JOINT TOPOLOGY DESIGN WITH ROUTING AND POWER CONTROL IN AD HOC NETWORKS

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By

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ABSTRACT

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We discuss the problem of designing an ad hoc network topology by jointly using power control and routing. A well-designed topology in ad hoc networks provides several advantages: increasing the capacity, decreasing the complexity and reducing the power consumption. We formulate the topology design problem as an Integer Linear Programming (ILP) model. An optimal topology is designed subject to interference and connectivity constraints with three different objective functions and two power control approaches. Common transmit power (COMPOW) and the adaptive power (ADPOW) are the two different power control techniques used in this thesis. The objectives of the models that are used in the topology design are maximizing the number of established links, using shortest path routing strategy and minimizing the maximum traffic load over the most congested link by load balancing. Performance comparisons between two power control approaches with three different objectives in the topology design are achieved using numerical results on a sample network. Minimum end-to-end throughput, total throughput, total power consumption and the number of established links are used as the performance metrics. The numerical results show that selecting the optimal power for both power control approaches provides similar performance results. Therefore, simplicity of the COMPOW makes it more attractive than ADPOW in the topology design.

Keywords: Ad hoc networks, power control, topology design, routing.

ÖZET

AD HOC AĞLARDA YÖNLENDİRME VE GÜÇ KONTROLÜ İLE BÜTÜNLEŞİK TOPOLOJİ DİZAYNI

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Ad hoc kablosuz iletişim ağlarında, yönlendirme ve güç kontrol yöntemleri kullanılarak topolojinin dizayn edilmesi bu tezde ele alınmıştır. Ad hoc ağlar çok çabuk değişen topoloji yapıları ile dikkat çekmektedirler. İyi bir topoloji dizaynı, kapasitenin etkili kullanımını, daha az karmaşık bir işletim yapısını ve daha az bir güç sarfiyatını bizlere sağlayabilmektedir. Biz bu tezde topoloji dizayn problemini bir tamsayılı doğrusal programlama modeli olarak ele aldık. Belirlenen kısıtları ve amaç fonksiyonunu göz önünde bulundurarak ve iki değişik güç yöntemi uygulayarak en uygun topolojiyi dizayn etmeye çalıştık. Bu güç kontrol yöntemleri Ortak Güç Kontrol yöntemi ve Uyarlanabilir Güç Kontrol yöntemleridir. Üç değişik amaç fonksiyonu kullanarak oluşturulan üç ayrı model, her bir güç kontrol yöntemi ile ayrı ayrı çalıştırılmıştır. Bu amaç fonksiyonları sırasıyla, olabildiğince fazla link kurmak, en kısa yolu kullanan bir yönlendirme politikası uygulamak ve en fazla trafik taşıyan link üzerindeki trafiği en aza indirerek diğer linkler üzerinde taşınan trafiği dengelemektir. Her iki güç kontrol yöntemini bu üç ayrı model içinde kullanarak, aralarında bir performans karşılaştırması yapılmaya çalışılmıştır. Bu karşılaştırmalarda ölçüt olarak bir uçtan bir uca taşınan en az bilgi miktarı, ağ içinde taşınan toplam bilgi miktarı, kurulan link sayısı ve harcanan toplam enerji miktarı kullanılmıştır. En sonunda yapılan karşılaştırmalar, her iki güç kontrol yönteminde de en uygun güç seviyeleri seçildiği taktirde aralarında performans ölçütleri bakımından çok önemli farklılıklar olmadığını göstermiştir. Bu nedenle, ortak güç yöntemi, sağladığı basit yaklaşım sayesinde daha cazip bir kontrol yöntemi olarak karşımıza çıkmaktadır.

Anahtar kelimeler: Ad hoc ağlar, güç kontrolü, topoloji dizaynı, yönlendirme.

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Chapter 1

Introduction

People developed many ways to communicate with each other since the early historical eras. Communication is the way of information exchange between people. This makes communication as one of the most important issues in the world. Developments of integrated circuits and computers caused very rapid improvements on the information exchange area. In this era, developments of packet forwarding techniques in communication continued with the invention of Internet. In a short period of time, Internet is accepted as the fastest and easiest way of information sharing all around the world. Today, anyone can reach any desired information at any location of the world in a second by using Internet. As the information sharing became easier, developments in computer and information technologies became faster than before. Technological developments in computer and communication technologies made possible to exchange larger amounts of data in a short period of time without any restrictions on physical location. Dependency on the wired communication devices was the main restrictions for any time and anywhere communication capability. The need for mobile communication capability forced people to find the wireless communication as a solution. People began to use propagation of signals in free space instead of wires. The main advances in wireless communication initiated with the technological developments in communication and computer devices. Wide application spectrum of mobile communication makes wireless communication techniques very popular in a short period of time. The cellular radio systems emerged to support as many users as possible by the limited frequency spectrum in 1980s. Cellular radio systems enabled communication at any time and anywhere without depending on a wire line. Especially after the mid-1990s, mobile communication systems become a main part of daily life with the decreasing cost of cellular communication devices. They enable people to use many different applications on the mobile wireless communication environment.

The dependency on a base station for network management and topology design is the main challenging issue for cellular radio communication systems. There is a need for the reliable communication in the nonexistence of a base station for many applications for continuous information flow at all times. Especially, military applications in the battlefield and search and rescue operations in a disaster are the most characteristic application areas for a network that do not need a previously established communication infrastructure. In such a situation, conventional cellular communication systems cannot provide an efficient information exchange between all users. Ad hoc networking is considered as a solution for removing the dependency on the previously established communication infrastructure. Ad hoc networking gained its popularity after mid-1990s. These networks enable military forces to communicate in rough terrains, track friendly forces, and use sensor networks by consuming less power resources. These networks can also be used in many commercial areas such as policing and emergency operations, restaurants, museums, personnel area networking in home and offices and information sharing in conferences. Many research groups all around the world recognize these benefits of ad hoc networks for both commercial and military areas. At the beginning, routing mechanism for ad hoc networks was the main research topic in the literature. With the increasing popularity of ad hoc networking, the importance of topology design became one of the main research areas for ad hoc networks. Designing the topology can provide power savings and network capacity increases. Controlling the transmit power level is the main way of topology design in the current researches.

In this thesis, the topology design by using power control approach is investigated. Topology design is considered as an optimization problem. The designed topology is an optimal topology according to the objective functions and constraints. The thesis is organized as follows:

In Chapter 2, wireless networking and ad hoc networks are briefly introduced. The characteristic features and challenges of ad hoc networks are discussed. The routing protocols for ad hoc network are briefly explained in two different classifications. These are the proactive (table driven) and the reactive (on demand) routing protocols. Then the topology design is defined with its benefits on the network performance. Power control is presented in a way of topology design. Common transmit power (COMPOW) and the adaptive transmit power (ADPOW) approaches are explained for topology design. Current works on topology design with power control approaches and routing are also presented. At the last part of Chapter 2, we define the framework of our topology design strategy and make a comparison with the current works in the literature.

One of the main application areas of ad hoc networks is the military network. The historical evolution of ad hoc networks in military area is discussed in Chapter 3. Ad hoc networking integration and improvement in military applications in some foreign armies and Turkish Military Forces are investigated. Five real scenarios that demonstrate usage of ad hoc communication in the battlefield are generated at the last part of this chapter.

In the fourth chapter, the ILP (integer linear programming) models that developed for topology design are introduced. Firstly, model is described by defining the assumptions used in the model construction. TDMA (Time Division Multiple Access) that is used in the models is explained. Three different objective functions are used in the ILP models. These are the maximum link model, shortest path routing model, and the load balancing models. The maximum link model has the goal of increasing the number of established links. Shortest path model uses the shortest path between source-destination pair. Load balancing model tries to decrease the maximum amount of carried traffic on the most congested link. Each model is implemented by using COMPOW and ADPOW approaches. The numerical results are obtained for the performance metrics of end-to-end throughput, total throughput, total power consumption and the number of established links. These parameters are compared for all three models in order to evaluate their performances. This comparison is presented in the last part of Chapter 4.

The conclusions obtained from the implementations in this thesis and the directions of future works on ad hoc networking are presented in Chapter 5.

Chapter 2

Wireless Ad Hoc Networks

This chapter gives brief information about the wireless communication networking. Historical evolution and the idea behind of wireless networking are explained. Some examples of wireless communication systems are presented. Modern wireless communication systems and wireless network topology design are introduced briefly. Definition and characteristics of ad hoc networking are explained. Design challenges of ad hoc networks, topology design and routing strategies are investigated. A literature survey about topology control with joint routing and power control approaches are presented in the latter parts of this chapter. The chapter concludes with a summary of the contribution of this thesis and its comparison with other studies using power control for topology design in ad hoc networks.

2.1 Wireless Communication Systems

Many researchers began to investigate new wireless communication methods and services after the introduction of wireless communication by Marconi in 1897. Especially after the 1990s, mobile radio communication industry has grown tremendously. Developments in digital and RF circuit fabrication improvements, miniaturization technologies, and digital switching techniques enabled cheaper and highly deployable mobile radio communication systems [1]. This provided more affordable mobile communication services to people all around the world. The increasing demand on mobile communication stimulates more researchers to develop new inventions in this field. These trends will continue in the next decade with an increasing rate in a wider application spectrum.

2.1.1 Evolution of Mobile Radio Communication

The modern wireless communication era was born with the development of highly reliable, miniature, and solid-state radio frequency hardware in 1970s [1]. The exponential growth in cellular radio and personal communication systems are directly related with the developed technologies since 1970s. The future growth is also very closely related with the developments of new application services, consumer needs and technology advances in the signal processing and networking areas. There were about 5000 radios in mid 1930s [1]. The number of radios in USA climbed from several thousands in 1940 to 86000 by 1948, to 695000 by 1958, and to about 1.4 million in 1962 [2]. With the emerging cellular based radio and cordless appliances, the number of mobile users in 1995 was about 100 million (about 37% of USA population). The number of worldwide cellular telephone users grew from 25000 in 1984 to about 25 million in 1993 [3,4]. The worldwide subscriber base of cellular telephony is approximately 630 million as of late 2001, compared with 1 billion wired telephone lines. Within the first decade of 21st century, it is estimated that there will be an equal number of wired and wireless communication customers throughout the world. Today, many wireless communication providers are presenting some new real-time services for their own users to generate new revenues. Wireless communication has become a very huge market area for all commercial companies.

The first public mobile telephone service was introduced in 25 major American cities, in 1946. Each system used a single, high-powered transmitter and large tower in order to cover distances over 50 kilometers. During 1950s and 1960s AT&T Bell Laboratories and other communication companies developed the concept of cellular telephony. This concept provided to use the same frequency spectrum in different cells by multiple users. The world's first cellular system was implemented by Nippon Telephone Company in Japan, in 1979 [1]. In Europe, the Nordic Mobile Telephone system (NMT 450) was developed in 1981. Advanced Mobile Phone Systems (AMPS) was the first U.S cellular system that was developed in 1983. In late 1991, the first U.S Digital Cellular (USDC) system hardware was installed. After the mid-1990s, the technologies using the cellular mobile systems were developed with an increasing speed. The expectations of users have risen with many different wireless communication applications served by mobile communication service providers.

There are many examples of newly emerging mobile wireless communication systems used in everyday life. Remote controllers for home entertainment devices, cordless telephones, garage door openers, and hand held walkie-talkies, pagers and cellular telephones are the examples of mobile wireless communication systems.

2.2 Ad Hoc Networking

Wireless communication is becoming the most widely used way of communication. In cellular telephone systems, each mobile seeks for a base station to make a successful transmission. Without an existing infrastructure, each user suffers from the lack of communication. But, there is an emerging need for wireless communication without any infrastructure. Mobile ad hoc networking is a solution for this problem. Mobile ad hoc network is a collection of mobile users that communicate over wireless links. The lack of a need for a previously established infrastructure in ad hoc network is the main difference from traditional wireless communication systems. Mobile users can dynamically form a network autonomously in a distributed fashion. In Figure 2.1, an ad hoc network structure is shown. In this figure, there is no base station to provide network management. In ad hoc networking, each user can behave as a router. This network uses multi-hop routing mechanisms for communication. Each node can receive or send a message to another node. There is no need for a base station to route a packet.

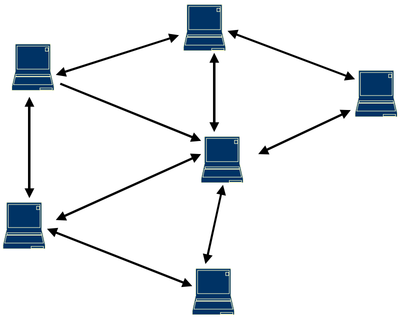

Figure 2.1 Ad hoc network formation

A node receiving a message either forwards it to the destination or discards it. During the network formation phase, each node computes possible paths to all destinations in the network and forms its own routing table. Since mobile users form these networks, the topology is dynamically changing and the paths are updated periodically. Ad hoc networks have many useful application areas in commercial, personal, and military areas. Especially in a natural disaster, the entire communication infrastructure may be destructed. Their independency from an existing infrastructure makes ad hoc networks very useful in such a situation. Also in a conference, all the attendances can share information by using their laptop computers through the wireless medium. Another application area is indoor applications. It is possible to build a wireless personnel area network (PAN) in our home or office by using ad hoc capable devices. By using PANS, we can remotely control networked appliances without using any wired structure. The Bluetooth technology and IEEE 802.11 standards can be used for these purposes.

Military applications are also an important application area of ad hoc networking. Military units are highly deployable, and possibly there would not be an existing communication infrastructure during a battle. Ad hoc networking can provide a reliable communication in worst-case rough terrain for all users in the battlefield. The military applications of ad hoc networks are discussed in Chapter 3.

These advantages of ad hoc networks make them very popular. There is an increasing demand and interest for ad hoc networks. Many research groups are currently involved in developing algorithms and protocols for ad hoc networking.

2.2.1 Characteristic Properties of Ad Hoc Networks

An ad hoc network uses the wireless medium for communication. Ad hoc network consists of a collection of geographically distributed nodes that communicate with one another over a wireless medium [5]. An ad hoc network differs from cellular networks in that there is no wired infrastructure. The lack of fixed infrastructure implies that all operations should be carried out in a decentralized manner.

Lack of a base station brings the necessity of a routing mechanism. Because of this need, ad hoc nodes should be equipped with routing capable devices. All the nodes can forward traffic to other nodes by using a specified routing mechanism, which is called multi hopping. Routing information becomes quickly obsolete because of the rapid movement of the nodes and fast changes in propagation conditions. This leads to frequent network reconfigurations and frequent exchanges of control information over the wireless medium.

Nodes in ad hoc networks typically operate by using batteries with limited lifetime. An exhausted battery may result in a disconnected network topology.

Mobility brings highly dynamic topology changes in ad hoc networks. Location changes of some nodes forces other nodes to use alternative paths in the network. If there cannot be an alternative path, reconfiguration of network becomes inevitable. The topology design algorithm must be run again and a new connected topology must be reconstructed.

The dynamic topology changes cause fluctuating traffic loads over the links where the link utilization changes continuously. When many users share bottleneck links, some congested links in the topology may arise.

2.2.2 Challenges in Ad Hoc Networks

The main characteristics of ad hoc networks are explained above. Designing an ad hoc network topology must cope with some design challenges. Three main challenges in the design operation of the ad hoc networking are [6]:

- The lack of centralized entity,
- The possibility of rapid platform movements,
- The fact that all the communication is carried over the wireless medium.

In traditional cellular wireless networks, there are a number of centralized network management entities, e.g. base stations, mobile switching centers, etc. These centralized entities perform the function of coordination. In ad hoc networks, these centralized entities do not exist. The lack of controllers brings the need for more sophisticated distributed algorithms to perform coordination in the network.

As mentioned before, ad hoc networks consist of mobile nodes. The mobility deeply influences the topology design and routing. Reconfiguration of the topology due to mobility plays a critical role in ad hoc networks. Topology design and routing algorithms must regard the mobility of nodes. Routing in such networks experiences link failures more often. Routing protocols must be adaptive to cope with time varying low-capacity resources.

Wireless medium also creates some challenges. Multiple users share the same frequency bandwidth in wireless medium. This creates medium access control (MAC) layer problems. The nonexistence of centralized authority complicates the problem of medium access control. Ad hoc networks need distributed medium access schemes. Mobile stations may collide with each other simultaneously for accessing the transmission medium. Consequently, simultaneous transmissions from mobile terminals may result in packet losses. This causes retransmissions and large delays [7]. Time division multiple access (TDMA) and some other MAC protocols are proposed for ad hoc networks [8, 9].

