investigating ad hoc routing issues.

Transmissions from different nodes are more prone to collide. Hence more coordination among the nodes are required. Allocation protocols employ a synchronous communication model and use a scheduling algorithm that generates an assignment of time slots to nodes. This assignment results in a transmission schedule that determines in which particular slots a node is allowed to use the channel. This effectively leads to a collision free transmission schedule. *Time Division Multiple Access* (TDMA) is an example of the allocation protocols based on reservation or scheduling. TDMA scheme has smaller delay and consumes much less power compared to the random access scheme. The savings in power are achieved by avoiding the overhearing effect through the elimination of the reception of all the packets inside the transmission range, by eliminating the re-transmissions with the direct scheduling of the nodes, and by putting the radio in sleep node when the node is not receiving or transmitting any packet instead of actively listening to the channel all the time.

In [30], a new single channel, time division multiple access (TDMA)-based broadcast scheduling protocol, termed the Five-Phase Reservation Protocol (FPRP), is presented for mobile ad hoc networks. The protocol jointly and simultaneously performs the tasks of channel access and node broadcast scheduling in distributed manner. The protocol allows nodes to make reservations within TDMA broadcast schedules.

In order to avoid collisions, deterministic transmission scheduling such as *Spatial TDMA* (STDMA) [3] has been proposed. In this scheme, transmission schedules are coordinated so that no conflicts occur. STDMA for multihop radio networks is generalization of TDMA for single-hop networks. STDMA defines a repeating transmission schedule, which is called a frame as shown in Figure 3.7. A frame includes a fixed number of slots, with each slot being assigned to a unique group of simultaneously transmitting links. Each frame contains at least one slot in which a node or a link can be successfully activated. The same transmission schedule is repeated in each frame.

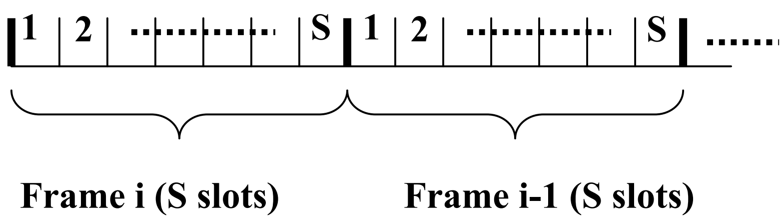


Figure 3.7: Frame (S length slot) used in STDMA.

The design of STDMA algorithms has received attention in the literature due its numerous benefits. In [31], Somarriba investigated the effect of power control algorithm for traffic controlled STDMA. With using power control, significant throughput improvement is achieved by utilizing interference in simulation results. In [32], two assignment methods are compared for STDMA. These two methods are: (i) Link assignment scheduling where transmitter and receiver node is determined in advance, (ii) Node assignment scheduling where a node can transmit to any of its neighbors. The preferable scheduling assignment algorithm can be determined with knowledge only of the connectivity of and input traffic to the network. For high traffic loads, link assignment scheduling is better than node assignment scheduling due to higher reuse efficiency [32].

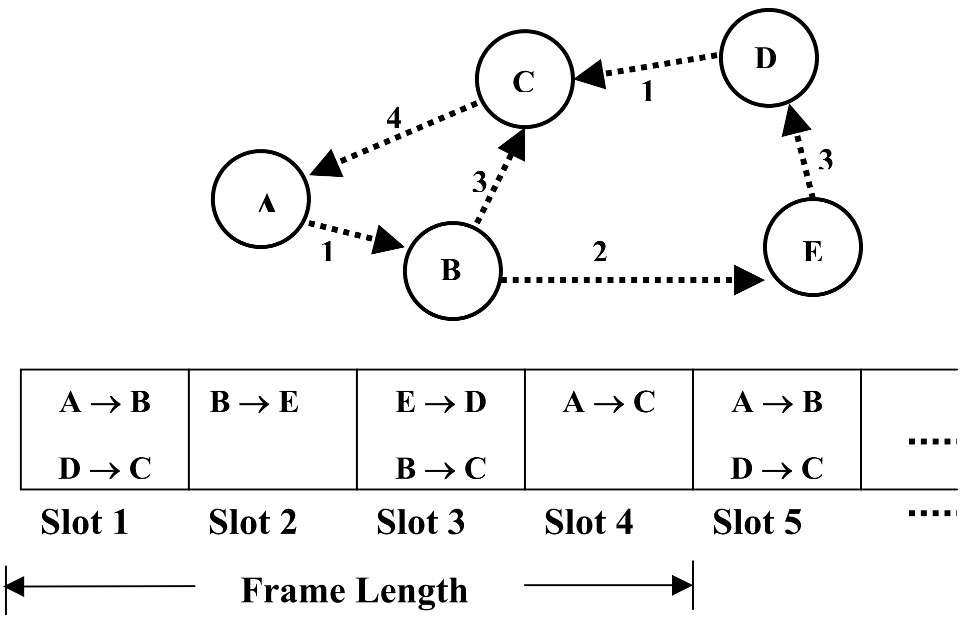


Figure 3.8: Link assignment scheduling scheme.

Figure 3.8 illustrates an example of link scheduling. Slots are assigned to unidirectional links in such a way that not conflicts occur. The frame duration, expressed in slots, is 4 slots. In [33], an integrated routing, link scheduling and power allocation policy is developed for a general multihop network that minimizes the total average power consumption in order to support minimum average rate requirements per link. Their policy can support higher throughputs than conventional approaches for radio resource allocation, at the expense of decreased energy efficiency. In [34], link scheduling assignment is studied. The topology control problem is formulated as a constrained optimization problem with objective that minimizes the traffic load of the most congested link in the network. In this paper, the solution takes too long time that cannot be tolerable for practical networks. So a faster solution is needed. In this thesis, a heuristic approach for this problem is studied.

Figure 3.9 is an example of node assignment scheduling. The minimum length schedule comprises of three slots with nodes A, C, F transmitting in slot-1, nodes B and E transmitting in slot-2 and node D transmitting in slot-3. Node assignment scheduling is also considered broadcast scheduling. In [35], an algorithm for broadcast scheduling in packet radio networks is presented. The goal of this approach is to maximize the network throughput. Throughput performance is not explored when connected topology is considered.

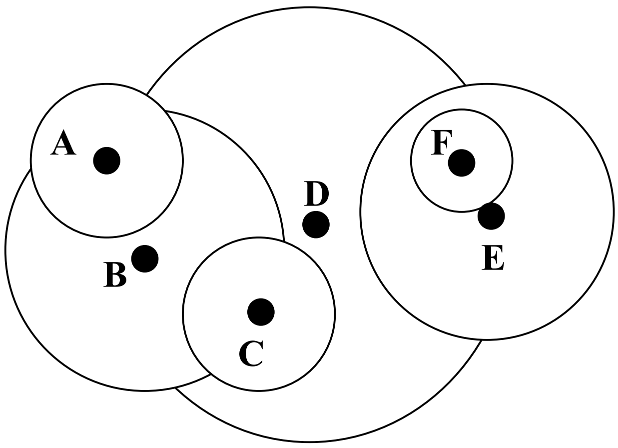


Figure 3.9: Node assignment scheduling scheme(Circles represent transmitting ranges of the nodes).

In this thesis, we work on combined scheduling and routing policy to create the minimum schedule length in STDMA based ad hoc networks. Our goal is to determine the shortest frame such that a higher throughput and lower packet delay are obtained. We use common power (COMPOW) algorithm for power control. Other power approaches are left as future studies. We use link scheduling assignment strategy. Description and details of scheduling of STDMA are given in the last section of this chapter.

3.3 Model Definitions and Assumptions

3.3.1 Network Model

We consider a network consisting of N nodes uniformly located over a given area. The network topology is modeled by a directed graph G = (V;E) where the elements of V represent the network nodes and E denotes a radio communication link between the nodes i and j. We assume that each node in the multihop packet radio network has a unique identifier, and it contains an omnidirectional radio transceiver. Due to particular characteristics of military networks as explained in the first section of this chapter, we consider an ad hoc network where nodes are organized into a number of non-overlapping clusters. In general, clustering provides a convenient framework for the operation of an efficient access control and bandwidth allocation scheme since capacity allocations are localized. Moreover, clustering architecture reduces the transmission overhead for the update of routing after topological changes. In the literature, the problem of cluster formation and maintenance has been studied extensively, especially in the context of routing [36, 37, 38]. Algorithms for cluster formation and organization have been proposed which are capable of reacting to connectivity changes and re-organizing their clusters. In most of these schemes, however, it is assumed that all routing is performed through a local-coordinator node, called as "clusterhead".

Units in military applications are physically located according to the chain of command. They accomplish their mission by forming a group and the headquarters manages them. This hierarchical architecture leads us to clustering formation. Units in the same group can be put in one cluster. Group commanders can be selected as cluster-head nodes in the clustering formation. Headquarters or chief of groups can be a good candidate for selecting root nodes in our clustered-based network. Headquarters and group commanders can be equipped with communication devices, which have high bandwidth capability. Therefore, it is a reasonable way to assign a link between the headquarters and group commanders. In our network, nodes cannot be members of more than one cluster at the same time. Nodes that belong to the same cluster establish unidirectional links with each other. Clusterhead nodes have the responsibility of routing packets that are sent to nodes outside of the cluster. The communication among the clusters is managed by the "root" node. Figure 3.10 shows an example of our network topology. Details of our clustering algorithm are presented in Chapter 4.

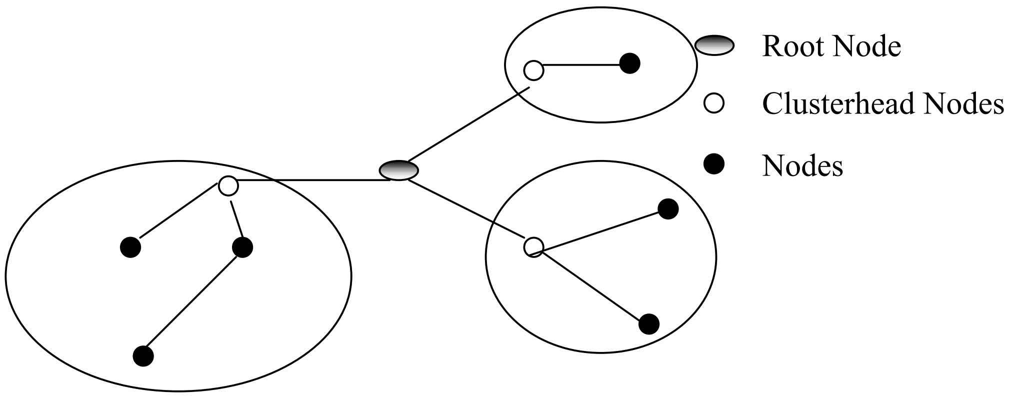


Figure 3.10: Sample network topology.

In this thesis, we have assumed fixed topologies only. Reaction to topological changes by re-clustering and adjusting the links are left for future studies.

3.3.2 Multiple Access Control (MAC) Model

Typically, ad hoc networks consist of a collection of nodes that try to communicate with each other over the same radio channel. One problem in this network is the formulation of Medium Access Control (MAC) protocol. In order to determine conflict-free channel assignments, we consider Spatial TDMA (STDMA) scheme due to advantages on power consumption and delay as explained in previous section. Time is slotted, and slots are grouped into fixed length frames, which is repeated. Slots are mapped to unidirectional links, which can occur at the same time. We consider only link scheduling since link scheduling is preferable due to higher reuse efficiency for high traffic loads. The entire network is synchronized on frame and slot basis. The slot synchronization mechanism is not described here, but can be implemented by using root node's clock. Topological changes are not considered in this thesis. We also assume that the following conflict-free communication property always holds:

- A node can either transmit or receive at any given time slot.
- A node can transmit to a single node at any given time slot.
- A node can receive data from only one node at any given time slot.

We use COMPOW as the power control algorithm, which implies that all nodes select the same transmit power level. In [39], it is shown that COMPOW can be more preferable than adaptive power scheme in concerning throughput, power consumption and complexity. Selecting of this power level is achieved by knowing the location of all the nodes. Common power level should be the minimum required power level which achieves the network connectivity. And this power level is fixed throughout the operation since topological changes are not considered.

3.3.3 Connectivity Model

We assume that each node in the network is assigned a unique identifier (ID). Although many studies on ad hoc networks have been proposed and implemented with bi-directional links, our work will be focused on unidirectional links. Unidirectional links can arise because of difference in wireless channel interference experienced by different nodes and difference in transmission power levels of different nodes [40]. A link (i; j) means that node j is within the radio transmission range of node i and that a possible data transmission exists from node i to node j. Link (i; j) does not necessarily imply that link (j; i) is also established.

Throughout the thesis, we assume that all nodes transmit at power level P which is the minimum in order to ensure network connectivity. We assume that all nodes within the communication range of the transmitting node can successfully receive the transmission. In this work, we make a decision of whether simultaneous transmission by different nodes are allowed by using the Signal to Interference Noise Ratio (SINR). In order to have a reliable link, a minimum SINR referred to, as SINR threshold β is used. If received signal power exceeds the sum of the power of the other ongoing transmission packets and the thermal noise by at least a factor of β, we assume that the transmission is successful between nodes i and j. Equation (3.1) illustrates the calculation of SINR for successful transmission.

$$\frac{P_{ij} * G_{ij}}{N_0 + \sum_{k \neq j} P_{kj} * G_{kj}} >= \beta \qquad (3.1)$$

$$\begin{aligned} &Where\ N_0 \quad is \quad thermal\ noise \\ &\qquad \beta \quad is \quad threshold \\ &\qquad P_{ij} \quad is \quad transmit \quad power \quad from \quad i\ to\ j \end{aligned}$$

The propagation effect is modeled by link gains where G_{ij} denotes the path loss on the link between nodes i and j and is calculated in (3.2). In order to determine the set of simultaneous transmission links, we use free space propagation model. Received signal power varies as d_{ij} Euclidean distance between transmitting and receiving node and α the path-loss exponent.

$$G_{ij} = \frac{1}{d_{ij}^{\alpha}} \qquad (3.2)$$

Given the value of transmission power level, the distances between nodes and the minimum required received power for error-free communication, we can determine the communication range of all nodes and the connectivity of the network. Unlike the simplified interference model, a more accurate interference model is used in this thesis where a receiver is not assumed to ignore interference from simultaneous neighboring transmissions. Especially when we consider transmission over the links of sensor networks, with many nodes, severe interference may occur at the other nodes. In Chapter 4, a hypergraph model for characterizing interference in the network is presented.

3.3.4 Traffic and Routing Model

All nodes have data to be sent to each other node in each frame. Packet lengths are fixed and equal to one slot duration. We consider connected networks. We say that a network is connected if there is a path between every node pair. It should be noted here that slot assignment algorithm provides contiguous slot numbers for each link. Slot assignment in Figure 3.11 shows a connected topology, which contains at least one feasible path from each node to all other nodes.

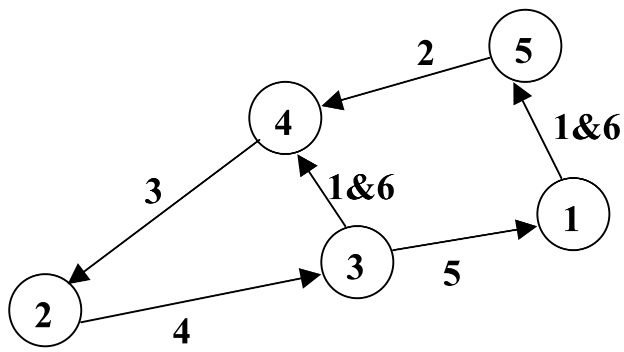


Figure 3.11: Connected network topology.

For example Node-1 has data to be sent to Node-2. First Node-1 sends it to Node-5 in slot-1. Later, Node-5 sends this data to Node-4 in slot number 2. Finally Node-4 transmits to Node-2 in slot-3 in order to achieve communication between nodes 1 and 2. Figure 3.12 shows another example of slot assignment where connectivity is not satisfied. Unlike a connected topology, there is no feasible path between every node pair. It causes increasing end-to-end delay. Because all data cannot be received by destined node within a single frame. As seen in example of Figure 3.11, Node-5 needs to wait for two frames before data destined for Node-2 is delivered. Node-4 can forward data in slot-3 of the second frame after receiving from Node-5 in slot-5 of the first frame.

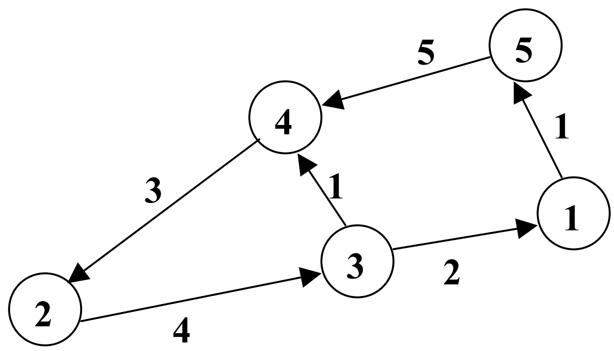


Figure 3.12: Slot assignment where connected topology is not satisfied.

Generally in ad hoc networks, every node cannot reach every other node in one hop. So we need a routing algorithm. In this work, routing algorithm is implicit. The goal of our MAC scheduling is to satisfy the network connectivity as well as creating as many simultaneous transmissions as possible. It means our algorithm determines the link scheduling in order to ensure that there is at least one path between each source-destination node pairs. Thus, routing is simply given when slot assignments are generated. In our clustered architecture, nodes that belong to the same cluster establish unidirectional links with each other. Clusterhead nodes have the responsibility of routing packets that are sent to nodes outside of the cluster. The communication among the clusters is managed by the "root" node. Our scheduling algorithm has a restriction on establishing the number of available links. For example, the root node can transmit to only clusterhead nodes. Therefore, this limitation creates bottlenecks over the links between root node and cluster-head nodes. This degrades routing performance.

3.3.5 Performance Measures

Like many resource management algorithms, we focus on performing both fairness and maximization of channel utilization. However, the main performance measure of our interest is the frame length. The frame length can be considered as the maximum end-to-end delay in connected topologies. In particular, the problem of finding an optimal schedule, which is a minimum-length schedule, is NP-complete [41]. STDMA scheduling eliminates collisions and removes the need for retransmissions. And spatial reuse of the channel results in simultaneous link transmissions. Both of them can be translated to a lower end-to-end delay. The goal of this work is to develop a heuristic algorithm for topology management based on clustering technique with the goal of minimizing the frame length. Limitation over some available paths creates bottleneck links which are not desired. Such bottlenecks may cause network partitioning due to more power consumption. Fairness is also considered during our scheduling algorithm.

In the next chapter, we discuss the topology design and scheduling problems in ad hoc networks.