In ad hoc networks, nodes correspond to battery driven devices. These devices have limited power capacities. This implies that ad hoc nodes communicate by using lower transmit power levels. This is critical, since higher transmit power reduces battery lifetime. Network lifetime can become longer by controlling transmit power levels. Also lower transmit power reduces the transmission ranges and interference to other nodes. Using appropriate transmission power level is one of the most challenging issues in ad hoc networking.

2.2.3 Routing in Ad Hoc Networks

Routing specifies the paths between source destination pairs. The conventional routing protocols such as distance vector or link state algorithms require periodic routing advertisements to be broadcasted by each router. This increases the network bandwidth overhead and introduces redundancy in paths. These protocols do not support dynamic topology changes. Ad hoc networks have a fast changing topology characteristic. There is no centralized controller to decide on routing between nodes. This implies that each node in ad hoc network must be capable of routing. As seen in Figure 2.2, routing can be accomplished in a multi-hopping manner. In that figure, node 4 is not in the transmission range of node 1, but they can communicate by using the intermediate node 2. Similarly, nodes 2 and 3 need intermediate node 1 to communicate with each other.

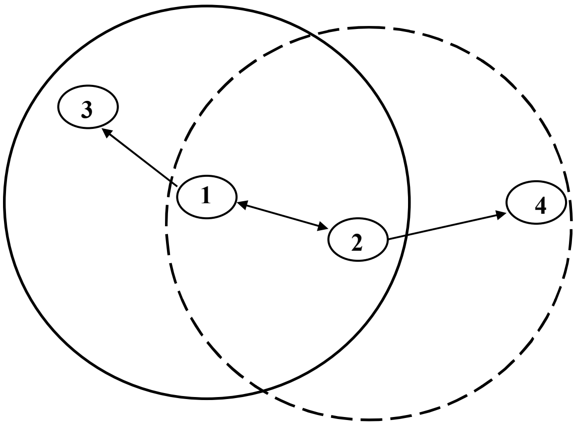

Figure 2.2 Multihop routing

Routing protocols in ad hoc networks must be self-starting, adapt to changing conditions and offer multihop paths across a network from source to destination. Frequent flooding of packets throughout the network can consume significant portions of available bandwidth. Ad hoc routing protocols must minimize bandwidth overhead. In general, the existing routing protocols can be classified as **proactive** and **reactive** routing protocols.

Proactive protocols attempt to continuously evaluate the routes within the network. When a packet needs to be forwarded, the route is already known and can be immediately used. All the route information for all destinations is stored in a table in each node. These algorithms are called as table driven algorithms [10,11]. The main disadvantage of proactive routing protocols is the additional control traffic that is needed to continually update stale route entries. The dynamic topology behavior of ad hoc networks causes many broken links. If the broken path has to be repaired when no traffic is flowing through it, the repair effort can be considered as wasted. This wasted effort can consume bandwidth resources.

On the other hand, reactive protocols create a route in case of a demand for that route. When a route is needed, some sort of global search procedure is employed [6]. Firstly, a source checks its own cache for a path to the destination. If it finds a path, it uses this path. If this cached path fails or there is no cached path to that destination, the source initiates a route discovery process. In this process, the source node floods the network with route request packets. When an intermediate node receives this packet, it checks if a route to the destination exists in its cache. If there is a cached route, it sends a route reply message containing the route to the destination back to the source node. A node can store multiple routes to a destination. If an available route cannot be found, the source rebroadcasts the route discovery message to all other nodes. When a node detects a link failure due to the topology change, it sends a route error message back to the source. When the source receives this route error message, it removes all routes using the broken link from its cache. A new route discovery process is then initiated. This procedure is called the route maintenance mechanism. Reactive protocols uses far less bandwidth than proactive protocols. In reactive protocols, since route information may not be available at the time a route request message is received, the delay to determine a route can be quite significant [6]. Because of this long delay, reactive protocols are not appropriate for real-time applications.

Pure reactive protocols suffer from delay at the route discovery phase. This delay makes them unavailable for real time applications. Also, pure proactive protocols have a disadvantage on using a significant portion of bandwidth to keep the routing information up-to-date. This results in waste of capacity. Below, some of the routing protocols used in ad hoc networks are explained briefly.

2.2.3.1 Dynamic Source Routing (DSR)

DSR is one of the purest examples of reactive (on-demand) protocol. All actions are taken only when a route is actually needed. DSR uses source routing algorithm, where each packet carries in its header the complete and ordered list of nodes through which the packet will pass. Other nodes forwarding or hearing any of these packets may easily cache this routing information for future use. The DSR protocol consists of two mechanisms [12]. First one is route discovery and the second one is route maintenance. They work together to allow the discovery and maintenance of source routes in ad hoc networks. Two mechanisms operate entirely on demand. There are no periodic updates of any kind.

2.2.3.2 Destination-Sequenced Distance Vector (DSDV)

DSDV [13] is a distance vector routing protocol. It is a proactive routing protocol. Routing is accomplished by using routing tables stored at each node. Each node periodically broadcasts its routing updates. The most important issues in DSDV are the generation and maintenance of these routing tables in each node. DSDV protocol requires each node to advertise, to each of its neighbors, its own routing table. Each routing table lists all available destinations and the number of hops to each node. In addition to the destination address and the next hop address, routing tables maintain the route metric and the route sequence number. Periodically or immediately after a topology change, each node broadcasts routing table update message. All the nodes update their routing tables according to the new topology.

2.2.4 Topology Design in Ad Hoc Networks

Topology is the set of communication links between node pairs used by a routing mechanism [14]. Ad hoc networks do not depend on a previously defined infrastructure. There is no base station or any other access point that can control the topology design.

All the nodes may be mobile. There are highly dynamic topology changes in ad hoc networks. An existing communication link may disappear due to the mobility. This dynamic nature of links makes topology design as a challenging issue in ad hoc networks.

The quality of the topology can be evaluated according to several criteria including connectivity, lifetime energy efficiency, throughput and robustness to mobility. Connectivity means that there must be at least one feasible route between all node pairs. Lifetimes of batteries are closely related with network lifetime. Existence of some exhausted battery implies that there are some disconnected nodes in the network. Using energy efficiency techniques can increase batteries lifetimes.

Besides connectivity and energy efficiency, high capacity is also desired from the topology design. A desired topology must provide as much throughput as possible. Gupta and Kumar [15] investigate the throughput of ad hoc networks. They define the throughput in terms of a bit-distance product. Suppose that the network transports one bit-meter when one bit has been transported a distance of one meter. Then the throughput is measured in terms of the number of bit-meters, which are transported per second. The achievable throughput for each source destination is $\frac{1}{\sqrt{n \log n}}$, where n is the number of nodes in the network.

Another challenging issue in ad hoc networks is to provide some degree of robustness to the mobility of nodes. One measure of robustness is given by the maximum number of nodes that need to change their topology information as a result of a movement of a node [5]. A desired topology must provide robustness to mobility.

After describing topology and its critical features, we can think about why the topology design is necessary. The importance of topology design lies in the fact that it affects the system performance in several critical ways. Firstly, as explained in [15], it affects network spatial reuse and hence the traffic carrying capacity. Using high transmit power levels cause high interference and this decreases throughput. Too small transmit power levels result in a disconnected network. In Figure 2.3, there is a very dense topology design, which causes high interference, high power consumption, and low throughput. There is a sparse network in Figure 2.4 that causes some disconnected nodes. A desired sample topology is shown in Figure 2.5. This topology provides lower interference, lower power consumption, and higher throughput by regarding global connectivity. Topology design has a vital impact on battery life. An inappropriate topology may cause high power consumption. On the other hand, by designing an optimal topology, the same amount of throughput may be achieved with lower power consumption. Topology design has also impacts on retransmissions caused by the collisions in the wireless medium. Choosing smallest transmission power while preserving network connectivity can reduce collisions. Wrong topology design also increases end-to-end delay and decreases robustness to node failures. If the topology is too dense, the spatial reuse reduces the network capacity. On the other hand, very sparse topology may cause high end-to-end delay and some disconnected nodes.

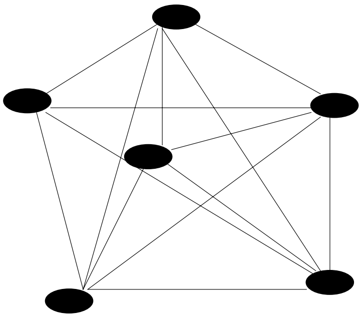

Figure 2.3 Dense topology design sample

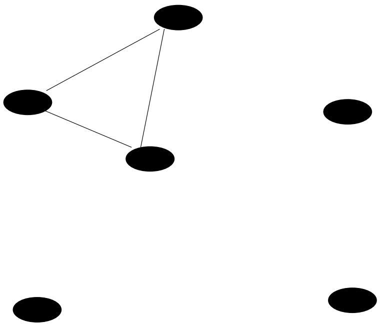

Figure 2.4 Sparse topology design sample

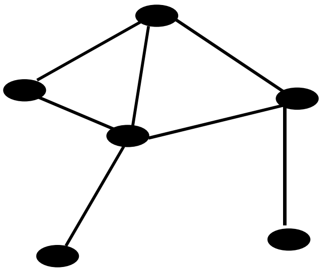

Figure 2.5 Desired topology design sample

There have been some studies in the area of topology control for ad hoc networks. In [16], an algorithm based on the Delaunay triangulation is given to choose logical links. In choosing these links, some heuristic guidelines are used such as not exceeding an upper bound on the degree of each node and choosing links that create a regular and uniform graph structure. Ramanhatham and Rosales [14] describe a centralized spanning tree algorithm for creating connected and bi-connected static networks. The objective is to minimize the maximum transmission power for each node. Rodoplu and Meng [18] propose a distributed topology control algorithm that guarantees connectivity of the entire network. They achieve the minimum power topology that contains the minimum power paths from each node to a designated master-site node. In [17], two distributed algorithms that adjust the node transmit power to maintain network connectivity is described. One of them is the distributed cone based topology control algorithm. This algorithm provides an increase in network lifetime while maintaining global connectivity with reasonable throughput in a multihop wireless ad hoc network. Network lifetime is increased by determining the minimal operational power requirement for each node in the network while guaranteeing the same maximum connected node set as when all nodes are transmitting with full power.

The topology depends on uncontrollable and controllable factors. Uncontrollable factors can be node mobility, weather, interference, and noise. Controllable factors are the transmit power and antenna direction. In the next part, power control approaches for topology design will be introduced.

2.2.5 Power Control in Topology Design

The mobility of nodes in ad hoc networks makes them dependent on devices with the limited power resources. This makes energy conservation a key requirement in the design of ad hoc networks. Transmit power control provides at least two objectives. Firstly, battery life can be extended by power control, and secondly, it can impact on the traffic carrying capacity of the network [19]. In Figure 2.6, node 1 uses 10mW transmit power to communicate with node 2. But, node 2 is in the range of 2mW power level. This means that node 1 wastes of 8mW in each transmission. This reduces battery life by 80%. Besides, power control increases the capacity usage of the network. Again in Figure 2.6, if node 1 uses 2mW power level, node 3 can make a transmission to node 4 simultaneously. This means that two links can be established in the network at the same time. This increases the capacity utilization of the network by using the bandwidth effectively. But, this is not possible if the node 1 transmits with 10mW power.

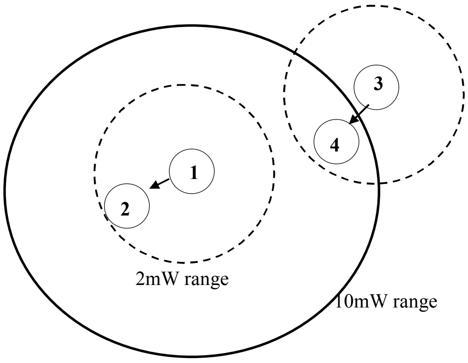

Figure 2.6 Power Control impacts on capacity and power consumption

Current researches on topology design with power control can be classified into three categories [19]. The first class tries to find an optimal transmit power to control the connectivity properties of the network. The second approach can be called as power aware routing. The third class aims to modify the MAC layer. In the first class, there are three main approaches for power control. These are selecting a common transmit power level for the whole network, using an adaptive power per node or adaptive power per link approaches. In [14], it is proposed that each node adjusts its transmit power level so that its number of one hop neighbors may be limited. They formulate topology control as a constrained optimization problem. The transmit power is minimized subject to the network being connected or bi-connected. In [17], the transmission power of each node is varied in order to control the topology of wireless multihop ad hoc networks. They develop a simple distributed algorithm where each node makes local decisions about its transmission power with regarding global connectivity. In [20], transmit power control is used to optimize the average end-to-end network throughput. Their objective is to investigate the effect of using different powers on the average power consumption and end-to-end throughput. They define the concept of clusters wherein a node adapts its transmission power level to establish connectivity with reduced number of neighbor nodes. In each cluster, nodes can adapt different power levels, or they may use the same power level. In [19], the use of a common transmit power level (COMPOW) at all nodes is proposed. This common power level must be the minimum required power to satisfy global connectivity. It is shown that the COMPOW protocol satisfies the objectives of maximizing the traffic carrying capacity, extending battery life and reducing the contention at the MAC layer.

ADPOW per node implies that each node may choose one of the offered power level and uses it for all its neighbors. ADPOW per link approach proposes that each link may use different transmit power levels to different neighbors.

2.3 Contribution to Joint Topology Design with Power Control and Routing

Topology design provides high capacity usage and less power consumption. An inappropriate topology may cause waste of valuable energy and capacity resources with high delays. Designing a desired topology, which provides the highest capacity usage and minimum power consumption, is a challenging issue. Transmit power control is the main method for controlling the topology. Mainly, there are two power control approaches in topology design. First one is using a common transmit power level (COMPOW) at each node. Second one is to use ADPOW for each link. A desired topology may be designed by using each of this power control approaches. But, there is a need for a comparison between both of these approaches to decide which one of them is better. This thesis mainly aims to get comparable conclusions about the performances of these power control approaches in the topology design. Numerical results for end-to-end throughput, total throughput, power consumption, and the established number of links are used to compare the performances.

In this thesis, topology design by using transmit power control approach is considered as an optimization problem. Two different power control approaches for the topology design is used. These are the COMPOW and the ADPOW per link approaches. In COMPOW approach, one common transmit power level is used at all nodes to communicate with all other nodes. In ADPOW approach, each node may select one of the offered power levels to communicate with any one of its neighbors. All the communications are reliable communications regarding the signal-to-interference noise ratio. Time Division Multiple Access (TDMA) is used to solve MAC problem in this thesis. Each time frame is divided into time slots. Three main objectives are used in each power control approach. First objective is maximizing the number of established links in a frame, second one is using the shortest path routing strategy and the last one is balancing the load over each established link in the network. In ADPOW approach, minimizing the total power consumption is considered as a secondary objective. In COMPOW, the most important feature is providing global connectivity. The optimization problem for designing a connected topology is formulated as an Integer Linear Programming (ILP) problem and solved for different power control techniques and objectives. The detailed explanations for the features of the problem are presented in the next chapter.

There are many different studies on topology design in ad hoc networks. It is proposed in [18] that there are no big changes in the network's traffic carrying capacity in case of all the nodes insist on using the common transmit power level instead of different transmit power levels. It is shown in [15] that the per node throughput for a random destination can never be more than $\frac{c}{\sqrt{n}}$ for every n where c is the capacity and n is the number of nodes in the network. COMPOW model guarantees a per node throughput of $O\left(\frac{1}{\sqrt{n\log n}}\right)$. Since $\frac{1}{\sqrt{\log n}}$ is negligible, it may be said that COMPOW provides the asymptotically optimum network capacity. An optimization approach is used to compare both power control approaches for end-to-end throughput, total throughput, and power consumption metrics. In this thesis, links are assumed as unidirectional links and the routing mechanism is considered as a part of optimization problem.

There is no work in the literature that compares the effect of both power control approaches on topology design by using the same simulation environment. Current studies use just one power control approach and compare with the simulation or analytical results obtained in other studies. In this thesis, we compare the performances of both power control approaches by using the same optimization environment. The details of modeling the topology design by using power control and routing is discussed in the Chapter 4.

Chapter 3

Ad Hoc Networks in Military Applications

Today, the current work on ad hoc networking technology has gathered an increasing interest by many of research groups from all over the world. The wide spectrum of application areas makes these networks popular for military customers. The use of spread spectrum is not only confined to military purposes. The developments in commercial areas can be easily integrated into military applications with little modifications. Users expectations have risen with the improvement of wireless technologies in commercial and military areas. This expectation brings a need for limitless wireless connectivity at any time and anywhere. Mobility must be considered as a main issue in today's communication systems. This can reduce the lack of infrastructure needs and costs of establishments. These factors make clear the idea behind the increasing amount of researches on ad hoc capable communication in both commercial and military areas.