Chapter 4

Greedy Heuristic Algorithm for Generating the Desired Topology

In wireless ad hoc networks, topology management has a significant importance due to its effect on network performance. Efficient link scheduling and routing algorithms are desired goals of achieving an optimal topology. Minimizing frame length in STDMA-based MAC algorithm results in lower end-to-end delay, which means maximum channel utilization. Meanwhile, methods of scheduling need to be based on the traffic requirements at each node as well as the quality of the links. Therefore, both scheduling and routing could be considered together. The problem of determining an optimal topology for ad hoc networks is addressed in [34] by providing an Integer Linear Programming (ILP) formulation and an example solution in CPLEX. Throughput is maximized in that paper for a given frame length instead of minimizing the frame length. The ILP approach is not practical due to long solution times. In this thesis, we focus on minimizing the STDMA frame length. But the minimum-length-scheduling problem is NP complete [2]. Therefore, we develop a heuristic solution.

This chapter introduces a new greedy heuristic algorithm for designing a connected hierarchical topology for ad hoc networks. We then introduce a scheduling algorithm for minimum frame length in STDMA-based link scheduling. The rest of the chapter is organized as follows. Section 4.1 describes interference model using hypergraphs. All maximal independent sets of the interference hypergraph are generated in Section 4.2. We continue with forming hierarchical clustered network structure and then with a detailed description of our STDMA scheduling algorithm. Finally, we present the distributed heuristic algorithm and discuss numerical results.

4.1 Interference Hypergraph Model for Ad Hoc Networks

The interference model widely used in the literature is binary, i.e., constraints always concern couples of transmitters. However, real-world interference is additive, i.e., the number of interfering stations should be taken into account for conflict-free communication. Consider the situation illustrated in Figure 4.1, where Node-1 is far enough from nodes 2, 4 and 5 to be allowed to use the same channels. What happens if links A, B, C and D all are attempted to establish simultaneously? Even though every single node may not be able to generate a signal strong enough to interfere with Node-1, the combined interference of the four links would sum up and cause a significant decrease of the signal to noise ratio for Node-1.

Therefore, binary constraints are not capable for describing many real world phenomena, and other structures should be employed. For example, an interference graph could be validly replaced by a hypergraph. In the literature [41], improved channel assignment algorithms for cellular networks were designed by modeling the interference constraints in terms of a hypergraph. They show the superiority of hypergraph modeling.

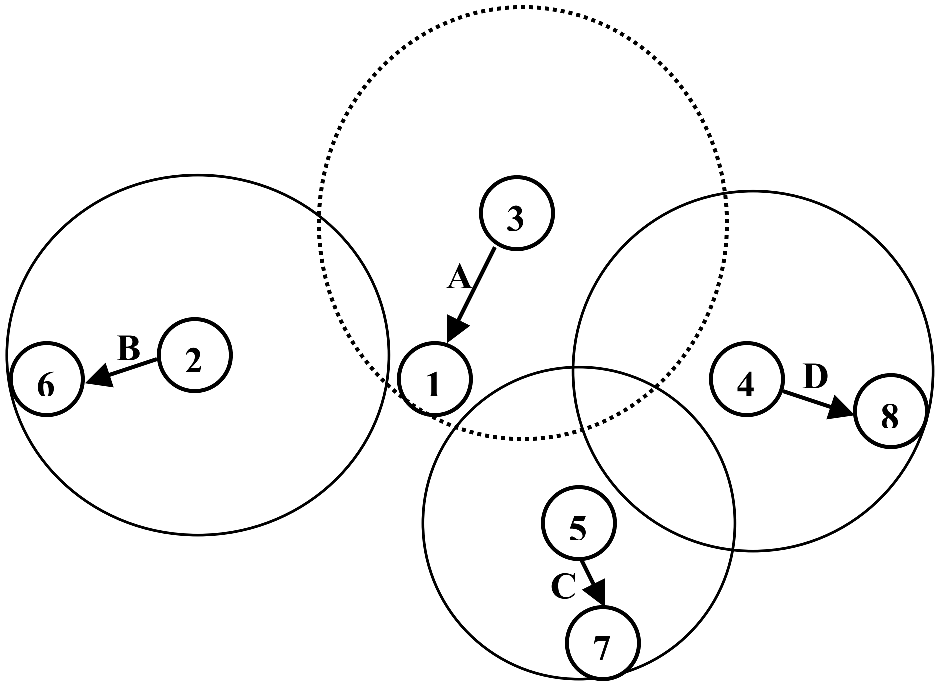


Figure 4.1: Additive interference of links B, C and D on Node-1.

In this thesis, we focus on hypergraph modeling of ad hoc networks. Especially in sensor networks that contain hundreds of sensor nodes, many transmission links may occur simultaneously. The effect of combined interference is very important when achieving efficient channel utilization.

A hypergraph *(H)* consists of a set of nodes (*V*) and a set of hyperedges (*E*). A hypergraph is an extension of a graph in the sense that each hyperedge can connect more than two vertices. The main distinction between a graph and hypergraph is that in a graph an edge can have no more than two vertices, but this restriction does not hold for a hypergraph. In our model, the set of vertices *V* corresponds to possible transmission links. The existence of a link (i; j) means nodes i and j are within the transmission range of each other, so that they can exchange packets via the common channel, in which case nodes i and j are called one-hop neighbors of each other.

Each hyperedge *E* is a group of links, all of which cannot be established simultaneously. Each transmission link is strictly considered as unidirectional. Therefore it is not implied that link (i, j) must be a vertex of any hyperedge which contains link (j, i). Our hypergraph representation is shown in Figure 4.2. In this graph, V={(1→5), (7→1), (10→3), (8→11), (4→9), (2→12), (6→2)} and E={(1→5,7→1),(7→1,10→3,8→11),(8→11,4→9,2→12),(2→12,6→2)}. From this graph it can be concluded that links 7→1, 10→3 and 8→11 cannot be established at the same time slot due to high interference. The links (7→1, 10→3), (7→1, 8→11) and (8→11, 10→3) can be established simultaneously since they do not form hyperedges.

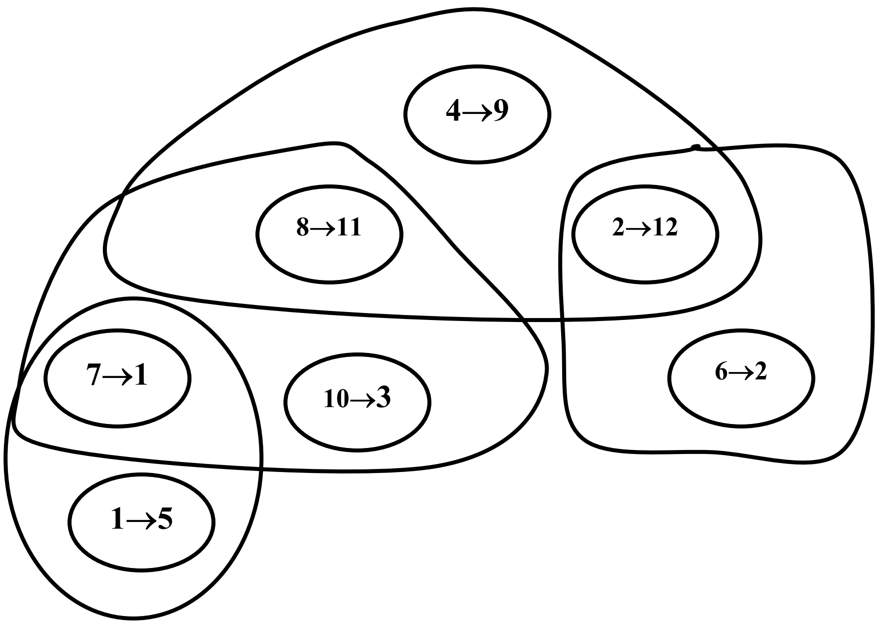


Figure 4.2: Our hypergraph model example.

4.2 Generating All Maximal Independent Set of Hypergraph

In wireless ad hoc networks, spatial reuse of the channel is highly possible. Efficient channel utilization is a very important performance measure for multihop wireless networks. In this thesis, we address the problem of minimizing the frame length for STDMA-based MAC protocols. This objective is achieved by the maximization of the channel reuse. It also means that more links can be established in the same time slot. In order to discover simultaneous transmission links, we take advantage of the property of the maximal independent set.

We call a subset of the vertex set $I \subseteq V$ *independent*, if it contains no hyperedges. An independent set $I \subseteq V$ is *maximal* if any enlargement of the set makes it dependent. We cannot add any vertex to a *Maximal Independent Set* (MIS) without breaking dependency. Therefore, within each of its supersets an edge can be found. We refer to the problem of finding such a set in a given hypergraph as the MIS problem. In our algorithm, any group of links that can be established at the same time slot form an independent set. If adding a new transmission link into an independent set causes collision, this independent set is called maximal independent set. In order to maximize of channel reuse, we need to explore MIS of hypergraph. Assigning these maximal independent sets to time slots minimize the frame length.

In Figure 4.2, links (1→5) and (10→3) can form an independent set since they do not contain any hyperedges. And the use of the same time slot for these two transmissions does not violate the interference constraint. But independent set which contains links (1→5) and (10→3) is not maximal since we can add a new transmission link, e.g., (8→11), to this independent set without breaking the interference constraint. New independent set {(1→5), (10→3) and (8→11)} cannot form maximal independent set since enlargement of this set is still possible. Adding link (2→12) makes the set {(1→5), (10→3) and (8→11)} maximal independent set. All maximal independent set of given hypergraph in Figure 4.2 are the follows:

MIS-1: (1→5), (10→3), (8→11), (4→9) and (6→2)

MIS-2: (1→5), (10→3), (8→11) and (2→12)

MIS-3: (7→1), (4→9), (8→11) and (6→2)

MIS-4: (7→1), (10→3), (4→9) and (6→2)

MIS-5: (7→1), (10→3), (4→9) and (2→12)

MIS-6: (1→5), (10→3), (4→9) and (2→12)

Transmission links in the same MIS can be established at the same time slot without any collision.

An algorithm for determining all maximal independent sets of a hypergraph is described [41]. We use the same algorithm in order to list all maximal independent sets of the interference hypergraph. This algorithm uses three sets:

1) *compsub*;

2) *candidates*;

3) *not*.

The set *compsub* is a set of vertices all of which form an independent set. The set candidates is the set of all vertices that are eligible to extend *compsub*, i.e., each of which forms an independent set with *compsub*. The set not is the set of all vertices which at an earlier stage already served as an extension of the present configuration of *compsub* and are now explicitly excluded. A recursively defined **extension** operator generates all extensions of the given configuration of *compsub* that it can make with the given set of *candidates* and that do not contain any vertex in *not*. All extensions of *compsub* containing any vertex in *not* have already been generated. The basic mechanism now consists of the following five steps.

1) Selection of the first vertex in *candidates*.

2) Adding the selected candidate to *compsub*.

3) Creating a new set *candidates* from the old set by removing each vertex which does not form an independent set with the selected candidate and *compsub* and forming a new set *not* in a similar manner from the old set not.

4) If both *not* and *candidates* sets are empty, no further extension of the present configuration of *compsub* is possible, nor is there a larger independent set including the present configuration of *compsub* in the hypergraph since *not* is empty. Hence, *compsub* contains a maximal independent set, which is generated. If only *candidates* is empty, no further extension of the present configuration of *compsub* is possible and there exists a larger independent set including the present configuration of *compsub*. This independent set has been generated before. Thus, the algorithm backtracks. If *candidates* is nonempty (irrespective of whether *not* is nonempty), the **extension** operator is called to operate on the sets just formed.

5) Upon return, removal of the selected candidate from *compsub* and its addition to the old set *not*.

The worst case time complexity of this algorithm is exponential in the number of vertices since the number of maximal independent sets grows exponentially with the number of vertices. But the maximum memory requirement is P+NP, where P is the maximum size of a maximal independent set and N is the number of nodes (P≤N). The memory requirement increases polynomially with the number of vertices.

4.3 Forming Hierarchical Clustered Structure

Obtaining a hierarchical organization of a network is a well-known and studied problem for wireless ad hoc networks. The task of discovering and updating routes in ad hoc networks is very critical. Flooding scheme is not preferred since wireless channel and battery power resources are very limited. The savings in communication bandwidth and energy consumption are desired by network operators. Partitioning the nodes into groups, called as clustering, provides the spatial reuse of the shared channel. In this thesis, we focus on clustering and hierarchical routing that are suitable for military networks. Our target application of the clustering scheme is providing a minimum STDMA frame-length as well as achieving a connected topology. We only consider the case when all nodes in the network have the same transmission range since COMPOW is used as the power control algorithm.

Such a partitioning of the links can be achieved by using proximity-based clustering algorithm. If the nodes are separated enough from each other, they can make conflict-free communication at the same time slot. In the clustering algorithm, we try to collect closer nodes into the same cluster.

We first list all possible transmission links in the network. If node j is inside of node i's transmission range, it is concluded that link (i, j) is a possible transmission link. Each possible transmission link corresponds to a node in the interference hypergraph. We next describe ***car (v,x)***, $v \in V$, which indicates the cardinality of a node. It is the total number of nodes in MIS-x if node v is included in MIS-x, otherwise is zero. After calculating ***car (v,x)***, and we find the total number of cardinality of node v, ***tot_car (v)***, as illustrated in (4.1).

$$tot\_car(v) = \sum_{x} car(v,x) \quad v \in \mathrm{V} \tag{4.1}$$

An example of calculating maximum total cardinality of node $v = (4 \rightarrow 9)$ in Figure 4.2 is shown below.

MIS-1: $(1\rightarrow5)$, $(10\rightarrow3)$, $(8\rightarrow11)$, $(4\rightarrow9)$ and $(6\rightarrow2)$ ***car(v,1)*** = 5

MIS-2: $(1\rightarrow5)$, $(10\rightarrow3)$, $(8\rightarrow11)$ and $(2\rightarrow12)$ ***car(v,2)*** = 0

MIS-3: $(7\rightarrow1)$, $(4\rightarrow9)$, $(8\rightarrow11)$ and $(6\rightarrow2)$ ***car(v,3)*** = 4

MIS-4: $(7\rightarrow1)$, $(10\rightarrow3)$, $(4\rightarrow9)$ and $(6\rightarrow2)$ ***car(v,4)*** = 4

MIS-5: $(7\rightarrow1)$, $(10\rightarrow3)$, $(4\rightarrow9)$ and $(2\rightarrow12)$ ***car(v,5)*** = 4

MIS-6: $(1\rightarrow5)$, $(10\rightarrow3)$, $(4\rightarrow9)$ and $(2\rightarrow12)$ ***car(v,6)*** = 4

tot_car(v) = 5 + 4 + 4 + 4 +4 = 21

The total cardinality of a bi-directional link $(i\leftrightarrow j)$ is given by

$$tot\_car\ (i\leftrightarrow j) = tot\_car\ (i\rightarrow j) + tot\_car\ (j\rightarrow i). \tag{4.2}$$

We try to determine the node, which has the maximum ***tot_car (v)***. Maximum total cardinality means that this link can be established simultaneously with a larger number of other links. Propagation is based on free space propagation model. Signal strength decreases by the square of a given distance. Short links do not suffer from interference with adjacent links. Therefore, there is higher possibility for establishing simultaneous short links. In the previous section, it is explained that maximal independent set is the group of simultaneous transmission links. So a link with maximum ***tot_car (v)*** means that it is a member of many simultaneous transmission link groups. By increasing the number of simultaneously established links, a higher channel reuse is obtained.

After listing the links with ***tot_car(v)***, we generate clusters and locate the nodes into that clusters until all nodes are placed in a cluster. The algorithm proceeds as follows:

Clustering algorithm:

1. **List** all nodes of the interference hypergraph in decreasing order, starting with the one with maximum value of ***tot_car (.)***.

2. **Take** the highest order node whose source or destination is not marked.

3. *If* this link's source or destination is assigned to any cluster, **Put** this link into that cluster, and **Mark** source and destination of that link.

4. *Else* **Put** that link into a new cluster, and **Mark** source and destination of that link.

5. **End** *If* all nodes are marked, otherwise **Go To** Step 2.

Before selecting the root node and the clusterhead nodes, we describe some lower and upper size limitations over the cluster size and select the root candidate node. Each node in the networks is the root candidate node.

$\boldsymbol{l}$ = lower level of cluster size.

$\boldsymbol{u}$ = upper level of cluster size.

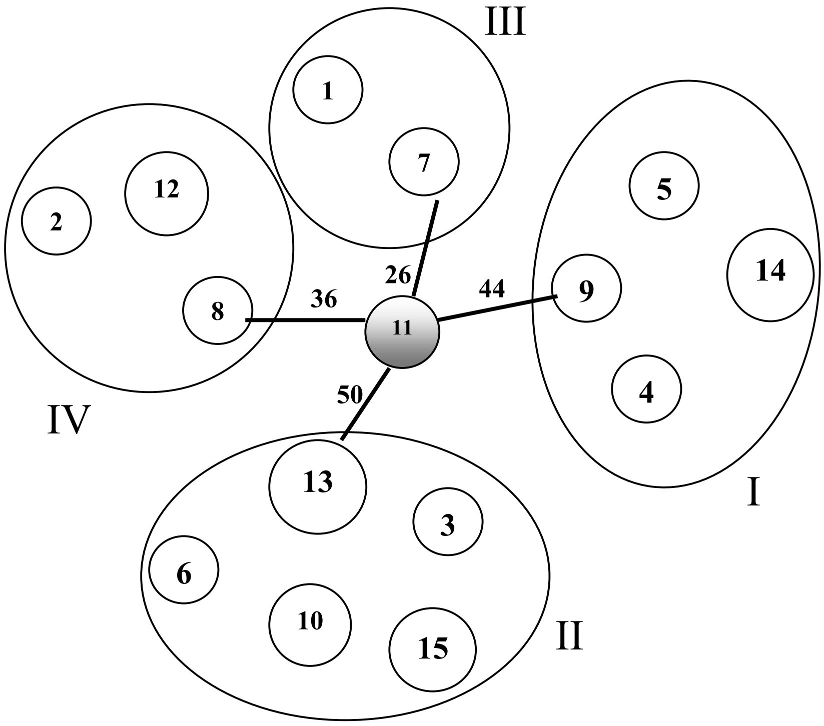


Figure 4.3: Un-balanced traffic load.

The limitations on cluster size provide load balancing. Ideally, it is preferable all clusters to be of the same size. Otherwise, different links would have different loads depending on the size of the cluster. For example in Figure 4.3, clusters have different sizes.

The link between clusterhead of Cluster-I and root is loaded with 26 s-d pairs where the link between clusterhead of Cluster-III and root with 50 s-d pairs. Network is partitioned sooner than expected since Cluster III has more nodes, and its clusterhead node needs to handle more traffic. In order to achieve load balancing, it is preferable all clusters to be of nearly the same size.