In this chapter, military communication concept that depends on the ad hoc networking is discussed. A literature survey about the past and future of ad hoc networks in military area has been done. Experienced communication technologies that support ad hoc networks for military purposes are investigated. Different military scenarios are generated that depend on the ad hoc networking applications in the battlefield.

3.1 Ad Hoc Network Concepts in Military

The first idea behind the development of the Internet was to provide a solution for data transfer between military units. It is the same idea that generated the first interest for the development of ad hoc networks. Information and computer technologies are developing with an increasing speed in this era. Mobility development makes very dynamic deployment of troops all over the world. Needs of gathering accurate and fast real time information from enemy and allies are vital in an operation. Real time information technology developments increased the required data size and quality needs for all users. Every user needs to be aware of other users in the same network. No need of an infrastructure, fast and easy deployment, distributed management, dynamic topology design, and controllable power consumption make ad hoc networks a very popular research subject in military and commercial areas. The motivations for ad hoc networking in military are discussed below in more details.

3.1.1 Motivation

The survivability need in the battlefield is the first motivation for mobile ad hoc network (MANET). Main characteristic of the battlefield conditions requires a continuous communication between all units. The highly dynamic location movements can characterize battlefield topology. In tactical and strategic manner, the desired results in a battlefield can be accomplished by attacking to enemy. A successful attack depends on rapid reactions to the changing scenarios in the battlefield. Wired dependent communication creates one of the main restrictions about the survivability in the battlefield. The wired communication cannot support the moving units completely. If we ignore the importance of this restriction, there will be lack of information flow between units during a battle. The success in the battlefield needs a continuous communication in all phase of the operation. Thus, the need for survivability makes inevitable the mobile wireless communication systems. In a war, all of the army's tactical notions are imposed to find the way to destruct the enemy command and communications and the fire support units, firstly. If this can be accomplished, there will be chaos in enemy troops. Therefore these systems must be operated in a distributed manner. Destroying a centralized target is easier than destroying distributed targets. If the enemy destructs some of the distributed command and control units, remaining units may continue to communicate in the network

Second motivation for MANET is that the military cannot rely on a fixed, previously placed communication infrastructure in the battlefield area. In some cases, there cannot be available terrestrial communications infrastructure in the rough battlefield terrains like desert or jungle. It is possible that in a war, the enemy may destroy previously available communications infrastructure. So rapidly deployable, self-organizing mobile infrastructure is the basic factor in a continuous and reliable battlefield communication.

A third motivation is related with the propagation characteristic of the signals. Propagation with a frequency much higher than the 100 MHz needs a line of sight (LOS) [11]. In the battlefield, terrain, foliage and the artificial obstacles make a communication impossible with the constraint of LOS. Therefore, multi-hop (store and forward) packet routing must be used to exchange messages between the users who are not within LOS of each other.

Ad hoc networking is designed for the need of survivability and communication in the battlefield at every time and every condition. In the next part, the historical evaluation of ad hoc networking in the military area is explained.

3.1.2 Early Works on Ad Hoc Networks

In 1960s the U.S Department of Defense presented the first packet switching technology named as ARPANET (Advanced Research Project Agency Network). It provided very important advance in dynamical bandwidth sharing between multiple users. Besides, it brings a solution for adaptive routing in the changing network topology and dynamically changing user demands. In 1972, DARPA (Defense Advanced Research Project Agency) recognized the advantages of packet switching in a mobile wireless environment. DARPA initiated a research program to develop a Packet Radio Network (PRnet) in the same year. The PRnet was aimed to develop an efficient way of sharing a channel with regarding the effects of incomplete and changing connectivity in the network [21]. As the PRnet became more familiar, the main ideas of the project were applied in a number of environments such as airborne and terrestrial, narrowband and wideband, satellite, etc. All of these networks were based on the idea of packet switching by sharing a common channel. The DARPA PRnet program demonstrated packet switching as an efficient solution to bandwidth sharing by using store-and-forward routing for a reliable communication between computers. Initial PRnet protocols used a centralized control stations. But, PRnet idea was quickly adapted into a distributed architecture, which uses multihop store-and-forward routing techniques. Dynamical bandwidth sharing required a medium access protocol. The PRnet used a combination of the ALOHA and Carrier Sense Multiple Access (CSMA) approaches. Developments of the radio and controller hardware became possible with the use of CSMA. Development of the PRnet required sophisticated design and debugging tools. As an example, a method was needed to update the software in the network while the network was operating. PRnet program demonstrated the technologies to support mobile users for MANET. The previous combining experiences on the packet switching to radio software and hardware and network management algorithms made possible this technology.

As the PRnet was being developed, the need to tie various networks together was recognized. This was the origin of the Internet program in 1974 and the PRnet was the first network whose design was “Internet aware” [21].

The basic PRnet’s feasibility was proven at the beginning of 1980s, but several major issues remained unsolved. The initial versions of the radios and controllers were large in size, need much power to operate, and have limited processing ability. The network management algorithms were demonstrated on relatively small networks, but larger network support was needed. The robustness of the network needed to be enhanced against the electronic attacks. The DARPA initiated the Survivable Radio Networks (SURAN) program in 1983 as a solution to above limitations. The SURAN program had three goals [11]:

- Developing a small, inexpensive, power efficient radios to support more sophisticated radio protocols,
- Develop an algorithm to scale very big networks,
- Develop techniques for robust and survivable packet radio networks in case of electronic attacks,

After foundation of the Low-cost Packet Radio (LPR), advanced network management protocols were developed fast. The hierarchical approach that is based on the dynamic clustering was proposed to handle larger networks. When the work on packet radio networks becomes popular in the DARPA programs. It brings the idea to adapt these efforts to the needs for the military. The Army Research Office (ARO) provided research funding to university researchers.

The importance of MANET became clear. During 1980s there were a number of Army effort to exploit PRnet technology. DARPA and the Army partnered in a series of experiment.

3.1.2.1 Task Force XXI (TF XXI)

At the beginning of the 1990’s, the technological developments created new era on the information system and the data communication. The radio packet switching technologies and routers developed fast, notebook computers became popular, and significant increases occurred in the computational capabilities and memory storage of the computers. The U.S Army started new efforts to accomplish the integration of the Army’s 21st century technology into the growing digitized world. It is called as the Task Force XXI (TF XXI). Like the Army, U.S. Naval Research Laboratory developed different type of packet radio networks for the use of ships at sea. Same efforts were observed in the air force. Packet radio networks interest was not limited to United States. The Royal Signals and Radar Establishment of the United Kingdom developed a packet radio network based on a narrow-band combat net radio [22]. At later stages, packet switching techniques are widely accepted and evolved very fast.

3.1.2.2 Tactical Internet (TI)

Soon, the idea of Internet in the battlefield became very popular and inevitable Development of Tactical Multinet Gateway (TMG) made possible the use of standard Internet protocols for tactical area in 1993. Early Army development of the TI architecture focused on reducing the overhead associated with the commercial IP protocols to avoid network congestion, subnet addressing schemes, autonomous system boundaries, and routing [23]. DoD (Department of Defense) has mandated for using open commercial protocols as a basis, so military can get the benefits of fast developments in commercial networking. The TI uses Open Shortest Path First (OSPF) routing protocol. It uses periodic hello messages to find out its neighbors. It includes vehicular and man packed mobile, wireless and multihop packet radios running on modified commercial Internet protocols. The first field experience of the tactical Internet was held in the Task Force XXI (TF XXI) Advanced War Fighting Experiment (AWE) in March 1997. During AWE a brigade task force with 1800 Single Channel Ground and Airborne Radios (SINCGARS) and 380 Enhanced Position Location Reporting System (EPLRS) radios and with 850 Internet controllers installed more than 1200 tactical platforms to connect to national training center [23]. This field experience provided valuable feedback on the development of Tactical Internet. In Figure 3.1, structure of the tactical Internet is shown. The communication infrastructure is focused on achieving information transfer horizontally (from battalion to battalion, etc.) and vertically (from battalion to brigade, etc.) across the battlefield. This is achieved through the employment of commercial Internet technology (e.g., IP routers) and open standards protocols (e.g., TCP/IP). COTS IP-based routers (e.g., Tactical Multinet Gateways (TMGs) and Local Area Network (LAN) routers) and Internet Controllers (INCs)—which are single circuit card, militarized Internet-based routers—provide the ability to send messages between any segment of the tactical battlefield network.

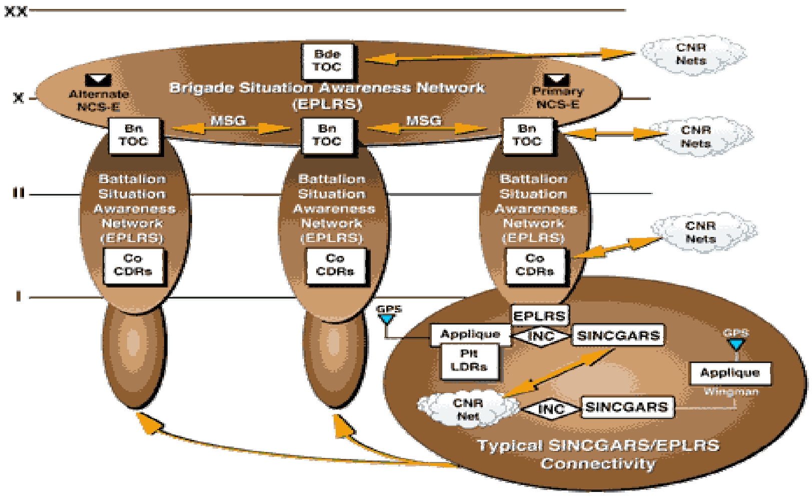

Figure 3.1 Tactical Internet structure

3.1.2.3 Global Mobile Information System(GloMo)

DARPA Global Mobile Information Systems (GloMo) is one of the main programs for integrating global information infrastructure into wireless medium in 1994 [44]. The goal of the GloMo program was "to make the mobile, wireless environment a first-class citizen in the defense information infrastructure by providing user friendly connectivity and access to services for wireless mobile users" [24, 25]. It aimed to provide office-environment, Ethernet type multimedia (voice, video, images, etc.) connectivity any time, anywhere, in handheld devices and also devices mounted on platforms moving in the air, water or land. The focus of the GloMo program is in the areas of mobile applications support, end-to-end networking, wireless networking, and wireless node design. Figure 3.2 resembles the GloMo initiatives that include self organizing, self healing networks, both flat and hierarchical multihop routing algorithms, ATM over wireless, geo-routing, satellite communication networks, heterogeneous networking with IP overlays, end-to-end network enhancements, security and survivability for ad-hoc networks.

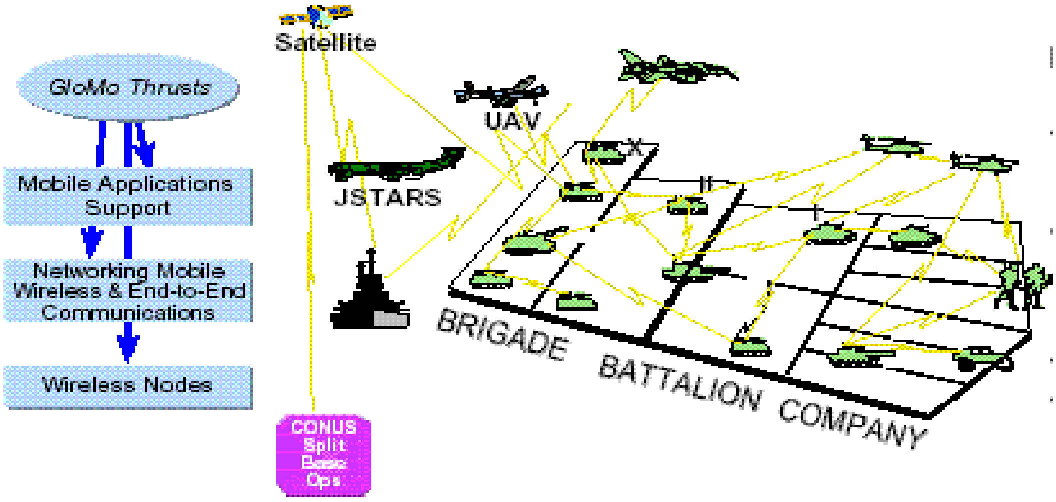

Figure 3.2 Global Mobile Information System Design

GloMo technology enables mobile users to automatically form ad hoc based voice, data, and multimedia information exchange in the network.

3.1.2.4 Near Term Digital Radio

Near Term Digital Radio Program (NTDR) is one of the programs in the TFXXI in May 1994 [26]. The NTDR is a networked data radio system as a communication backbone for the Army. It aims to provide communication for users from brigade level to platoons. It is a fully distributed, adaptive UHF packet radio network. It supports mobile operations. The NTDR system is intended to reduce the multihop delays and interference at the MAC layer while increasing the capacity of the network. As shown in Figure 3.3, NTDR is based on layered architecture: Media Layer, Internet Layer, and the Intranet Layer [26]. The Intranet Layer is based on two-level hierarchical architecture (with clusters and cluster heads). The Internet layer is based on peer NTDR communication. The NTDR cluster heads serve as an area router between clusters. When local topology changes routing information is updated in each cluster without informing to other clusters. This reduces the routing overhead. It is based on the open shortest path first (OSPF) routing protocol. NTDR operates in a frequency band of 225-450 MHz in discrete tuning steps of 625 kHz. The point-to-point information transfer rate is 375 Kbps. Network configuration is semi automatic. Each NTDR radio is supported with a network management terminal to generate network initialization set. After then, the NTDR autonomously provides network communication during mobile operations. It automatically updates routing tables and re-establish cluster heads in a distributed manner.

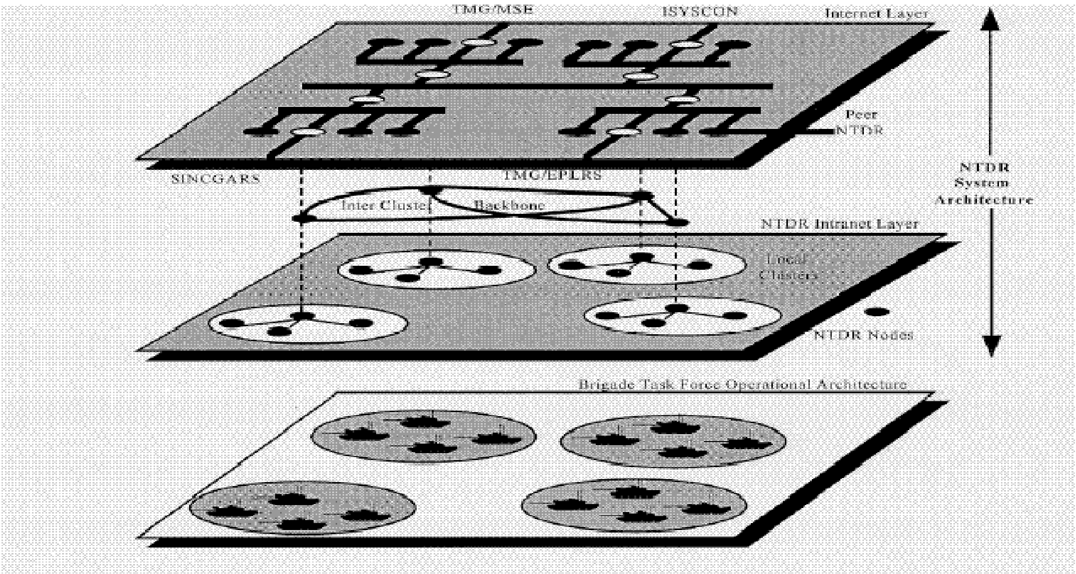

Figure 3.3 NTDR Architecture

The U.S Army's Task Force XXI (TF XXI) Advanced War fighting Experiment (AWE) in March 1997 may be the largest scale implementation (include thousands of nodes) of a mobile, wireless, multihop packet radio network [24]. Army Battle Command Systems (ABCS) host platforms were installed on Ethernet LANs connected through Tactical Multinet Gateway (TMG) IP routers at Brigade and Battalion Tactical Operations Center (TOCs). SDR (Surrogate Digital Radio) at each of the TOCS provided wireless Ethernet connectivity across the battlefield. The SDR operates in the 300 to 500 Mhz frequency band, uses TDMA protocol to provide a guaranteed network throughput of 180 kbps. The Surrogate Digital Radio (SDR) provided a reliable wide bandwidth network communication for ABCS during the TFXXI AWE [23]. Communications technologies for the Force XXI battlefield will integrate new technology into existing systems over time by time. The Army has proposed a COST based systems architecture and modernization strategy to fully integrate information systems and services in the battlefield.