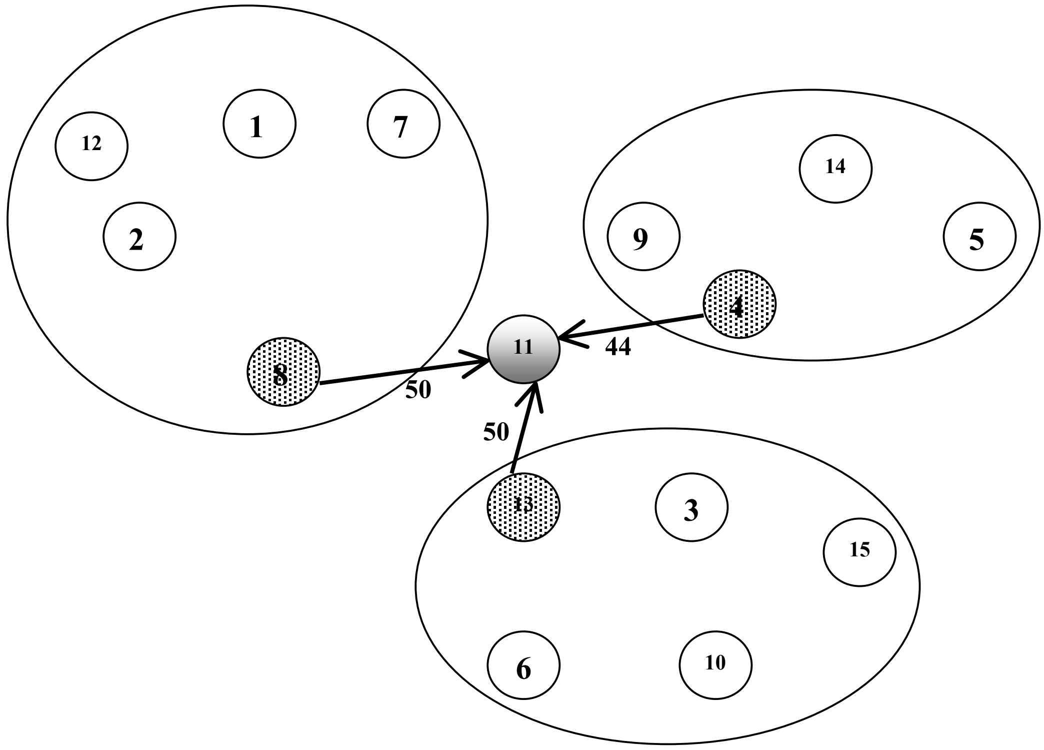


Figure 4.4: Load balancing over the congested links.

In Figure 4.4, a more balanced topology is shown. In that figure, clusters almost have the same size five. Traffic load over the bottleneck links is almost the same. Upper bound of cluster size also has effect on network partitioning. Higher upper bound causes sooner network partitioning. Consider the cluster which has ten members, is subject to rapid battery depleting since its clusterhead has heavy traffic load. Therefore, formation of clusters has to be managed wisely.

Reforming cluster algorithm is executed when current clustering formation violates the size limitations. Different clustering formation corresponds to different root candidate nodes. The output of the clustering algorithm is used as an input for reforming algorithm. Reforming cluster algorithm is given below.

<u>Reforming cluster algorithm:</u>

1. *For* i=1 to C where C is the number of clusters.

   If (Cluster_size(i) < ***l***)

   For j = 1 to Cluster_size(i)

   Find the link with the maximum cardinality whose source is the Node_j of i^{th} cluster and destination is the node of k^{th} cluster, where $i \neq k$ and k=1,..,C,

   Put Node_j into k^{th} cluster *iff* (Cluster_size(k) < ***u***), otherwise **Go To** Step 3.

2. *Else if* (Cluster_size(i) > ***u***)

   j = 1

   Find the link with the maximum cardinality whose source is the Node_j of i^{th} cluster and destination is the node of k^{th} cluster, where $i \neq k$ and k=1,..,C,

   Put Node_j into k^{th} cluster *iff* (Cluster_size(k) < ***u***), otherwise **Go To** Step 3.

3. **Terminate** the algorithm.

After reforming clusters, the next step is to select the root and clusterhead nodes. It is preferable that the root node stays relatively static and robust, and has a large power capability. In military networks, headquarters are good candidates for the root node. They are well protected against enemy attacks and equipped with devices that have high bandwidth and non-limited energy. Another important parameter for determining the root node is the ability of connection to each clusterhead. It is critical that the root node should be able to communicate with all clusters so that connectivity constraint is satisfied. Like the root node, clusterhead nodes can be selected by concerning in military chain of command architecture. In our algorithm, total cardinality of the link between the root candidate and the clusterhead candidates, defined by (4.2), is used. Root and clusterhead nodes selection algorithm is described below.

Root and clusterhead nodes selection algorithm:

1. *For* i =1 to N where N is the number of nodes in networks.

   For j =1 to C (i) where C (i) is the number of cluster, built for the root candidate node-i.

   Take each link whose source is the root candidate node-i and destination is the node of j^{th} cluster.

2. **Calculate** the total cardinality of that link.

3. **Find** the link with the maximum cardinality,

4. *If* the maximum cardinality is equal to zero, i++ and **Go To** Step 1.

5. *Else* **Choose** node-i as the "*root*" and the destination of that link as the "c*lusterhead*".

An example of the hierarchical topology is illustrated in Figure 4.5 where each node is included in one cluster, and each cluster has one clusterhead for communication with the root node. The architecture has only one root so as to manage the connection among clusters.

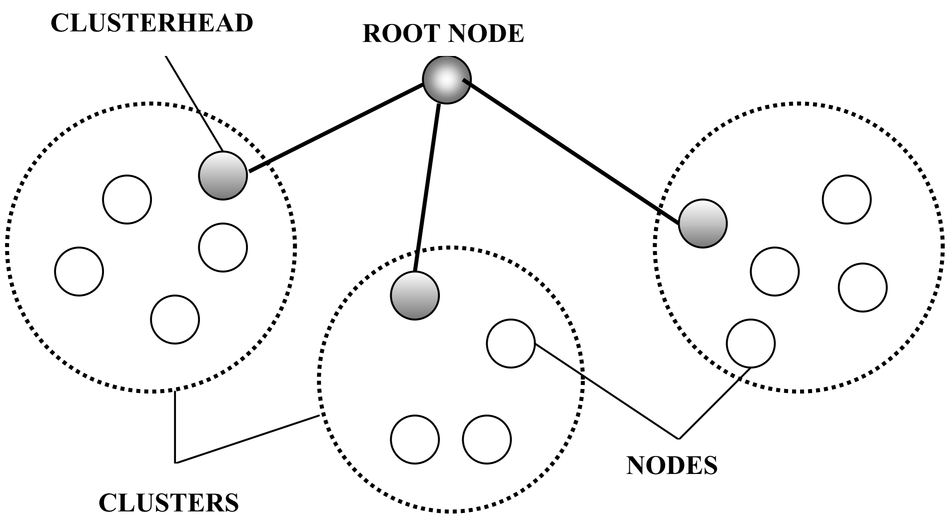


Figure 4.5: Clustering architecture.

4.4 Assigning Time Slots to Selected Links

We consider an ad hoc network where nodes are organized into a number of clusters. In general, clustering provides a good framework for an efficient medium access control and bandwidth allocation scheme since capacity allocation is localized. As explained in Chapter 3, methods of channel allocation and routing are strongly related. Routing algorithm is based on available transmission links. Link scheduling is performed by traffic requirements and routing information at each node. We focus on link scheduling in this section.

Each transmission that can occur simultaneously is assigned to the same time slot. It means that in each slot, multiple nodes can access the channel.

Nodes that belong to the same cluster are connected with each other via direct links or in multiple hops. The data destined to nodes that are outside of the cluster are routed through the clusterhead node. The root node manages the communication among the clusterhead nodes. Our link-scheduling algorithm is based on these rules. Data is first received by the clusterhead node, then it is sent to the root node and lastly it is transmitted to the clusterhead node in order to reach the destination. For achieving hierarchical routing, we need to perform link scheduling so as to design a connected topology. Connected topology implies that each node can reach to all other nodes within an STDMA frame. Our goal is to minimize the frame length as well as optimally assigning time slots to selected links without breaking routing rules. The minimum length scheduling is NP complete [41]. A greedy heuristic is proposed in this thesis.

Our goal is to route the data contained at each node to the root node and route the data at the root node to each node as soon as possible. We refer to this as the *data collection and distribution problem*. The construction of a scheduling is based on the symmetry of the operations of distribution and collection. We first collect the data to the root node and then distribute this to all other nodes as shown in Figure 4.6. Constructing these spanning trees should be efficient which implies that the connected topology should be formed with a minimum frame length. In order to minimize the frame length, more transmission links should be scheduled at the same time slot. Therefore, desired goal is to discover the simultaneous conflict-free transmission groups in the scheduling algorithm.

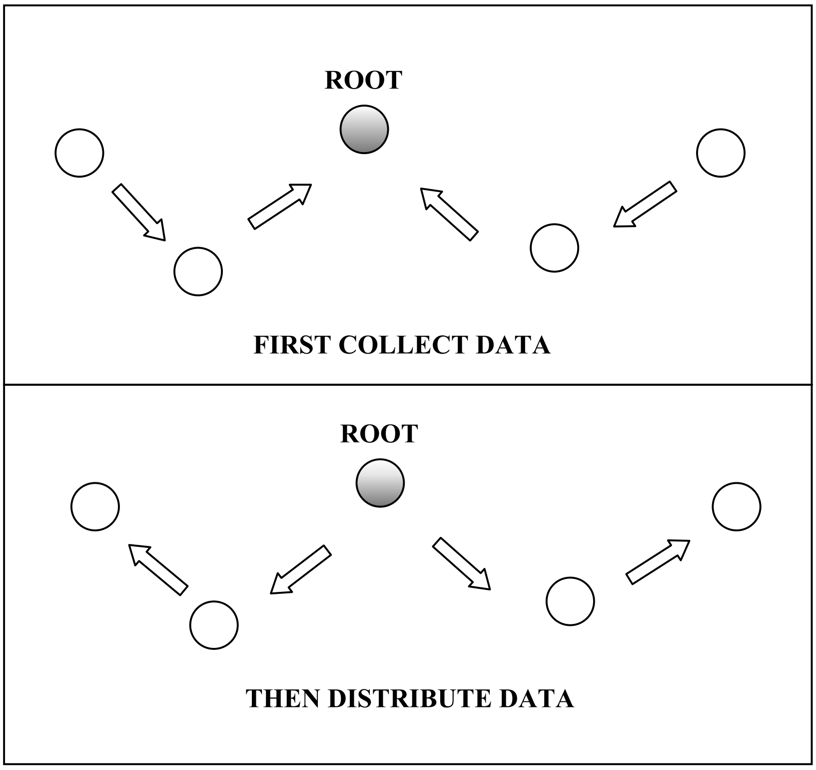


Figure 4.6: Collection and distribution spanning trees for connected topology.

In order to distribute the data first, the links between the root node and clusterhead nodes are assigned time slots. Slots equal to the number of clusters should be allocated for transmission between the root node and clusterhead nodes. Since it is proposed conflict-free property, which implies that a node can transmit to a single node at any given time slot. In Figure 4.7, we have three clusters and 15 nodes. Root node can transmit to only one clusterhead node. In this figure, the root node is Node-11, clusterhead nodes are Node-8, Node-13 and Node-9. Slot-1 is for link (11→8), slot-2 is for link (11→13) and slot-3 is assigned for link (11→9).

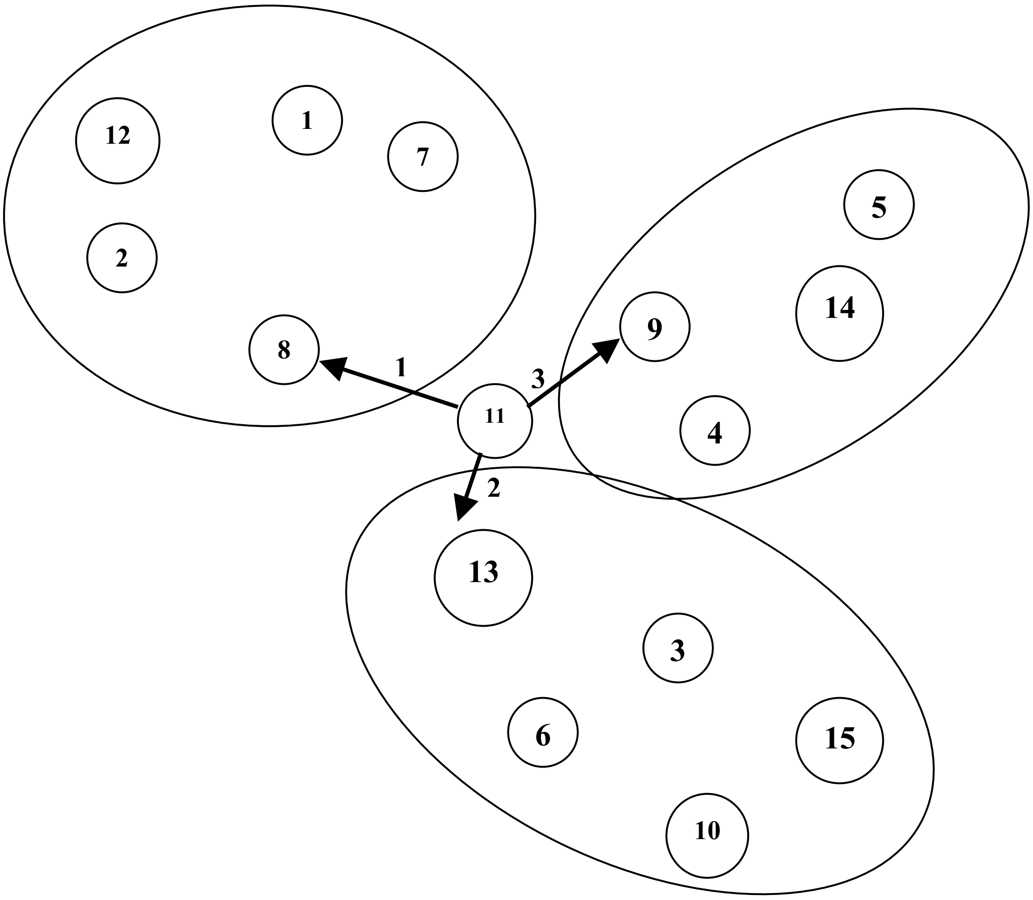


Figure 4.7: First slot assignments for connecting to clusters.

Then we define possible transmission links within each cluster so that packet will be routed from the clusterhead to all other nodes in the cluster. In order to minimize STDMA frame length, scheduling needs to assign larger number of simultaneous links to each slot. In the case of a tie, the set, which has less total cardinality, is selected for assignment. More cardinality means that there is higher possibility to establish these links. So unassigned link set can be easily selected in the next steps. The slot assignment algorithm is given below.

Slot assignment algorithm:

1. *For* i=1 to C where C is the number of clusters

   Assign slot-i to the link between the root node and the clusterhead node of the i^{th} cluster, and **Mark** clusterhead nodes as reached.

2. **List** all of possible links from the set of reached nodes to unreached cluster members.

3. **List** all simultaneous transmission links set.

4. **Select** the set with largest number of links or the set with less total cardinality in the case of a tie.

5. i++ and **Assign** slot-i to the selected set, and **Mark** the destinations of the set as reached.

6. *If* all nodes are reached **Finish**, *Else* **Go To** Step 2.

An example for the execution of the algorithm is illustrated in Figure 4.8 where possible transmission links are shown. Links from the clusterheads to unreached nodes are:

Link (8→12), Link (8→2), Link (8→1) and Link (8→7),

Link (9→4), Link (9→14) and Link (9→5),

Link (13→3), Link (13→6), Link (13→10) and Link (13→15).

Simultaneously transmission links sets in same example are:

Set-1 = (9-4) and (13-6) with *tot_car (set-1)*=256

Set-2 = (9-14) and (13-6) with *tot_car (set-1)*=195

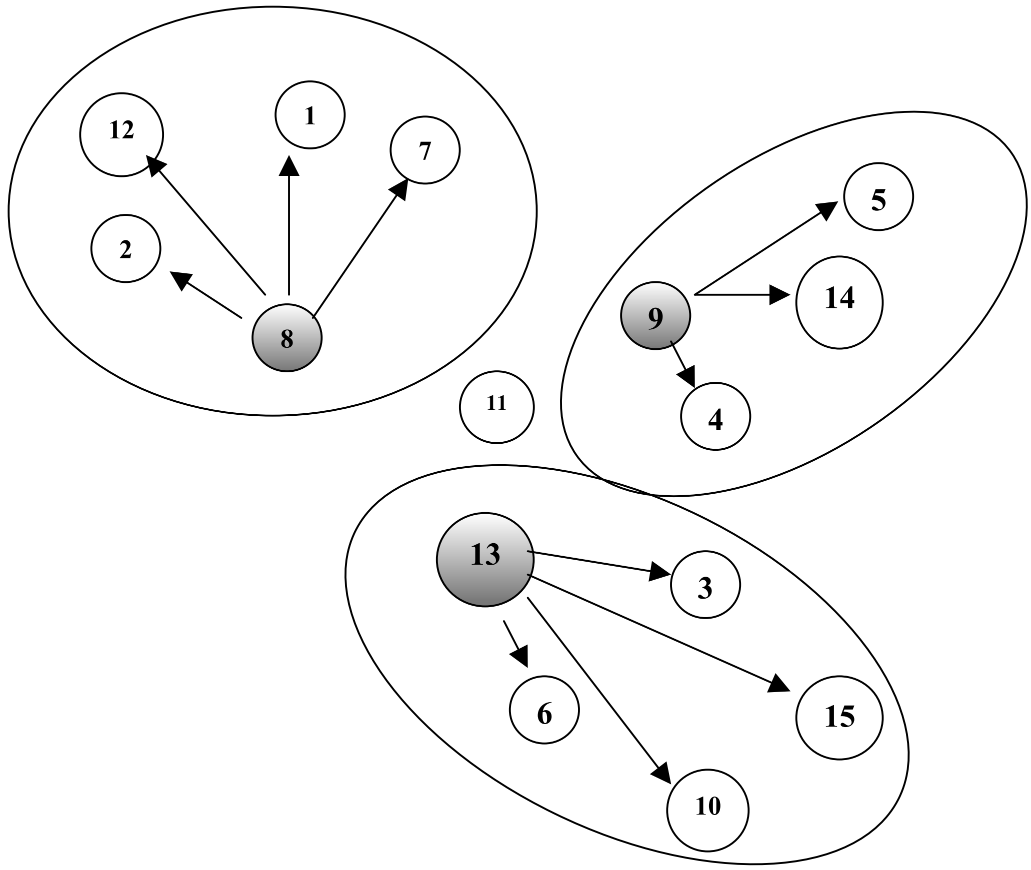


Figure 4.8: Possible links from reached nodes.

Both of them have the same number of links. Set-2 is selected for the new slot since it has less cardinality value. So slot-4 is allocated for the links (9-14) and (13-6). The same procedure is applied for assigning links for each slot until all nodes are reached. This process is for constructing distribution-spanning tree. The same operation of distribution is performed for the collection case while considering reverse direction of transmission links.