3.1.3 Current Works on Ad Hoc Networks in Military

In the 21st century, computing and information technologies become highly dynamic. Capacity and the processing speed of the computer-based systems develop faster and faster day by day. The energy capabilities of batteries increased gradually over the last few decades. The new networks need to carry all forms of traffic such as video teleconferencing, electronic messaging, data using robust, internet worked data services. In these networks, many or all of the nodes may be moving in vehicles, tanks or helicopters. Network topology design is very dynamic and the links between mobiles appear and disappear in a matter of seconds. The future tactical information systems will enable the soldier to gather, integrate, and synchronize information in a timely manner, allowing rapid planning, acting and reacting capabilities in the battlefield. This new information system must be capable of gathering information from vertical and horizontal command and control systems, sensor systems, and many different weapon systems. In the future, battlefield will not be limited in a specific area. This brings communication requirement at farther distances. This makes the satellite based and self organized networks very critical. A military unit cannot transport their wire line communication equipments with them. Also it is not guaranteed that there will be a wireless infrastructure for use of their communication at everywhere. Besides, the current military communication networks cannot support the growing demand for information services on the battlefield [23]. These entire requirements lead to ad hoc networks in military and commercial areas. Many advanced armies have recognized the inevitability of the ad hoc based modernization strategies in communication system at the near future. Today many of advanced countries are interested in ad hoc networks to transfer variety of tactical communication traffic. In the following part of this chapter, some efforts in military communication developments and the projects in various countries will be introduced.

3.1.3.1 Future Combat System (FCS) Program

In the U.S, the DARPA and the Army initiated Future Combat System (FCS) Program to create next generation weapon and information systems at the end of 1990s. This is a joint DARPA and Army program that aims to develop future systems and technologies, which can achieve the Army's vision of "Objective Force" [27]. The Objective Force is U.S Army's force for the new millennium. It is organized, manned, equipped, and trained to be more strategically responsive, deployable, agile, versatile, lethal, survivable, and sustainable across the entire parts of military operations. FCS tactical formations enable the Objective Force to see first, understand first, act first, and finish decisively for tactical success. This force will be lighter and more mobile than before. The Army is planning to create an “Objective Force” by 2010. FCS is presented as a “networked system of systems”. As illustrated in Figure 3.4, it will include robotic reconnaissance vehicles and sensors, tactical mobile robots, mobile command, control and communications platforms, networked fires from further ground and air platforms, and advanced three-dimensional targeting systems. The goal of this program is to start and develop new and improved combat vehicle and information technologies to enable transformation of the Army to the Objective Force. The FCS will provide networked fires and maneuver in direct combat. It will perform intelligence, surveillance, and reconnaissance functions more rapidly and accurately in the battlefield. The direct and indirect fire supply of the friendly forces will be provided smartly. The Army’s goal is to equip the first unit with FCS by 2008 and reach to initial operational capability by the year 2010 [28].

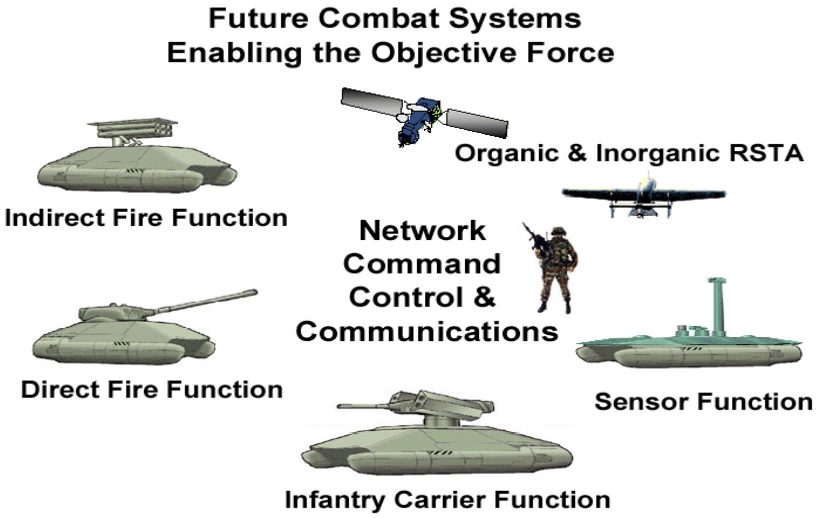

Figure 3.4 Future Combat Systems

DoD has selected 16 contractors to develop new technologies for communication part of the FCS. The FCS concept regards the need for high data-rate and mobile communications in order to support real time awareness, fire control and robotic missions. Its system must be robust against jamming and detecting by the enemy forces. DARPA plans to meet those opposing constraints by using mobile ad hoc network with directional antennas at low frequencies [28]. Transmitting large amount of data quickly while avoiding jamming and detection will require significant developments in transmitters, receivers, and directional antenna technology. TRW(Carson, California), one of the contractors in FCS, is developing a mobile, wideband, and millimeter-wave radio. The radio features are 100 Mbps rate, peer-to-peer communication, extreme anti-jam, low probability of intercept and detection. BBN (Cambridge, Mass.), another contractor, is developing a networking technology called Utilizing Directional Antennas for ad hoc networking (UDAAN). The UDAAN systems will develop network and MAC layer protocols to improve network performance in capacity, latency, robustness, and security.

3.1.3.2 Small Unit Operations Situation Awareness System

Joint Tactical Radio System (JTRS) is a series of communication development programs in the U.S Army. The Small Unit Operations Situation Awareness System Program (SUO SAS) is one of the programs included in JTRS. It started in 1996. It aims to provide situational awareness information and communications capabilities to soldiers in the battlefield. Especially, it brings a solution for the operations in rough terrain and forest areas that reduces communication capability. The SUO SAS has a jam-resistant characteristic. It has a self-forming capability. It has been exercised in October 2002, in a rescue operation scenario [28]. During the company-level operation, approximately 50 airborne, mounted and dismounted soldiers used SUO SAS equipment to provide situational awareness with reliable and secure communications. They maneuvered through heavy forests and open areas and then entered a building within a mock city to rescue the downed aircrew. As the rescuers came closer to the downed aircrew, the aircrew's SUO SAS radio automatically joined the rescue team's network, informing with the exact position of the aircrew. This system will become the main step for the future military communication technology when integrated with the other efforts in the development programs. Figure 3.5 introduces the main characteristic of the SUO SAS system in possible military applications.

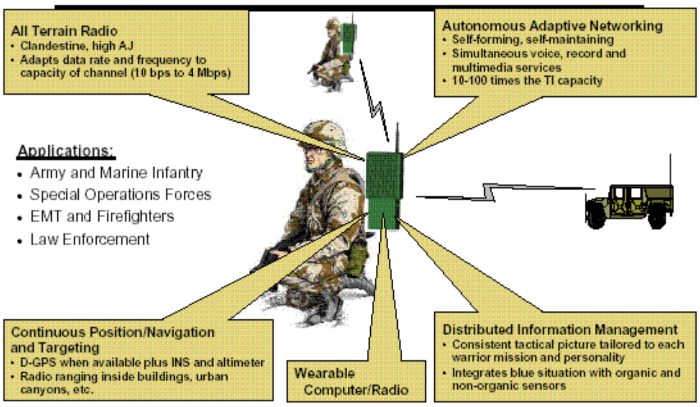

Figure 3.5 SUO SAS

3.1.3.3 Sensor Networks

Networked micro sensor technology will be one of the most important military information technologies in the future. There are two main goals for the use of wireless sensors. These are detecting the events and estimating the parameters of these events. All the obtained information needs to be transmitted outside of the network. Multiple smart sensors construct these networks. They can communicate over wireless medium, and they are not expensive. These networks have wide range of applications. They generate new capabilities for reconnaissance, surveillance, and many other tactical applications. Smart disposable micro sensors can be deployed in the battlefield. They may be located on the ground, on bodies of soldiers or vehicles. They may also be used under water. Their main mission is to detect and tracks threats, airplanes and all kinds of vehicles, personnel and chemical-biological agents, and target of weapon systems. A typical scenario may include a number of sensors spread over the enemy terrain. First step is detecting if a vehicle is present. The second step is categorizing this vehicle as a tank, a jeep or a carrier. The speed, direction, and the cargo of the vehicle are learned at the definition stage. Then, the third step includes the transmission of this information to control centers by using wireless or satellite communication. There are three conceptual layers in wireless sensor networks [29]. These are the cluster layer, sensor network layer, and wireless network layer. In the cluster layer, collaborative signal processing occurs and by informing the cluster heads, the data can reach to whole sensor network. And then over the wireless network, it arrives outside of the network. The main idea behind dividing sensor networks into clusters is to reduce the amount of power spent on long distance transmissions and decreasing probability of detection by the enemy.

3.1.3.3.1 SensIT

The research program about the Sensor Information Technology at DARPA is called as SensIT [28]. This program aims to create desired characteristics of networked sensor technology. These sensor networks consist of multiple sensor devices. These devices are capable of making embedded processing of information, storage, location, and positioning knowledge by using a GPS algorithms. The results of this processing are shared by the neighbors over the wireless medium. Battlefield is a highly dynamic environment. So these sensor devices should be ready for rapid deployment in an ad hoc fashion. Current networking techniques, especially developed for voice and data with dependence on fixed infrastructure, will not suffice in the future. This program will develop new networking techniques for highly dynamic ad hoc environment. As a result, the network of SensIT nodes will support detection, identification, and tracking of threats. They will be able to communicate both within and outside of the network.

3.1.3.3.2 Self-Healing Minefield

One of the projects as a part of SensIT is the networked minefield. Its name is the Self-Healing Minefield (SHM) program [28]. It is concluded recently by DARPA. It took 3-year effort to develop the key technologies for a mobile, intelligent, and networked anti-tank mine system. The program was planned in two-phases. The first phase took 2 years, which focused on the subsystem development and a small-scale integrated test. The second phase is focused on refinement of the technologies and scaling to a tactically significant field text. The Self-Healing Minefield is an antitank landmine system that does not rely on antipersonnel landmines. Contrary to the current mixed minefield systems, the

Self-Healing Minefield employs intelligent mobile antitank mines alone to defeat all enemy breaching. Instead of a static complex obstacle, the Self-Healing Minefield is an intelligent, dynamic obstacle that responds to an enemy-breaching attempt by physically reorganizing. The Self-Healing Minefield consists of surface dispersed antitank mines. These mines can detect an enemy attack of the minefield and respond autonomously. If the enemy destroys some of the mines, the rest of the network continues to exchange routing information. They can recognize the need of rearrangement of the minefield by detecting breaches. By using an algorithm some of the mines move to new locations. So the open breach in the minefield becomes connected to obstacle by this dynamic formation. The Self-Healing Minefield forces the enemy to attack the minefield more and more times. This delays the enemy assault and increases the need of fire supports compared to the current mixed system minefield. An ongoing modeling effort indicates that a self-healing minefield will provide greatly increased military effectiveness of the obstacle.

Self-Healing Minefield will be designed to [28]:

- Autonomously identify and respond to an enemy attack within 10 seconds of a breach attempt or vulnerability in the minefield.
- Resist multiple breach attempts.
- Be mobile in all environmental conditions and terrain where enemy tanks can operate.
- Rapidly assemble a scalable communication network and self-geo-locate in 5-15 minutes.
- Have a robust mine-to-mine communication resistant to enemy countermeasures.
- Have a Non-GPS based geo-location with 1-meter location accuracy.

The development of mine mobility, mine-to-mine communications, and minefield behaviors—integration of these technologies into small numbers of antitank landmine-sized prototypes—is the main focus of the program. Successful prototype systems will continue research and development. DARPA desires to implement this system in a battlefield at least with 50 mines.

Additionally, single component technologies necessary to assure a robust Self-Healing Minefield are under development.

The Massachusetts Institute of Technology's Lincoln Laboratory is working with Self-Healing Minefield (SHM) systems contractors to ensure radio communications reliability. The SHM uses radio links as the primary mode of communication between mines. Following network setup, each node transmits periodic signals to indicate its status to the rest of the network. The absence of expected transmissions from one or more mines is one of the main indicators used to identify and locate breach attempts. Remaining mines use their radio links to inform more distant mines of the breach attempt, and to coordinate the response. The SHM may also communicate with a remote controller via a reach-back option. Mine-to-mine radio links are short range. Their low transmit power, wide-beam antennas, and low antenna height, make them susceptible to jamming by an attacker. The SHM has a multi-layered response to jamming. If radio jamming is successful, the network can maintain connectivity at lower data rates via acoustic links. If acoustic links are jammed, the network enters the autonomous response mode, which will maintain minefield integrity for several more hours. However, minefield integrity during repeated breach attempts will be maintained longest if radio communications are available. The SHM radio network uses spread-spectrum communication techniques, with robust protocols and reconfigurable networks, to minimize jamming sensitivity. The threat model includes "smart-jamming" techniques such as frequency following, time following, and focused attacks on network control data. The threat model is used to evaluate the effectiveness of different measures that can be taken to improve network robustness. In Figure 3.6 there is a demonstration of Self Healing Minefield concept. At scene 2 minefield deployed, then at third scene all the nodes construct the network in a distributed manner. Enemy assault to minefield shown at scene 4, minefield detects the breaching and decides the way of reacting at scene 5. Scene 6 shows the movement in minefield, new network established at scene 7 and ready to stop the enemy at scene 8.

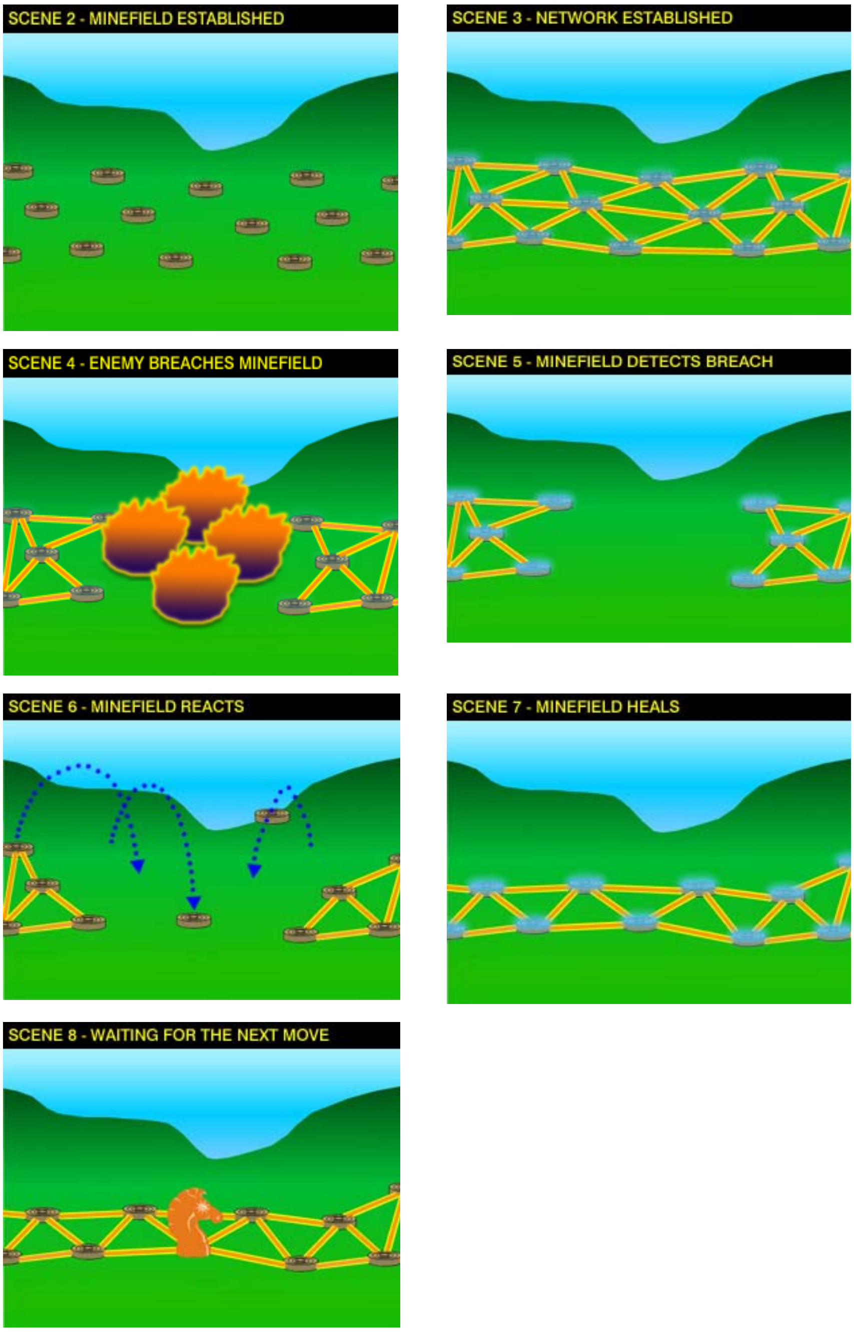

Figure 3.6 Self-Healing Minefield Demonstrations

3.1.3.4 Unmanned Air Vehicle

A great demand for the Unmanned Air Vehicle (UAV) is recognized during the literature survey. The main objective of the unmanned systems is to reduce the casualties in a war. The integration of UAV's with the sensor networks beyond the enemy terrain increases the data transmission capability in a reconnaissance operation. Also power consumption may be greatly reduced by the sensors to reach UAV instead of a control or radar center. There are some projects under development in DARPA to integrate UAV to sensor networks and other technologies.

3.1.3.5 Force Tracking in Ad Hoc Networks

Determining the exact location of the friendly troops on the battlefield is the most important and challenging issue for all commanders. A misidentification causes to be destroyed by the friendly fire. To prevent this, one of the recently developing solutions is tracking systems design. The blue-force tracking systems are developed for this needs in the battlefield. This system provides identification and location information of friendly forces [30]. System firstly sets its location information by using the GPS embedded characteristics, then this information can be exchanged during the communication. The Grenadler BRAT tracker unit is served for this purpose by the US Army [30]. Tracker systems can be the first example of using MANET network, during the Iraq War by the USA. [31]. Trackers are used to identify enemy and friendly forces. Force 21 Battle Command Brigade and Below computer network works as a battlefield Internet. The GPS navigation system warns whenever a vehicle leaves from the planned paths. Tank commanders can obtain the detailed information about an unknown vehicle by using this network. This network is tested, by bouncing data transmission from vehicle to vehicle until hitting the brigade command center. Also, this network provided a faster position update than the satellite-based communication. This exercise is the first use of MANET in a real battlefield. There is a development effort about tracker systems in Israel. A patrol level tracker is developed in Israel [30].

3.1.3.6 NATO and European Digitization Efforts

Digitization of the battlefield is introduced by the U.S Force XXI AWE in 1997. Many western countries understood the importance of digitized battlefield after this exercise. After then, huge cost of digitization and modernization programs began in the European Armies.

The United Kingdom is one of the main countries that looks for creating future soldier technology. Future Integrated Soldier Technology (FIST) [32] is the name of the project by the UK Ministry of Defense (MoD) to modernize their military forces by the year 2026. The subproject BOWMAN [33] is the communication part of the FIST. BOWMAN provides an easy to use, tactical, secure, voice and data communications systems for Britain's military services in support of land until at least 2026. BOWMAN will provide data messaging and a number of other capabilities in support of UK Digitization of the Battlefield (DBL). It will be used for the battle management system. It must be able to integrated into a more sophisticated digitized system in the future.

The BOWMAN has some stages. Digitization Stage 1(DS1) is focused at brigade headquarters level. In this stage, the main objective is to integrate existing infrastructure and a number of information systems applications into new digitized combat and battlefield management program until the year 2006. This program considers situational awareness, increased accuracy of the engaged weapon systems and providing the connected network data flow all the times in a battlefield. These requirements provide the commanders to see the whole picture of the battlefield in a real time.

The French Army has initiated a digitization program named as System Information Command Forces (SICF) [27]. It is the divisional command and control information system terminal for use of battalion and below levels.

The Swedish Defense is also trying to generate next century soldier technology. They ordered a pilot study of the next generation military radio systems from Sectra.

The Netherlands Army signed a contract with the Xantic. Project name is TITAAN (Theatre Independent Tactical Army and Air force Network) [27]. It aims to develop a flexible and integrated communication and information system.

German Army is trying to develop the program Infanterist der Zukunft (IDZ) [27]. IDZ aims to develop a future soldier technology with weapon and information systems. Thales Communication is the main contractor for communication and display technologies. They try to integrate a chest worn-computer. This new computer enables data and voice communication networking with the other 10 members of the platoon. Also it provides to communicate with higher headquarters. The personnel radio in this system has an embedded GPS. It uses both Bluetooth and hard-wired technology. The first versions of the IDZ elements are expected to be available in 2004 [27].

Many other countries have different soldier modernization programs to join the digitized battlefield generation efforts.

3.2 Digitization in Turkish Army

It is clear that the 21st century battlefield depends on the C4I (Command, Control, Communication Computer and the Information). The new advances in C4I will provide faster information gathering and reacting capabilities to Armies. The Turkish Army is fully aware of this reality. Army was influenced by the idea of digitized battlefield efforts all around the world. By the development of the Internet technologies, tactical Internet networks are established in Turkish Military Forces in 1990’s. The TAFICS (Turkish Air Force Integrated Communication System) was constructed as an information network for the brigade and above levels. The need of tactical area networking for the Army and below was obvious. The TASMUS (Tactical Area Communication Systems) project started as a solution for this purpose in 1996 [34]. The main contractor of the program was the national company Aselsan. There were other seven subcontractors for the program development. The first deliveries of the system to military units are completed recently. Its exercises on the battlefield have begun, and provide very useful feedback on the development phases of the system. The TASMUS will be the backbone of the Turkish Army tactical networking in the battlefield at the beginning of 21st century. It aims to provide an accurate information flow in the battlefield. Integration of the TASMUS with the TAFICS will provide actual data flow from the lowest to highest command levels in the Army. It uses mixture of both wireless and wired technologies. It has three sub-systems called as Wide Area Subsystem (WAS), Local Area Subsystem (LAN) and the Mobile Subsystem (MAT) [34]. WAS connects the TASMUS to TAFICS and PTT lines with wired technologies. It includes the System Entrance Points (SGN). All of the SGNs communicate with each other on a wireless medium. They can communicate directly or by hopping over the intermediate neighbors. All have the global path knowledge in the network through PTT, TAFICS or all other SGNs. In hierarchical order each SGN serves as an access point for some of defined LANs. Each LAN can communicate with its own SGN by using MAGN (Mobile Subscriber Entrance Point). Each LAN has one MAGN. All wireless and wired devices in a LAN are connected to MAGN. Every battalion and brigade headquarters will have a MAGN in the future. So, each of them will construct a LAN in a battlefield at the tactical command center. In the system all the voice, data, and image transfer provided by the LAN. Connections to the MAGN can be both wired and wireless devices. If the brigade or battalion commander is away from the command center, wireless MAT (Mobile Sub Terminal) provides communication with MAGN. It is carried over the jeep. MAT has an ad hoc capable device. If a MAT cannot reach the MAGN directly, it may use another MAT to reach the MAGN. MAT is a multiple hop routing capable device. This means that, each MAT can route a packet from one MAT to another until it hits the destination. Once the network established, every MAT has global knowledge of the network. And this knowledge is updated periodically. Brigade, battalion and company commanders use MAT to reach the MAGN in a mobile environment. At the below level, Personnel Radio Terminal (KIT) is used by the platoon leaders, squadron and company commanders. This device is also optionally routing capable. Its limited battery life creates disadvantage of routing capable usage. Both of MAT and KIT have power control abilities. Power control can be operated manually. MAT uses Aselsan RT-5101 radio terminal. KIT uses Aselsan RT-5114 radio terminal. Both of them can communicate each other. 5100 radio terminal uses TDMA technique. This radio family has electronic warfare capabilities. They use direct sequence spread spectrum to avoid from jamming by the enemy. Extending the propagation energy into a wide frequency band makes difficult to be recognized by the enemy. It is operated in a distributed manner. There is no need for a predefined infrastructure. All the nodes can form a network by using the control channels. At the beginning of the network initiation, one selected head radio can assign control channels to each node. Once the network is designed, all the slot reservations can be achieved in distributed manner. If a failure occurs in the network topology, all the nodes update their routing tables automatically. Every node has path knowledge to all other nodes in the whole network. An external GPS device can be connected to MAT. So the physical location information can be exchanged automatically between all the nodes in the network. Figure 3.7 shows the architecture of TASMUS. It has a hierarchical structure like a tree. Top of the system, SISKON (System Control) can control all the terminals in the network. This system will be the backbone for Army communications in the near future by integrating new developed technologies such as Artillery Fire

Control Computer (BAIKS 2000), digitized maps, sensor networks and many other applications in the battlefield.

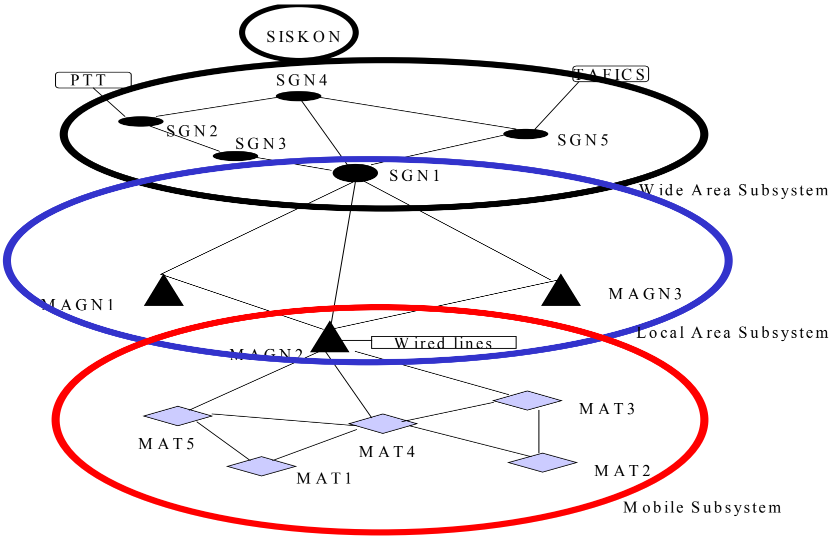

Figure 3.7 TASMUS structure

3.3 Military Application Scenarios for Ad Hoc Networks

All the inventions are initiated by the needs of people. Up to here the needs of future battlefield is stressed in a global manner. Many different research programs are introduced as a solution to these needs. In this part, some special ad hoc based military application scenarios will be presented.

3.3.1 Airborne Operation Scenario

In the first scenario the 10th corps is continuing to attack for the last three days. As seen in the Figure 3.8, it has not been able to get a successful penetration in the enemy terrain. The enemy forces are capable of refreshing their ammunition and forces easily. The Corps commander recognized the importance of the mountain, which controls the enemy supply roads. This mountain lies on the enemy terrain and far away from the friendly forces. He decided to make an airborne operation to control this area. This operation would cause enemy into lack of supply. 2nd Brigade took the airborne mission. Operation was successful and the troops reached the target. Brigade aimed to deploy the area as fast as possible. The need of communication for the command and information flow is obvious. But there is no infrastructure for the communication in that area. The Brigades signal units are mostly destroyed during the airborne phase. Brigade commander can contact with the Corps Command Center by using satellite radio. But there would not be any data transmission during the operation between brigade and below levels vertically or horizontally. This communication can be realized if ad hoc technology is available. Although some communication units were destroyed completely, the ad hoc capable devices can provide fast and easy network establishment in the area. Once the whole units are synchronized, continuous and reliable communication will be possible in a distributed manner. This network solves the communication problem without any need of a predefined infrastructure. So this technology is beneficial for the usage in enemy terrain operations.

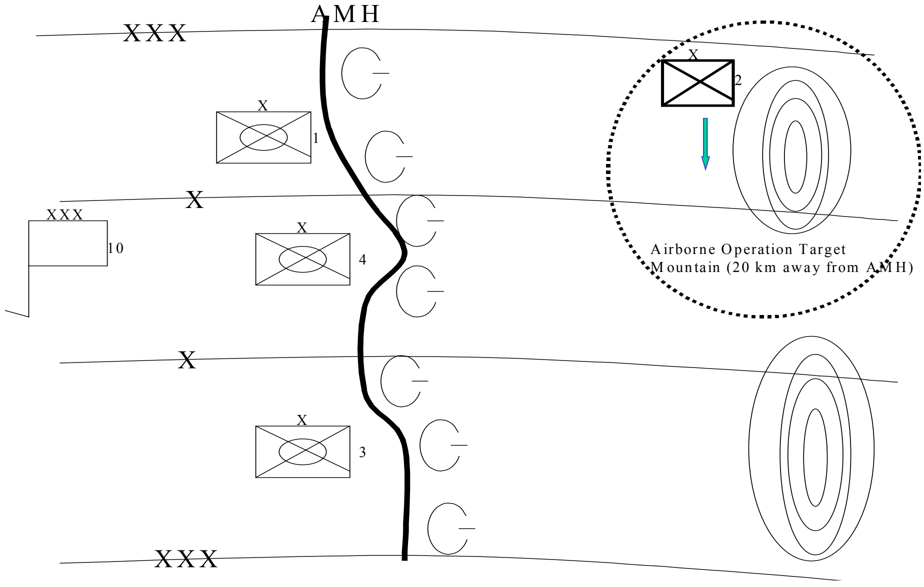

Figure 3.8 Airborne operations

3.3.2 Divergent Forces Scenario

4th tank and 1st and 2nd infantry companies are assaulting the enemy collaboratively. This is illustrated in Figure 3.9. The roads and the terrain forced them to approach the target from different ways. Operation continues during a dark night. The 4th tank commander suddenly recognized some forces coming through him beyond the target area. He is not sure whether they are enemy or friendly forces that belongs to 2nd infantry company. Before he tried to communicate, they became invisible beyond a hill. These troops should be identified before they move closer. But, they are not in LOS. And the communication infrastructure was destructed at the beginning of the battle. By using ad hoc capable devices they formed the information network on the terrain. Tank commander checked the digital map on his mobile information terminal. He knows, by using the tracking technology, exact location of all the friendly forces are displayed on that map. This information is provided periodically over the ad hoc radio communication. He is able to get the information about the units, which are not in its LOS. This is possible by using multiple hopping over some other units by ad hoc devices. This technology prevents the casualties by the friendly fire.

Ad Hoc networks reduces casualties by the friendly fires

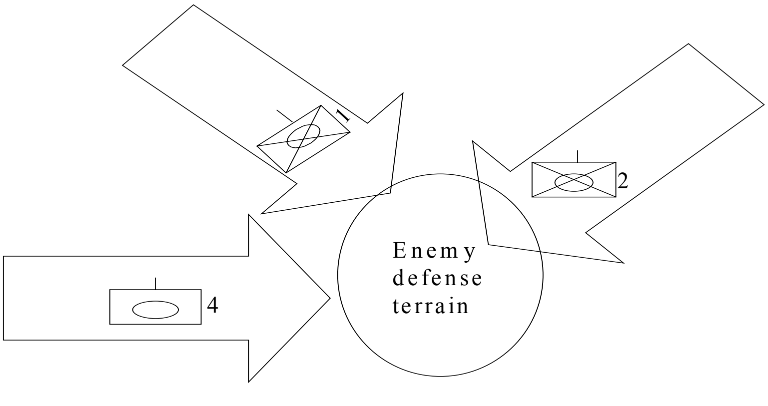

Figure 3.9 Divergent forces in an operation

3.3.3 Deep Valley Operation Scenario

The 5th infantry company takes the mission for a terrain search and captures operation against terrorists. They are informed that the terrorists are staying in a deep valley. This is a very rough terrain. In a deep valley the LOS connection is missed with all of the outside infrastructures. Also, highly bending curves of the valley reduces the LOS dependent communication between units in the same valley. This scenario is illustrated In Figure 3.10. The company commander assigned three squadrons in the valley and the 4th squadron over the edges of the valley. The 4th squadron's mission is to maintain LOS connection with other three squadrons. This usage provides a continuous communication between all units at every time by hopping over the 4th squadron. This can only be provided by ad hoc capable communication devices.

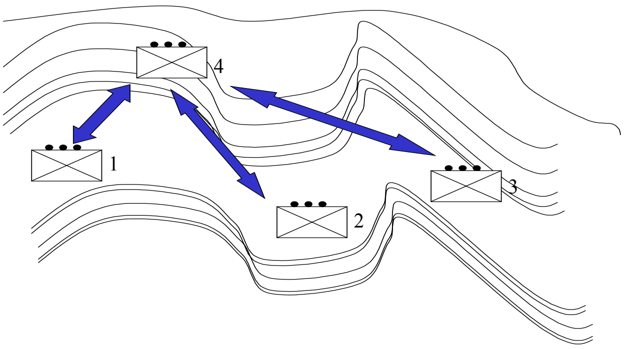
Operation in a deep valley requires multiple Hop routing

Figure 3.10 Deep valley operation

3.3.4 Low Transmit Power Scenario

Ad hoc networks may be operated with low power capable devices. This is a very important issue in a battlefield. Transmission with high power may cause easily detected by the enemy signal units. When the troops are not in contact with the enemy, battlefield picture is not clear for all commanders. If our forces aim to approach the enemy as much as possible before being recognized, communication could not be permitted unless a sudden contact occurred. By using ad hoc radios, it is possible to maintain communication all time. The risk of detection by the enemy will be reduced in case of using low power transmission. A tracking device may be integrated into the system. This ensures command center to see the locations of its troops on the area. Multiple hopping from device to device provides this information with low transmit power levels. Commanders use this information to correct the route of misrouted troops into correct path in the area.