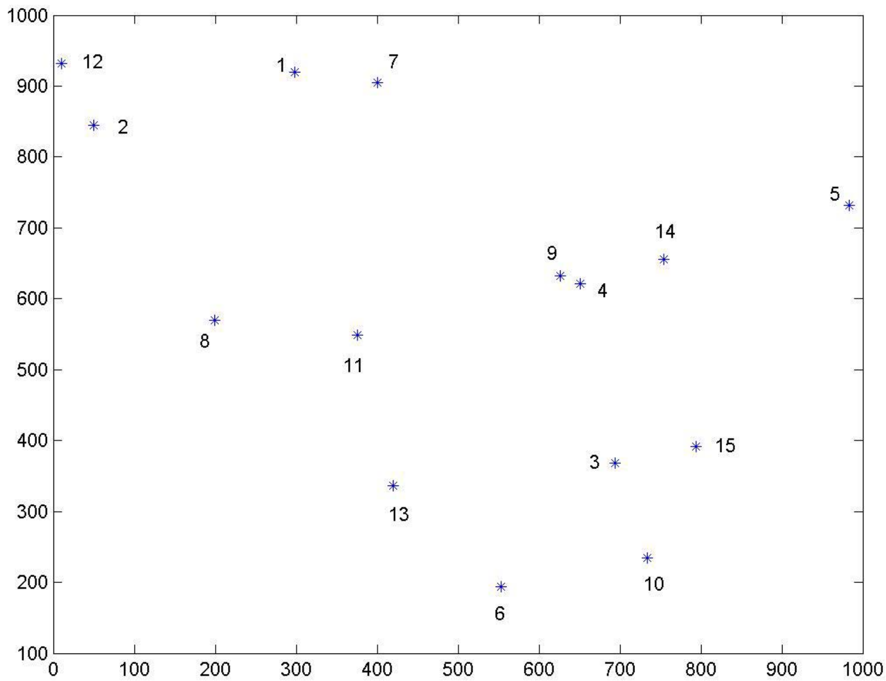


Figure 4.9: The picture of the sample network.

4.5 Numerical Results of Greedy Heuristic

An ad hoc network with 15 randomly located nodes is generated in a square area of 1000 m by 1000 m as shown in Figure 4.9. All nodes are assumed to transmit at a common power level P_c. We use four different common power levels: P_c = 3mW, 4mW, 5mW and 6mW. Thermal noise N_0 is 5nW and threshold value β for establishing link is 6 dB. Free space propagation model is used where the path loss exponent $\alpha = 2$. STDMA is used to access the channel. The algorithm is executed for different cluster size constraints and different common power levels.

Transmit Power Level = 3 mW. Lower Bound of Cluster size = 2 Upper Bound of Cluster size = 5 Number of Cluster = 4 Frame Length = 20 slot		
head node	***tail node***	***slot number***
3	**13**	**1**
5	**14**	**2**
12	**2**	**2**
2	**8**	**3**
14	**9**	**4**
15	**10**	**4**
9	**4**	**5**
10	**6**	**5**
4	**11**	**6**
1	**7**	**7**
6	**13**	**7**
13	**11**	**8**
7	**11**	**9**
8	**11**	**10**
11	**8**	**11**
11	**7**	**12**
7	**1**	**13**
11	**13**	**13**
11	**4**	**14**
8	**2**	**15**
13	**3**	**16**
2	**12**	**16**
4	**9**	**17**
3	**10**	**17**
10	**6**	**18**
9	**14**	**18**
3	**15**	**19**
4	**5**	**20**

Table 4.1: Table of link assignment schedule list.

An example topology obtained with P_c = 3 mW is illustrated in Table 4.1. The relationship between frame length, transmit power level and cluster size constraints are investigated. The inter-relation between the number of clusters and load balancing is also explored.

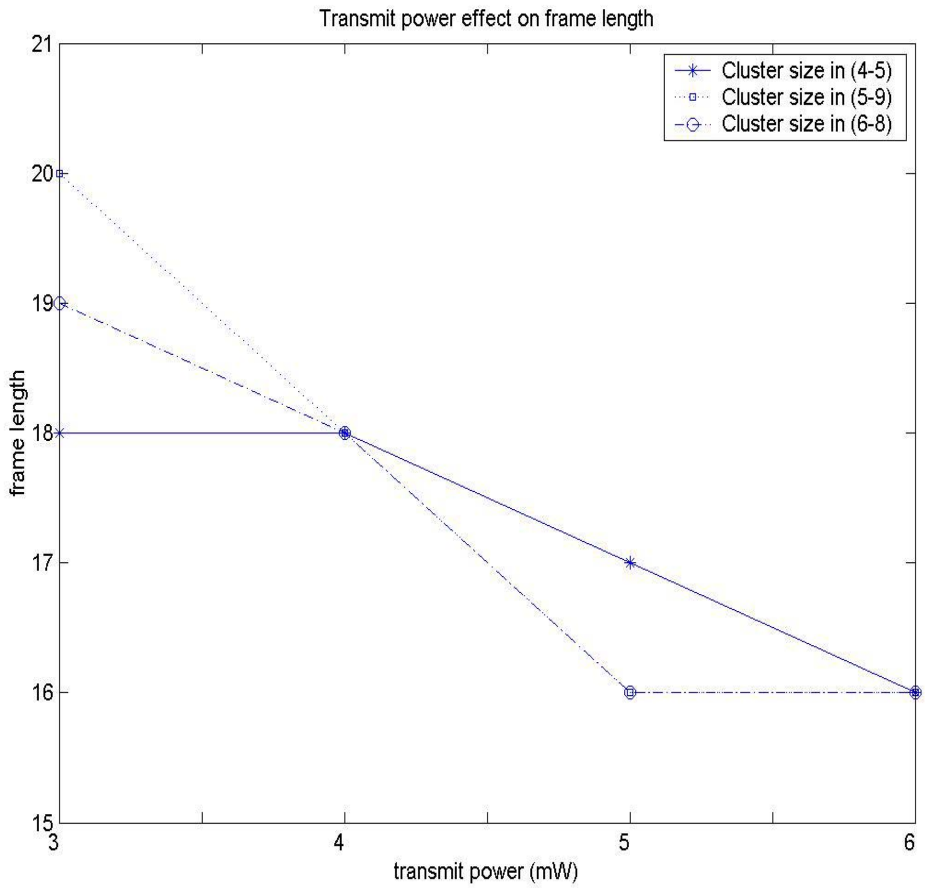


Figure 4.10: Transmit power effect over the frame length.

Figure 4.10 shows the frame lengths versus transmit power levels for different cluster sizes. P_c = 3mW is the minimum power required to satisfy connectivity. It can be concluded that increasing in power level decreases the frame length since high power level makes it possible to establish more and longer links. Gain is linearly proportional with the transmit power level in SINR formula in (3.1), but interference is not linearly dependent since interference contains constant thermal noise. Since interference does not increase as fast as the received signal power as the transmit power is increased, it becomes possible to establish more simultaneous links. Therefore, the minimum transmit power level is not the optimum when minimizing frame length is considered. More transmit power has the improvement in the frame length by up to 20% by reducing the frame length from 20 slot to 16 slot while the power consumption increases by 66 % by using P_c = 5mW instead 3mW.

In some cases in Figure 4.10, we have possibility to use less transmit power level in order to get the same frame length, i.e., the frame length constraint with 18-slot can be achieved by using P_c = 3mW instead 4mW and 16-slot frame length can be achieved by using P_c = 5mW instead 6mW. Power savings respectively by 33 % and 20 % are achieved for the above frame length constraints. These power savings cannot be ignorable for battery operated networks since longevity is a prominent concern.

Determining of the number of clusters is directly related with the selection of the upper and lower bound of the cluster. From our numerical results, we can say that there is an optimal value for the number of clusters. Figure 4.11 shows the optimal value for the number of clusters which is 3 in our sample network.

Generally speaking, increment in the transmit power level more than a certain value does not reduce the frame length, i.e., P_c = 5mW is the optimal value for 2-clustering formation and P_c = 6mW is expected as an optimal power level for 3-clustering formation. Same conclusion is not observed for 4-clustering formation.

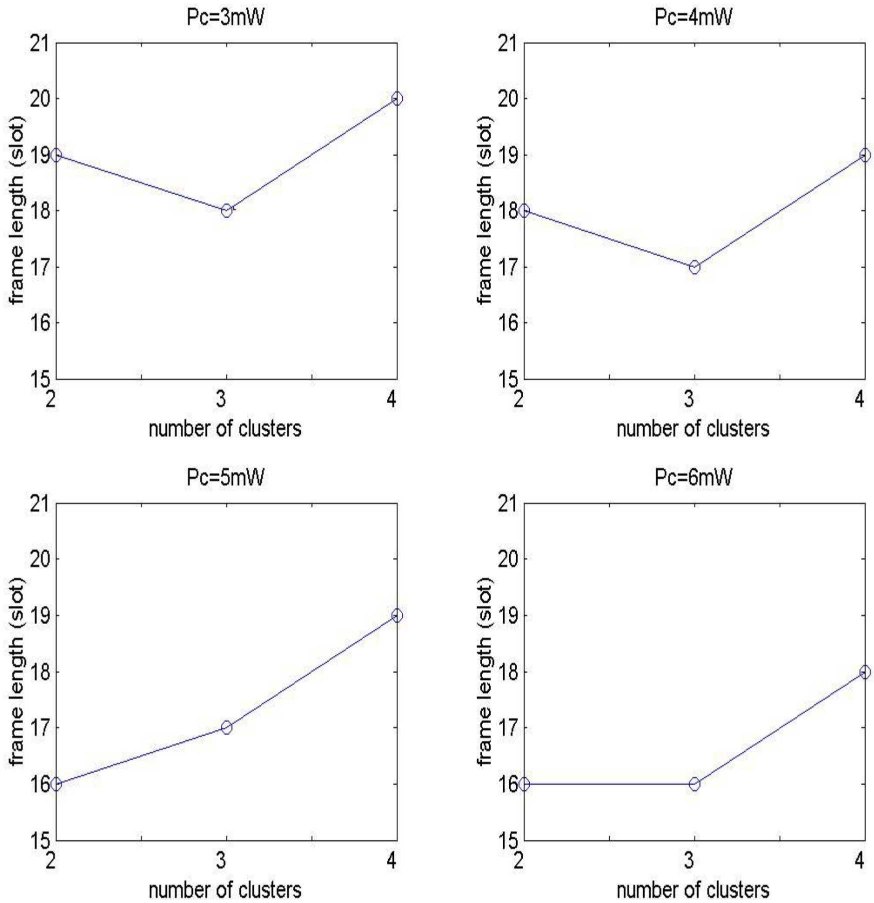


Figure 4.11: The effect of cluster numbers over the frame length.