3.3.5 UAV/Sensor Network Scenario

Commanders use multiple sensors to be aware of enemy movements as soon as possible. These sensors can be deployed by artillery, by airplanes or manually. Mostly they lie in the enemy zone. Sensor networks can gather information about enemy activities. If one or more of them is destructed by the enemy or other factors, rest of them can reestablish the network. They need to transfer obtained data to outside of the network. This requires high power to reach the destination at very large distances. This causes not only the detection by the enemy but also exhaust the battery life. UAV and sensor network collaboration for data transfer needs less power than the previous case. Figure 3.11 shows a sample collaboration scenario. In this model UAV can gather the stored data from sensor network. And then UAV may transfer this information to command control center. UAV and sensor network link establishment can be planned at defined times. At the other times, sensors are just gathering data from the terrain. They communicate just in the local network. This imposes power saving and reduces detection of probability by the enemy.

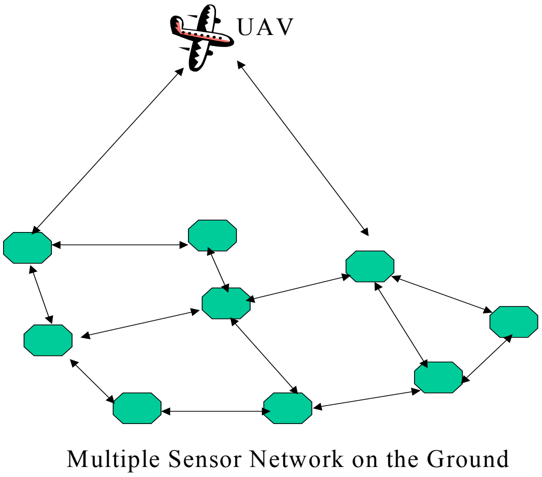

Figure 3.11 Multiple sensor network collaboration with UAV

Chapter 4

Joint Topology Design and Routing with Power Control

The main aim of this chapter is to design an optimal topology in a given network by using two different power control approaches. These are the common transmit power (COMPOW) and the adaptive transmit power (ADPOW) control approaches. Effects of both power control approaches in the topology design are investigated. Total power consumption, minimum end-to-end throughput, total throughput, number of established links are the performance metrics that are used for making a comparison between both power control approaches. Three different objective functions are considered during the topology design. These are maximizing the number of links, using the shortest path routing strategy and balancing the load over the links. The numerical results and the comments on the comparison of these models are presented in the fourth section of this chapter. In the next section, the idea and the framework of this thesis will be introduced. Description of the model is introduced in the second section, and mathematical modeling is given in the third section of the chapter.

4.1 Motivation

Topology of a network consists of the wireless link establishments between distributed mobile nodes. Topology design is making the decision about which communication links should be established and how the routing mechanism should behave. Topology design strategy has a significant effect on the capacity, power consumption and the delay of the network. A desired topology design may provide the highest network capacity with minimum power consumption. Since ad hoc networks consist of mobile nodes, less power consumption increases the lifetime of batteries. Also, convenient topology design reduces the interference effects and collisions during the transmission. This reduction decreases the delay by reducing the retransmission efforts. Topology design reduces complexity by operating connections in a simpler fashion.

Designing the topology by using COMPOW and ADPOW in order to make a comparison between them is the main goal of this thesis. Comparison metrics are end-to-end throughput, total throughput, power consumption and the number of established links. Topology design is regarded as an optimization problem. Topology is designed in a centralized manner. Regarding the signal-to-interference noise ratio that is greater than a threshold value provides a reliable communication. Time Division Multiple Access (TDMA) is used as a MAC scheme. This guarantees the collision free transmissions. TDMA structure is given in Figure 4.1. Each time period consists of frames with N slots. Each time slot is assigned for one or more communication links depending on the interference constraint.

Three objective functions are used to design the topology with each power control approach. First objective is maximizing the number of established links within a frame. By increasing the number of established links, we expect to increase the throughput. Using the shortest path routing strategy for topology design is the second objective. By using this routing strategy, we expect to reduce the unnecessary link establishments and decrease the unnecessary loads on the links. And balancing the load over each established link in the network is the third objective. We expect to maximize the minimum end-to-end throughput by minimizing the carried traffic on the most congested link. Network connectivity must be satisfied by the designed topology in all models.

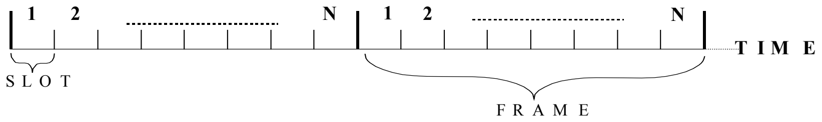

Figure 4.1 TDMA structure

Comparing the effects of different power control approaches for the ad hoc network topology design by using the same simulation environment is the main motivation of this thesis. As mentioned in Chapter 2, there are some studies about the ad hoc network topology design with power control in the literature. But, there is not any study that compares the performances of different power control approaches in the same simulation environment. Comparing the performances of these power control approaches with different objectives of the desired topology is another motivation behind of this study.

4.2 Model Description

In this work, we consider a square area where the stations are randomly distributed. Mobility is not considered. All the nodes are considered with fix locations. Time Division Multiple Access (TDMA) is used for medium access control. All frames contain N time slots. The existence of a reliable communication between any two nodes in a specified time slot is called as a link between those nodes. A link is established in a time slot by considering interference and other constraints.

Capacity of each established link is considered as 1 unit capacity. All the sender-receiver pairs that are using an established link share this capacity for their own communication.

In this thesis, topology design is implemented in a centralized manner. A synchronized network model is considered. All nodes have the global location knowledge of all other nodes. The constructed topology is desired to be a connected topology. This means that there must be at least one feasible path from one node to all other nodes in the network within each frame. This guarantees the existence of data transmission between all nodes in the topology. Feasible path implies a source destination pair connection by using some established links, which follows each other in an increasing slot assignment order. Figure 4.2 shows a connected network topology. At this topology, every node can reach all other nodes within a frame. The number over the dashed line indicates the slot number. Number 4, over the dashed line between nodes 2 and 4, implies that there will be a communication between source node 2 and destination node 4 at slot 4. Here, the feasible path from node 2 to node 1 (source destination pair (2-1)) follows the route node2-node4-node1 within slots 4, 6 respectively. The route, following node2-node4-node5-node1 within slots 4, 5 and 1 respectively, is not a feasible path for the same source destination pair (2-1), since the slot assignments do not provide an increasing order.

Each node can make either transmission or reception in a time slot, but not both.

Each node can receive from only one node in a time slot. Also each node transmits to only one other node in a time slot.

Different power levels and frame lengths are used for both COMPOW and ADPOW control approaches. In the ADPOW control technique, usable power levels are quantized into Q levels. The total power consumption is minimized for the ADPOW as a secondary objective.

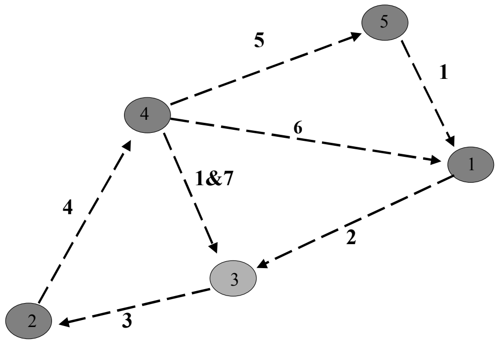

Figure 4.2 Connected topology design example

Links are regarded as directed. This means that a link between any two nodes is established by specifically defining the source and destination nodes.

We use a free space propagation model. The path loss is given by (4.1) where G_{ij} represents the gain between sender node i and receiver node j, where α corresponds to the path loss exponent. Gain between all nodes is used to calculate the received signal strength at a communication link. In this thesis, we use $\alpha = 2$ which corresponds to the free-space propagation.

$$G_{ij} = \frac{1}{\left|x_i - x_j\right|^{\alpha}} \tag{4.1}$$

Nodes that are simultaneously transmitting cause interference. We provide reliable communication between node pairs by considering the effect of interference. We use (4.2) to calculate the signal-to-interference noise ratio (SINR) [1]. For a reliable communication SINR must be greater than or at least equal to a threshold value. In our model, threshold is regarded as β =4 or 6 dB. If the SINR is greater than or equal β, we assume that reliable communication is provided.

$$\frac{P_{ij} * G_{ij}}{N_0 + \sum_{k \neq j} P_{kj} * G_{kj}} >= \beta \tag{4.2}$$

$Where\ N_0\ \ is\ \ thermal\ noise$

$\beta\ \ is\ \ threshold$

$P_{ij}\ \ is\ \ transmit\ \ power\ \ from\ \ i\ to\ j$

In the next part, the mathematical formulations are presented to implement these requirements into an ILP model.

4.3 Mathematical Modeling of The Problem

In this section, the mathematical model, which is used to describe the joint topology design with routing and power control problem, is presented. In mathematical modeling, all the topology requirements are expressed as constraints. All constraints and the objective function are formulated in mathematical expressions

Firstly we state notions used in the problem:

W = {1,2,3,4,…….,W}	set of time slots
N ={1,2,3,4,5,6,……,N}	set of nodes
P ={(1; 2), (1; 3)…(1;N)…(N; N-1)}	set of all possible source-destination pairs
N_0	thermal noise
β	threshold value for reliable communication
P_c	common power level for COMPOW
Q	number of power levels for ADPOW

We define some decision variables to formulate the problem. The variables in this work are:

$k(i, j, w)$: This is a binary variable, which indicates the link establishment. If there is a link between source nodes i and destination j at slot w, it takes value 1 otherwise takes value 0.

$u(i, m, j, w)$: This is a binary auxiliary variable to define the reachability for node j. If node j is reachable from node i by using intermediate node m at slot w, it takes value 1 otherwise 0.

$a(i, j, w)$: This is a binary variable that indicates the reachability to node j from node i at slot w. If reachable, it is 1 otherwise 0.

4.3.1 Primary Constraints for Link Maximization

In the next step, the mathematical equations are generated to formulate the relations between defined variables.

4.3.1.1 Primary Constraints for Link Maximization with COMPOW

This model is used to design the topology with common power approach. In this model, the objective is to maximize the number of established links in a frame. Equation (4.3) gives the objective function of link maximization with common power approach.

$$Max \quad \sum_{i,j,w} k(i, j, w) \quad \forall i, j, w \tag{4.3}$$

Equation (4.4) guarantees that reliable communication by considering the interference. This equation says that for a reliable communication the received signal strength between any source-destination (s-d) pair must be at least β times greater than the overall summation of thermal noise and the interferences by the other simultaneously transmitting nodes. M Is a very big scalar.

$$N_0 + P_c * (\sum_{i,j} G_{id} * k(i,j,w) - G_{sd} * k(s,d,w)) \le P_c * G_{sd} / \beta + M * (1 - k(s,d,w)) \ \forall s,d,w \quad (4.4)$$

Equation (4.5) states that each node cannot transmit and receive in the same time slot, and it can communicate with at most one node in each time slot.

$$\sum_j k(i,j,w) + k(j,i,w) \le 1 \quad \forall i \ne j \in N, \quad \forall w \in W \qquad (4.5)$$

Equation (4.6) states that if node m is reachable from node i in (w-1) slot and there exists a link between m and j at slot w, then the destination node j is reachable from node i in w slots by using the intermediate node m.

$$u(i,m,j,w) \ge a(i,m,w-1) + k(m,j,w) - 1 \quad \forall i,j,m,w \qquad (4.6)$$

Equation (4.7) implies that if destination j is reachable from source i by using intermediate node m in w slots, then node m is reachable from node i in (w-1) slot.

$$u(i,m,j,w) \le a(i,m,w-1) \quad \forall i,m,j,w \qquad (4.7)$$

Equation (4.8) states that if there is no established link between nodes m and j at slot w, then node j is not reachable from source node i by using node m. If node j is reachable from source node i by using node m in w^{th} slot then there should be an established link between the nodes m and j at slot w.

$$u(i,m,j,w) \le k(m,j,w) \quad \forall i,m,j,w \tag{4.8}$$

Equation (4.9) states that if node j is not reachable from node i then there exists intermediate node m which provides reachability between nodes i and j. In other words, if j is reachable from node i for any intermediate node m in w^{th} slot, we can say that j is reachable from node i in w slots.

$$a(i,j,w) \ge u(i,m,j,w) \quad \forall i,m,j,w \tag{4.9}$$

Equation (4.10) implies that if node j is reachable from node i by using any intermediate node m in w slots, then node j is reachable from node i in w slots.

$$a(i,j,w) \le \sum_m u(i,m,j,w) \quad \forall i \ne j,w \tag{4.10}$$

Equation (4.11) states that at slot 0 no node is reachable from any other node in the network. This is called as the initial condition.

$$a(i,j,w) = 0 \quad \forall i \ne j \ and \ w = 0 \tag{4.11}$$

Equation (4.12) implies that all nodes must reach all other nodes in the network within a frame. This is called as the final condition, and provides the full connectivity. W Represents the last slot in the frame.

$$a(i,j,w) = 1 \quad \forall i \ne j \ and \ w = W \tag{4.12}$$

Equation (4.13) says that every node is always connected to itself.

$$a(i,i,w) = 1 \quad \forall i,w \tag{4.13}$$

4.3.1.2 Primary Constraints for Link Maximization with ADPOW

The same model is modified to run in ADPOW control approach. The modifications of constraints on the previous model are explained below.

In this model $P(t)$ is the transmit power level. In this work, we offer Q different power levels for use of each node. Each node selects one of the power levels to establish a link by considering optimization of the model.

For ADPOW model, a new binary variable $k(i,j,w,t)$ is defined instead of binary variable $k(i,j,w)$. It also indicates the link establishment. If there is a link with power $P(t)$ between the source node i and destination node j at slot w, it takes value 1, otherwise 0.

The objective function of this model is given in (4.14). This objective mainly increases the number of established links in a frame. Furthermore, total power consumption is also minimized as a secondary objective. Here γ is a very small scalar in order to guarantee that maximization of links has the higher priority.

$$Max \quad \sum_{i,j,w,t} k(i,j,w,t) - \gamma * \sum_{i,j,w,t} k(i,j,w,t) * p(t) \quad \forall i,j,w,t \tag{4.14}$$

Equation (4.15) is the modified version of (4.4) by considering ADPOW approach.

$$N_0 + \left(\sum_{i,j,t} G_{id} * P(t) * k_{ijwt} - \sum_{t} G_{sd} * p(t) * k_{ijwt}\right)\right) \leq \left(P(t) * G_{sd} * \sum_{t} k_{sdwt}\right) / \beta + M * \left(1 - \sum_{t} k_{sdwt}\right) \forall s,d,w \tag{4.15}$$

Equation (4.16) replaces (4.5) by considering ADPOW approach. This equation states that each link may either transmit or receive in the same slot. It also guarantees that each node establishes a link with only one of its neighbors in the same time slot. Main difference of this equation from (4.5) is the transmit power level can be selected.

$$\sum_{j,t} k(i,j,w,t) + k(j,i,w,t) \le 1 \quad \forall i \ne j \in N, \quad \forall w \in W \tag{4.16}$$

Equation (4.17) is the ADPOW version of (4.6). It states that if node m is reachable from node i in $(w-1)^{th}$ slot and there exists a link between m and j at slot w by using one of the power levels, then the destination node j is reachable from source node i in w^{th} slot by using the intermediate node m.

$$u(i,m,j,w) \ge a(i,m,w-1) + \sum_{t} k(m,j,w,t) - 1 \quad \forall i,j,m,w \tag{4.17}$$

Equation (4.18) replaces (4.8) in the ADPOW approach. It guarantees that if there is no established link between nodes m and j by using all offered power levels, and then node j is not reachable from source node i by using node m. If node j is reachable from source node i by using node m in w^{th} slot with at least one of the offered power levels, this provides that there is an established link between the nodes m and j at slot w.

$$u(i,m,j,w) \le \sum_{t} k(m,j,w) \quad \forall i,m,j,w \tag{4.18}$$

4.3.2 Shortest Path and Load Balancing Models

The main objective of the above formulation is maximizing the number of links. We update this model by defining two new objective functions to obtain better throughput results. These are the shortest path and the load balancing. Below, the new designed model variables and constraints are explained.

4.3.2.1 Primary Constraints for Shortest Path Model

For this new model some new variables are defined:

$x(p,i,j,w)$: This is a binary variable indicating which source destination pair uses an established link between nodes i and j at slot w. If this link is used by the p^{th} s-d pair, it takes value 1 otherwise 0.

$u(p,m,j,w)$: This is a binary auxiliary variable defining the reachability to a node j. If node j is reachable for p^{th} s-d pair by using intermediate node m at slot w, it takes value 1 else 0.

$a(p,j,w)$: This is a binary variable indicating the reachability to node j for p^{th} s-d pair at slot w. If reachable, it takes value 1 otherwise 0.

The objective function and the constraints for this formulation are given below.

The objective function of the shortest path routing model in common power model is given in (4.19). This objective aims to minimize the number of total link usage by regarding the other desired characteristic property of the topology. The numerical results are presented in the next part of the chapter.

$$Min \sum_{p,i,j,w} x(p,i,j,w) \tag{4.19}$$

The objective function of the shortest path routing model in ADPOW model is given in (4.20). This objective aims to minimize the number of total link usage as a main objective. Minimizing the total power consumption is regarded as a secondary objective by considering other desired characteristic properties of the topology. The numerical results are presented in the next part of the chapter.

$$Min \left(\sum_{p,i,j,w} x(p,i,j,w) + \gamma * \sum_{i,j,w,t} p(t) * k(i,j,w,t) \right. \tag{4.20}$$

Equation (4.21) is the same as (4.4).

$$N_0 + P_c * (\sum_{i,j} G_{id} * k_{ijw} - G_{sd} * k_{sdw}) \le P_c * G_{sd} / \beta + M * (1 - k_{sdw}) \ \forall s,d,w \quad (4.21)$$

Equation (4.22) is the same as (4.5).

$$\sum_{j} k(i,j,w) + k(j,i,w) \le 1 \quad \forall i \ne j \ , w \qquad (4.22)$$

Equation (4.23) states that if node m is reachable for any p^{th} s-d pair, in $(w-1)^{th}$ slot and the link between nodes m and j at slot w is used by p^{th} s-d pair, then the destination node j is reachable for p^{th} s-d pair in w slots by using the intermediate node m.

$$u(p,m,j,w) \ge a(p,m,w-1) + x(p,m,j,w) - 1 \forall p,m,j \ne source\ of\ p, w \ne 0 \quad (4.23)$$

Equation (4.24) states that if node j is reachable for p^{th} s-d pair in w slots by using the intermediate node m, then that node m is reachable for p^{th} s-d pair in $(w-1)^{th}$ slot. In the reverse case, if node m is not reachable for any p^{th} s-d pair in w-1 slot, then node j is not reachable for p^{th} s-d pair in w slots by using the intermediate node m.

$$u(p,m,j,w) \le a(p,m,w-1) \ \forall p,m,j \ne source\, p, w \qquad (4.24)$$

Equation (4.25) is complementary to (4.23). This equation implies that if node j is reachable for p^{th} s-d pair in w slots by using the intermediate node, then link between nodes m and j at slot w is used for p^{th} s-d pair. In the reverse case, if the link between nodes m and j at slot w is not used for p^{th} s-d pair, then node j is not reachable for p^{th} s-d pair in w slots by using the intermediate node m.

$$u(p,m,j,w) \leq x(p,m,j,w)\ \forall p,m,j \neq source\, p,w \qquad (4.25)$$

Equation (4.26) states that each node is not reachable to any other node at slot 0 except itself.

$$a(p,j,w) = 0 \quad \forall\, p,j \neq source\, p,w = 0 \qquad (4.26)$$

Equation (4.27) implies that each node is reachable to itself in all time slots.

$$a(p,i,w) = 1 \quad \forall\, p,i = source\, p,w \qquad (4.27)$$

Equation (4.28) states that if node j is reachable for p^{th} s-d pair in w slots by using the intermediate node m, then node j is reachable for p^{th} s-d pair.

$$a(p,j,w) \geq u(p,m,j,w) \forall\, p,m,j \neq source\, p,w \qquad (4.28)$$

Equation (4.29) implies that if node j is reachable for p^{th} s-d pair in w slots by using any one of intermediate node m, then node j is reachable for p^{th} s-d pair in w slots.

$$a(p,j,w) \leq \sum_{m} u(p,m,j,w) \forall\, p,j \neq source\, p,w \qquad (4.29)$$

Equation (4.30) states that if there is a link between nodes i and j at slot w, and then this link will be used by at least one of the p^{th} s-d pair.

$$k(i,j,w) \leq \sum_{p} x(p,i,j,w) \forall\, i,j,w \qquad (4.30)$$

Equation (4.31) guarantees that each node is always connected to itself.

$$x(p,i,i,w) = 1 \forall\, p,i,w \neq 0 \qquad (4.31)$$

Equation (4.32) states that each node is always reachable to itself.

$$a(p, j, w) = 1 \, \forall p, j = destination\ p, w = W \tag{4.32}$$

4.3.2.2 Primary Constraints for Load Balancing Model

At the third step, balancing the traffic on each link is expected to be useful for increasing the end-to-end throughput. For investigating the effect of load balancing, new constraint and objective functions are generated.
Firstly, a new integer variable Max_Flow is defined to denote the traffic flow on each link in the network.

Equation (4.33) is the objective function of the load-balancing model with the common power approach. This objective minimizes the load on the maximum loaded link as a main objective. Furthermore, reducing the unnecessary usage of links is aimed as a second objective.

$$Min\ (Max\_Flow + \gamma * \sum_{p,i,j,w} x(p,i,j,w) \tag{4.33}$$

Equation (4.34) is used for ADPOW control approach in load balancing. In this objective function, minimizing the total transmission power consumption is aimed as a secondary objective. Main objective is to minimize the total load over the most congested link.

$$Min\ (Max\_Flow + \gamma * \sum_{p,i,j,w} x(p,i,j,w) + \gamma * \sum_{i,j,w,t} p(t) * k(i,j,w,t) \tag{4.34}$$

All the primary constraints for shortest path model are also used for the load-balancing model. An additional constraint is generated in (4.35) to define the most loaded link in the network. By minimizing Max_Flow, we may increase the minimum end-to-end throughput.

$$\sum_{p} x(p,i,j,w) \leq Max\_Flow \, \forall \, i \neq j, w \tag{4.35}$$

Next, we introduce additional redundant constraints that are not necessary, but used to obtain faster solutions by limiting the feasibility set. They are called redundant constraints.

4.3.2.3 Routing Constraints for Shortest Path and Load Balancing Models

First type of the redundant constraints is called routing constraints.
Equation (4.36) states that, there must be at least one link that reaches to the destination of a p^{th} source-destination pair.

$$\sum_{i,w} x(p,i,j,w) \geq 1 \;\; \forall \, p, j = destination, j \neq i$$

(4.36)
Equation (4.37) implies that, there must be at least one link leaving from the source of p^{th} source-destination pair.

$$\sum_{j,w} x(p,i,j,w) \geq 1 \;\; \forall \, p, i = source, i \neq j \tag{4.37}$$

Equation (4.38) implies that, no link out of the destination of p^{th} source-destination pair can be used to carry flow for p^{th} source-destination pair.

$$\sum_{j,w} x(p,i,j,w) = 0 \; \forall \, p, i = destination \;\; of \;\; p \;, i \neq j \tag{4.38}$$

Equation (4.39) guarantees that if the destination of a link is the source of p^{th} source-destination pair, it cannot carry flow for p^{th} source-destination pair.

$$\sum_{i,w} x(p,i,j,w) = 0 \;\forall\, p, j = source\ of\ \ p, i \neq j \tag{4.39}$$

Equation (4.40) states that if the destination node j of a link at the last slot W is not equal to the destination of p^{th} source-destination pair, this link cannot be used to carry flow for p^{th} source-destination pair.

$$\sum_{j \neq Dest of\ p.} x(p,i,j,w) = 0 \;\; \forall\, p, i \neq j, w = W \tag{4.40}$$

Equation (4.41) provides not to use the same link more than once for the same source destination pair in a frame.

$$\sum_{w} x(p,i,j,w) \leq 1 \;\; \forall\, p, i \neq j, j \neq i \tag{4.41}$$

4.3.2.4 Cut-set Constraints for Load Balancing Model

Second class of additional constraints is obtained by dividing the network into two sets. These sets are complementary to each other. These network division constraints are called as Cut Set Constraints. Equation (4.42) states that traffic flow from all elements of each set to other set must be greater than or equal to multiplication of the number of nodes in two sets. V is the set of nodes in the network. s_p And d_p denote the source and destination nodes for p, respectively. Figure 4.3 shows a sample division. Set S has 2 elements, and set

(V-S) has 3 elements. This means that there must be at least 6 traffic flows from set S to set (V-S).

$$\sum_{\substack{p:s_p\in S\\ d_p\in S}}\ \sum_{w}\ \sum_{\substack{i\in S\\ j\in(V-S)}} x(p,i,j,w) \ge |S|*|V-S| \qquad (4.42)$$

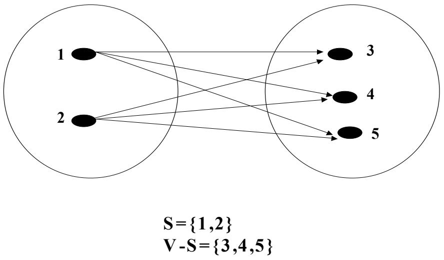

Figure 4.3 Cut Set of The Network

4.3.3.5 Routing Redundant Binding Constraints for Load Balancing Model

Third type of the additional constraints is the routing redundant binding constraints. These constraints aim to increase the relationship of variables with each other. These constraints are used only for the load balancing model to improve the solution time and results.

Equation (4.43) implies that if a link between node i and node j is established and used by the p^{th} source destination pair at slot z before last slot w, then node j is reachable in a frame.

$$a(p,j,w) \le \sum_{i,z}^{w} x(p,i,j,z)\ \forall p, j \ne source\, of\ p, w \ne 0 \qquad (4.43)$$

Equation (4.44) implies that if a link between nodes i and j is not used for p^{th} source destination pair in any slot $z \le w$ then node j is not reachable in a frame by using node i.

$$u(p,i,j,w) \le \sum_{z=1}^{w} x(p,i,j,z) \; \forall p, i \ne j, j \ne i, w \ne 0 \tag{4.44}$$

Equation (4.45) implies that the smallest time slot, which provides the reachability to node j must be used to established link between nodes i and j for p^{th} source destination pair.

$$u(p,i,j,w+1) - u(p,i,j,w) \le x(p,i,j,w+1) \, \forall \, p, i \ne j, j \ne i, w \ne W \tag{4.45}$$

4.4 Model Parameters and Numerical Results

Integer Linear Programming (ILP) models given above were solved by Cplex optimization software. Two different power control approaches are tried with three objective functions. Maximizing the number of links, shortest path routing, and minimizing the traffic on the most congested links are the objectives of the models. Transmit power level and the frame lengths are the parameters in each model. End-to-end throughput, total throughput, established number of links, and total power consumption are the performance metrics. In the following part, the parameters used in each model are introduced. At the last part of this section, performance comparisons between all implemented models are presented.

4.4.1 Model Parameters

All the models are implemented for a network that has 5 nodes, which are distributed on a square area, as shown in Figure 4.4. The distances between all nodes are presented in Table 4.1 These distances are used in (4.1) in order to calculate the gain between nodes. We obtain the optimal solutions for link maximization and shortest path model, but the load-balancing model takes too long time to reach an optimal solution. Sub-optimal solutions obtained within a runtime limit of 20 hours are given for this model. We investigated different combinations of constraints to find the best solution in a shortest time period. Table 4.2 shows the solution times and the minimized maximum traffic loads on the most congested link for load balancing model with different constraint combinations. Different combinations of constraints give different throughput results. The maximum end-to-end throughput obtained result is 0.250. As shown in table, this result is obtained in five different constraint cases. But, the best result obtained within the shortest time is given with the combination of primary, routing and routing redundant binding constraints. All the implementations of load balancing model are achieved by using this set of constraints.

Basically, three different models are generated according to objective functions. These are the maximum link model, shortest path model, and the load-balancing model. Also, each model is implemented with common power and adaptive power approaches.

Transmit power level is one of the parameters. We use four different common transmit power levels for all three models with COMPOW approach. These are 4mW, 6mW, 10mW, and 14mW respectively. The 4mW common power level is a critical level, since it is the minimum required power for providing the connectivity of the network. The common power level 14mW makes each node reachable from all other nodes in one hop.

Four different power level sets are used for the maximum link model and shortest path model with ADPOW. These are the {1mW, 4mW and 6mW}, {2mW, 4mW and 6mW}, {4mW, 6mW and 10mW}, {2mW, 3mW and 4mW} power level sets, respectively. In the load-balancing model with ADPOW, we obtained solutions for only {2mW, 3mW and 4mW} power level set.

Frame length is the second parameter used in all three models. For all the three models with common power approach, three different frame lengths are implemented. These are the 8-slot, 10-slot and 14-slot frame lengths. For models with ADPOW approach, 6-slot frame length is also tried in addition to the frame lengths used in models with COMPOW.

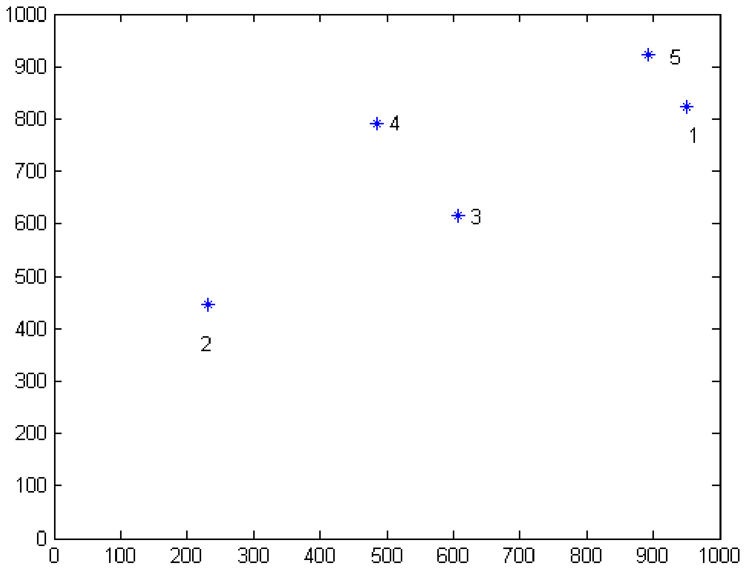

Figure 4.4 Network model of thesis

Nodes	**1**	**2**	**3**	**4**	**5**
1	0	811.8	401	466	116.1
2	811.1	0	412.1	430	814.3
3	401	412.1	0	213.6	418.2
4	466	430	213.6	0	426.3
5	116.1	814.3	418.2	426.3	0

Table 4.1 Distances between nodes (meter)

Constraint CASE	Solution Time	Best Integer	Best Node
PRIMARY	Initial	0.2207	
	9180 sec	6.0340	1.0264
	20000 sec	5.0380	1.0264
	36548 sec	5.0340	1.0264
PRIMARY ROUTING	Initial	0.2260	
	3600 sec	4.0320	1.0300
	4500 sec	4.0310	1.0300
PRIMARY CUT SETS	Initial	0.2280	
	28642 sec	6.0380	1.0300
	35000 sec	5.0360	1.0300
PRIMARY R&R BINDING	Initial	0.2207	
	3600 sec	4.0310	1.0264
PRIMARY ROUTING CUTSETS	Initial	0.2280	
	3600 sec	4.0330	1.0300
	17000 sec	4.0310	1.0300
	38000 sec	4.0300	1.0300
PRIMARY ROUTING R&R BINDING	Initial	0.2260	
	3600 sec	4.0330	1.0300
	7442 sec	**4.0300**	**1.0300**
PRIMARY CUTSETS R&R BINDING	Initial	0.2280	
	20544 sec	5.0380	1.0300
PRIMARY ROUTING + CUT SET R&R BINDING	Initial	0.2280	
	3600 sec	5.0340	1.0300
	15000 sec	4.0370	1.0300
	24712 sec	4.0340	1.0300

Table 4.2 Different Constraints Set Performance Comparison Table

4.4.2 Numerical Results and Performance Comparison of Models

In this section, performance comparisons of all models are discussed. All the results of metrics for each model are shown in Figures 4.5 - 4.10.