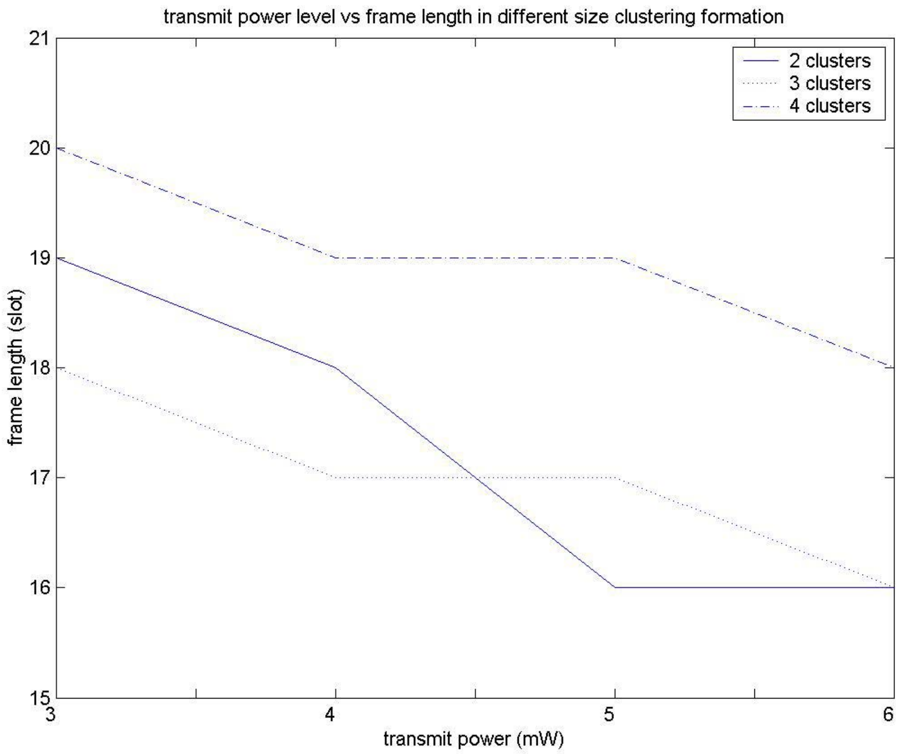


Figure 4.12: The effects of joint transmit power level and clustering size.

As explained in Section 4.4, slots equal to the number of clusters should be first allocated for transmission between the root node and the clusterhead nodes. This conflict-free property results in an increase of the frame length for higher clustering formation. Therefore, results for 4-clustering formation is undesired when considering both reducing power consumption and minimizing the frame length as seen in Figure 4.12. 3-clustering formation gives the best improvement for both power savings and the frame length while using P_c = 3mW and 4mW. For strong power-constrained operations, 3-clustering formation is preferable since less frame length is achieved.

4.6 Distributed Algorithm of Heuristic Solution

In this section, we describe a distributed algorithm which sets up gain and adjacency matrix used as an input in the proposed algorithms. As mentioned earlier, ad hoc networks are typically dynamic and hence, computation must be distributed. In centralized greedy heuristic, we use gain matrix. Because our problem is based on free space model, distance matrix can be used as a gain matrix. For empirical results, we need gain matrix that covers the gain value between each node pairs. The signal strength can be used as a gain value. The main assumption that we make here is that each host has the capability of measuring the signal strength and has GPS. We also make two other common operational assumptions, namely, we assume slot synchronization is ensured by GPS clocks, that every node has a unique ID. After distributing the data that include the gain matrix, the algorithm in the previous chapter is executed at the root node. Then scheduling lists are distributed to all other nodes.

The distributed algorithm is message driven for priori-known N nodes. It is executed in three phase. In the first phase, each node broadcasts hello(n) message in lexicographical order for measuring signal strengths. In the next phase, the root node is responsible for collecting the information of signal strength measurements and adjacency list matrix. Second phase is based on building a spanning tree rooted at the root. Each node must keep a table for gain and adjacency list matrices for the whole network. At the last phase, the root node propagates the link_scheduling message indicates which link is occurred at which time slot. In the procedures, we use the following notation for N given nodes:

- n, node ID.
- hello(n), a hello message broadcasted by node n.
- request(n), request message broadcasted by node n in order to construct all-pairs gain matrix.

- parent(n,m), a message shows that node m select node n as a parent.
- signal_strength(n,m), requested information message that carries signal strength values(gain matrix) to all neighbor nodes measured by child node m sent to node n and adjacency matrix of node m.
- link_scheduling, broadcast message which includes the link schedule list.

Firstly, in lexicographical order each node broadcast hello(n) message. In each time slot, only one node can transmit a hello(n) message. In the first phase, there is no collision since synchronization is provided. Receiver node can identify sender node ID. The node receiving this message starts to generate its own gain matrix by measuring the signal strength. After N slots, all nodes construct their gain matrix and adjacency lists.

The root node starts the execution of the second phase of the algorithm by broadcasting a request (n) message. The initiating node becomes the root of the spanning tree. Each other node joins the spanning tree by designating as its parent link the link on which it is first contacted. This is called a propagation order-spanning tree [42]. A node marks the sender of the first received broadcast as a parent and sends a parent (n,m) message to sender node. Then it broadcasts the request message further. This node ignores the other broadcast message since it has already joined the spanning tree. In this way, each node comes to know its parent and its children in the spanning tree.

Last part of this phase, which is called the collection part, is maintained by the leaves of spanning tree and goes up to the root node. A node sends a signal_strength (n,m) message to its parent node after it has added one from all its children. As a result, when the root node receives the signal_strength (n,m) messages from its children, it can build the all-pairs gain matrix.

At the last phase of the algorithm, which is also called the diffusion phase, the root sends to each of its children link_scheduling message after executing the scheduling algorithm. Each node, which receives link_scheduling message, broadcasts it to its children. The algorithm terminates when every node in the network gets the link_scheduling message.

Since links in ad hoc networks are prone to failure due to interference, broadcast environment is not reliable. When a node is broadcasting collisions can occur. Hidden terminal and exposed terminal problems are generally occurring on broadcast channels. So it might not necessarily result in the building of a spanning tree. Reliable broadcast is needed for executing our algorithm. In [43], an adaptive medium access control (MAC) for the reliable broadcast of packets in wireless networks is proposed. If node s has a broadcast packet to be sent in its assigned slot, it immediately transmits a request-to-broadcast (RTB) control packet. Each neighbor of s then responds with a short clear-to-broadcast (CTB) control packet. Thus all nodes within two hops of node s are informed of its intent to broadcast in its assigned slot, and refrain from accessing the channel for the remainder of the slot. Once the channel becomes idle, node s broadcasts its packet. If channel remains idle throughout the sensing interval, any other node t with a broadcast packet may attempt to claim the slot by sending its own RTB. In this case, a neighbor of t responds with a *negative*-CTB (NCTB) packet if and only if detects packet collision. The presence of collision indicates that two or more nodes are contending for the slot. If node t detects no NCTB packets, it then uses the remainder of the slot to broadcast its packet. Otherwise, its contention for the slot was unsuccessful and t defers transmission until its assigned slot, or some later idle slot in the frame as determined by the backoff scheme, whichever comes first.

Chapter 5

Conclusion

A unified approach to MAC and routing has been studied for topology design in wireless ad hoc networks. A heuristic solution was proposed by scheduling on STDMA and by using common power control algorithm. In particular, we focused on the problem of minimizing end-to-end delay. Moreover, hierarchical topology was designed by performing clustering formation. The heuristic algorithm was evaluated through numerical results. A distributed manner of proposed algorithm was also given in this thesis.

Our focus was on addressing the relations between hierarchical routing and link scheduling assignments. By executing the heuristic algorithm, simultaneous transmissions have been assigned to the same time slot while taking into account the desired topology considerations. Once the hierarchical topology is designed, routing is simple since the constructed topology has a tree structure. A new interference model was proposed by using hypergraph modelling. Clustering formation has been achieved by taking advantage of the maximal independent set of hypergraph. One key point in this algorithm was the metric of assigning the time slot to the selected links. Loading and congestion at each node were not dependent on the scheduling discipline only but also routing decisions. Fairness was considered and optimal cluster size has been investigated. We looked the problem whether the minimum transmit power level is the optimum one for COMPOW scheme. Generally, the results indicated that the minimum power level was not the optimum while minimizing frame length since increasing in power level decreases the frame length. It has been concluded that there was a trade-off between power savings and the frame length constraint. Additionally, it was observed that there was a possibility of power saving while obtaining the same frame length results. Optimal transmit power level could be achieved for some clustering formation.

From the numerical results, we obtained an optimal value for the number of clusters. The results for higher clustering formation was undesired when both power savings and minimizing frame length were considered. For strong power-constrained operations, the optimum clustering formation was observed.

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