The first performance metric is the maximum value of minimum end-to-end throughput in each model. The best-obtained result for this metric, in maximum link model with COMPOW, is 0.2. This result is obtained for 4mW transmit power level and 10-slot frame length parameters. For the maximum link with ADPOW model, the best result of minimum end-to-end throughput is 0.167. This is obtained for the {2mW, 3mW, 4mW} power set and 8-slot parameters. Better result for minimum end-to-end throughput value 0.5 is obtained in shortest path model with COMPOW. Also, 0.5 is the best minimum end-to-end throughput result of shortest path model with ADPOW and load balancing with COMPOW models. The best result for load balancing model with ADPOW is 0.333. This means that, shortest path and load-balancing models provide higher minimum end-to-end throughput than the maximum link model. Besides, shortest path model with ADPOW gives the best value of minimum end-to-end throughput by consuming 72mW power. But, the same result is obtained with 90mW power consumption in shortest path model and load balancing model for 6mW common power level and 14-slot parameters. Generally, increase in the common transmit power level does not have a great effect on minimum end-to-end throughput.

Second metric is the total throughput. The highest result of this metric, 21.8, is obtained in maximum link model in the expense of less minimum end-to-end throughput. This means that there is an inverse relation between total and minimum end-to-end throughput metrics. Maximum link model gives higher total throughput results with the cost of unfair capacity sharing. But the shortest path and load balancing models provide fairer capacity sharing in the expense of less total throughput.

Number of established link is the third comparison metric in this thesis. The maximum link model establishes more links than the other two models. However, establishing more links do not necessarily correspond to higher throughput since number of links can be increased by establishing some links at multiple times. This causes congested links in the network.

For the power consumption metric, maximum link model consumes more power than the other two models. The power consumption is same for COMPOW in shortest path and load balancing models. These two models provide almost the same minimum end-to-end throughput. By considering the same power consumption, shortest path model may provide better total throughput than the load-balancing model.

The same highest value of minimum end-to-end throughput and total throughput results are obtained in both COMPOW and ADPOW approaches. ADPOW approach provides more link establishments than COMPOW, but this does not correspond to an important improvement on other metrics. There is a little difference between these two approaches for the power consumption metric. The most important thing for COMPOW is to select the minimum required power for a connected network. So, obtaining the same results with almost the same power consumption in a simpler form of topology design makes COMPOW more attractive than the ADPOW approach.

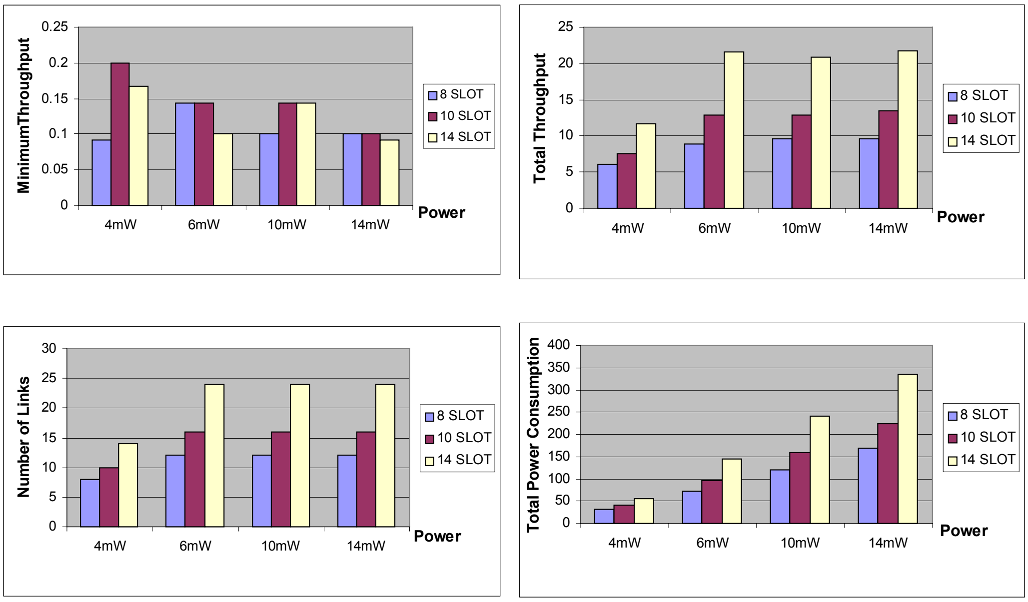

Figure 4.5 Graphical representations of results for maximum link model with COMPOW

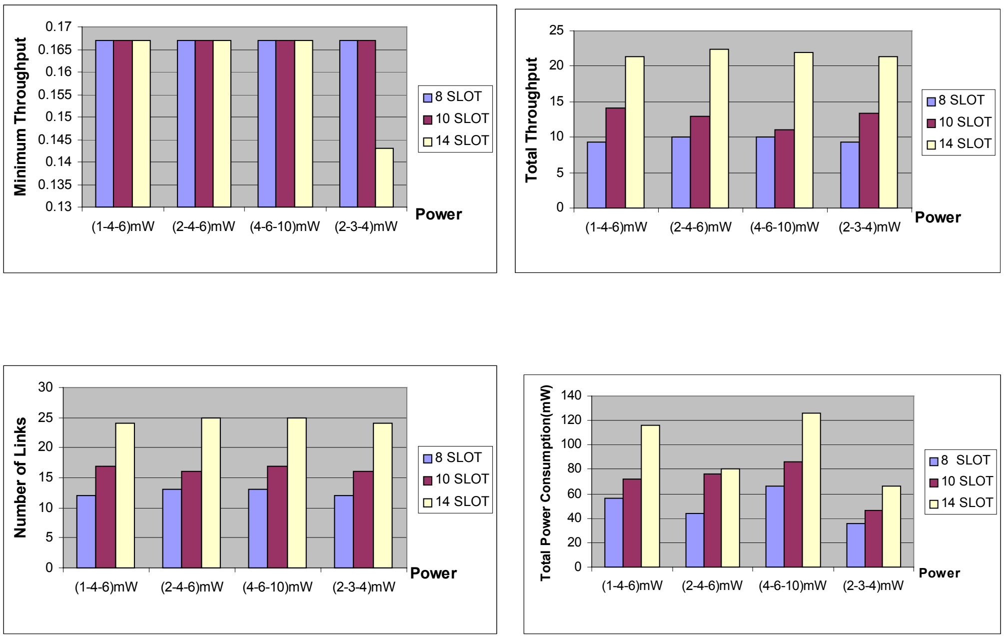

Figure 4.6 Graphical representations of results for maximum link model with ADPOW.

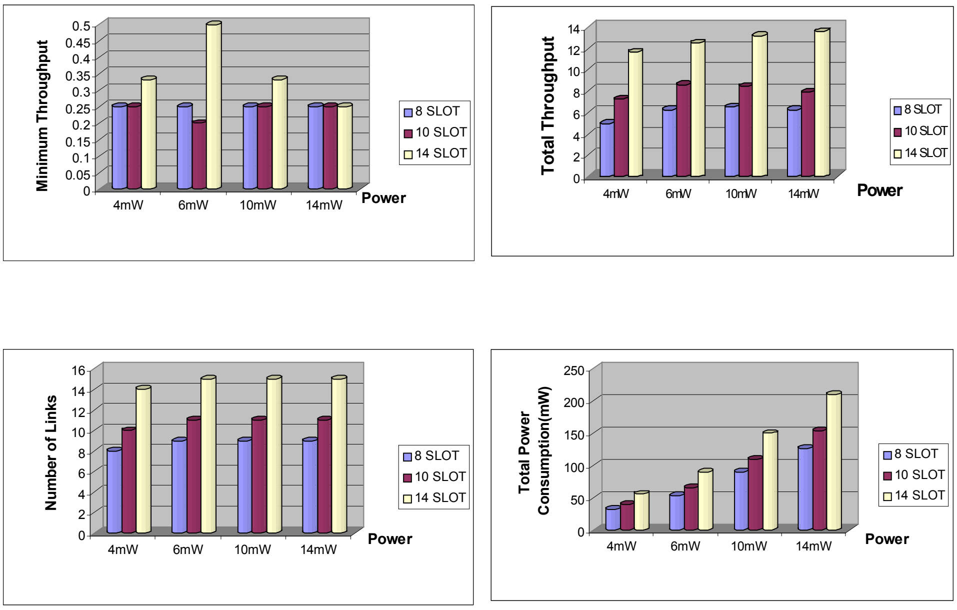

Figure 4.7 Graphical representations of results for shortest path model with COMPOW

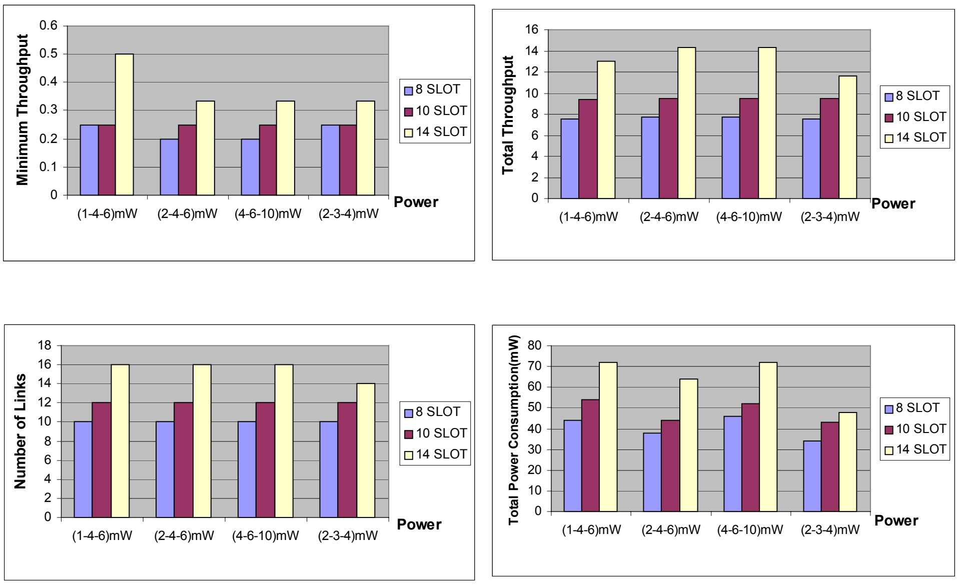

Figure 4.8 Graphical representations of results for shortest path model with ADPOW.

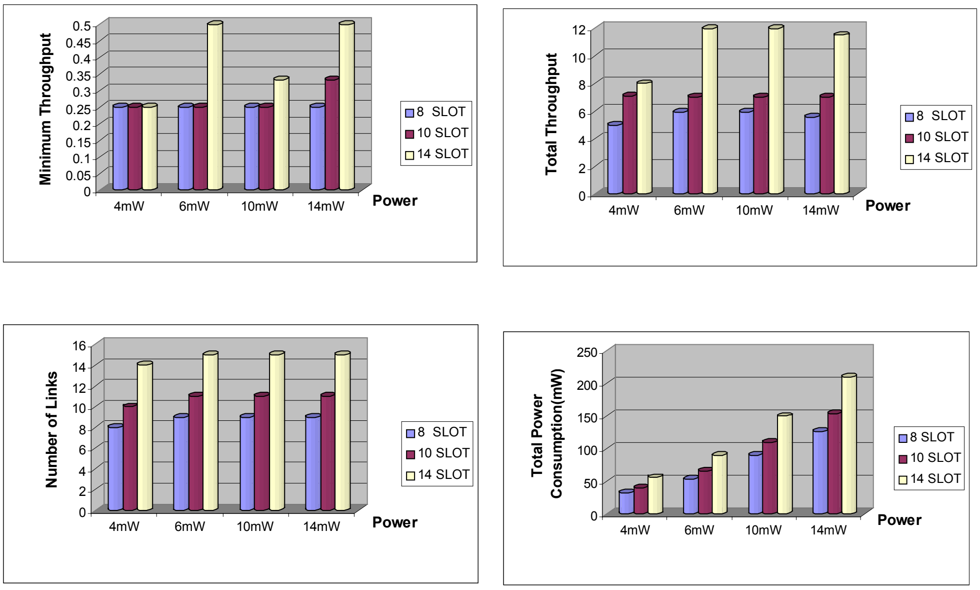

Figure 4.9 Graphical representation results for load balancing model with COMPOW.

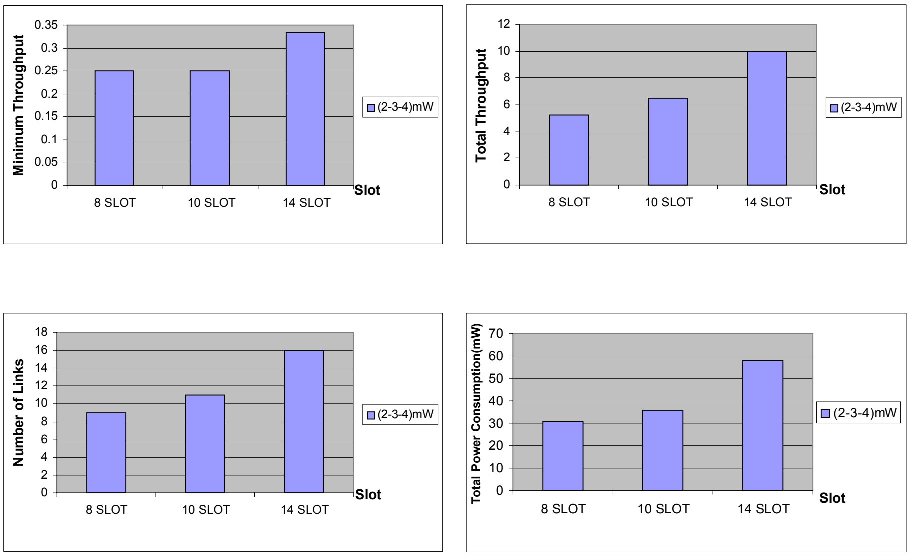

Figure 4.10 Graphical representation results for load balancing model with ADPOW.

Chapter 5

Conclusion

Ad hoc network is a type of wireless communication networking. The lack of a need for the previously established infrastructure is the main characteristic of these networks. Designing the network topology is a critical issue since it improves the network capacity and power consumption. Mobility causes a highly dynamic topology changes. In the literature, the current studies related with topology design are using the transmit power control and routing as a way of topology design.

In this thesis, designing a network topology by using joint power control and routing strategy is investigated. Topology design is considered as an optimization problem. Two different power control approaches are studied during the topology design. These are the common transmit power (COMPOW) and the adaptive transmit power (ADPOW) approaches. Performance comparisons between these two power control approaches are presented. The minimum end-to-end throughput, total throughput, total power consumption, and the number of established links are the performance metrics used for comparison. MAC is achieved by using TDMA approach. Three different models are built in order to design the topology for three different objectives. The maximum link model is aimed to increase the number of established links in a frame. Shortest path model uses shortest path routing strategy for topology design. The load-balancing model tries to decrease the load on the most congested link in the network. Each of these three models is used in conjunction with COMPOW and ADPOW control approaches.

The numerical results, obtained for the defined metrics, in three models with COMPOW and ADPOW, conclude that the maximum link model causes an unfair capacity sharing in the network. Simultaneously communicating links are established in more time slots than other links. There is no big change for the minimum end-to-end throughput metric in load balancing and shortest path models. But, the shortest path and load balancing models provide higher minimum end-to-end throughput results than the maximum link model. Total throughput results in maximum link model are higher than the shortest path and load balancing models in the expense of higher power consumption. Maximum link model consumes more power than the other two models. But, shortest path model and the load balancing models almost have the same power consumption. Increase in frame lengths increases total throughput in all three models. Increase in the common transmit power level does not mainly affect the minimum end-to-end throughput, but it increases the number of links and total throughput at the expense of high power consumption.

Also, there is no big difference between common power and adaptive power control approaches for the minimum end-to-end throughput, total throughput, and number of established link metrics. For the common power levels except minimum required power for connectivity, the ADPOW control approach provides less power consumption than COMPOW approach. This means that same amount of data can be carried by consuming less power. This extends the battery life of the network. But, if we choose the minimum required power level, the same results of metrics can be obtained almost the same power consumption in both power control approaches. The most important thing is to select the optimal power in each of these approaches. Simplicity of COMPOW makes it more attractive than ADPOW approach.

Developing a distributed and heuristic algorithm to make this comparison between two power control approaches in larger networks with faster solution times is considered as the main direction of future works for joint topology design with routing and power control.

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