FREQUENCY ALLOCATION AND CLUSTERING IN FREQUENCY HOPPING AD HOC NETWORKS

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FREKANS ATLAMALI TASARSIZ AĞLARDA DAĞITIK FREKANS TAHSİSİ VE ÖBEKLEME

ÖZET

Frekans atlama, haberleşmede girişimi kontrol etmek ve frekansı tekrar kullanmak için kullanılan bir tekniktir. Askeri ağlarda frekans atlama ile girişim azaltılabilir ve sinyal bozucuların sistemler üzerindeki kötü etkileri en aza indirilebilir. Doğru frekans tahsisi yapabilmek, askeri ağlarda güvenlik, gürbüzlük ve en kötü durumdaki kullanıcının bile başarım sağlaması bakımından önem kazanmıştır. Askeri ağlar genellikle merkezi olmayan tasarsız ağlardır. Tasarsız ağlarda hiyerarşi ve ağ kontrolünü sağlamada öbekleme kullanılabilir. Öbeklemenin başlıca faydaları, girişimi azaltmak, güç ve kanal verimliliği sağlamak ve dağıtık algoritma uygulamayı mümkün kılmak olarak sıralanabilir.

Bu çalışmada frekans atlamalı tasarsız ağlarda; bağlantılı öbekleme ve frekans tahsisi problemleri ele alınmaktadır. Frekans tahsisi için; ağ bilgisine dayalı merkezi çözüm, karışık tamsayılı programlama ve dağıtık olarak uygulanabilir bir algoritma önerilmiştir. Öbekleme için tamsayı programlamaya dayalı bir optimal yöntem ve dağıtık olarak uygulanabilir bir algoritma önerilmiştir. Bu yöntemler TDMA-tabanlı bir tasarsız ağ benzetim ortamında test edilmiştir. Yapılan benzetimlerle, önerilen dağıtık-uygulanabilir algoritmaların merkezi çözümlere oldukça yakın başarıma sahip olduğu gösterilmiştir.

Anahtar Kelimeler: Kablosuz, Frekans Atlama, Frekans Tahsisi, Tasarsız Ağlar, Öbekleme.

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FREQUENCY ALLOCATION AND CLUSTERING IN FREQUENCY HOPPING AD HOC NETWORKS

ABSTRACT

In this work, clustering and frequency allocation in TDMA-based frequency-hopping ad hoc tactical networks are examined. We propose Mixed Integer Linear Programming based optimal clustering solution along with a distributed load-balanced clustering algorithm. As for the frequency hop set allocation, we first propose a centralized global algorithm and a centralized MIQP solution based on full channel information. Then we propose a distributed channel allocation algorithm. Simulation results reveal that the proposed algorithms perform very closely to the benchmark solutions in terms of throughput, delay and hop count performance.

Keywords: Wireless, Frequency Hopping, Frequency Allocation, Ad Hoc Network, Clustering.

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List of Symbols

Variable	**Description**	**Related Section**
x_{ji}	Connection parameter of node i to cluster j	2
c_{ji}	Throughput capacity between node i and j	2
I_j	Clusterhead parameter of node j	2
I_{max}	Maximum clusterhead count	2
$\mathcal{N}$	User set	2
N_{max}	The maximum users in a single cluster	2
C_i	The total throughput of i to its neighbors k	2
U_i	The amount of users i exceeds in throughput	2
i^*	Potential clusterheads with a value of U_i	2
$\mathcal{N}^*$	Proposed clusterhead set	2
$\mathcal{CH}$	Clusterhead set	2
f_{min}	Minimum frequency band	3
f_{max}	Maximum frequency band	3
W	Bandwidth	3
N_f	Frequency band count	3
N_0W	Additive White Gaussian Noise power	3
P	Users power	3
d_{ij}	Distance between i and j	3
Π	Frequency pattern Set	3
Π_c	Most suitable pattern set for cluster c	3
pi_c	Pattern set allocated to cluster c	3
$\overline{\pi}$	Pattern set allocated to all clusters	3
$I_{n,k}$	The noise+intereference level n user is exposed at channel band k	3
$h_{n,m,k}$	The pathloss between user n and m at cgabbel k	3
β_1	First sideband coefficient	3
β_2	Second sideband coefficient	3
$N^c_{f,min}$	The minimum frequency band number allocated to a cluster c	3
$N^c_{f,max}$	The maximum frequency band number allocated to a cluster c	3
I_n	The average interference of user n in all channels	3
$F(\overline{\pi})$	The maximum interference of the average user interference	3
a_{ij}	The neighbor parameter of cluster i and cluster j	3
$Cost_{ij}$	The routing cost between users i and j	4

1. INTRODUCTION

1.1 Radio Communication Systems

The scientists who saw and investigated the impacts of electricity and magnetism contributed in the early establishment of radio technology. Maxwell proved the existence of electro-magnetic waves, Faraday proposed that electromagnetic forces extend into the empty space around the conductor, and Hertz produced a set of experiments that validated Maxwell's theory of electromagnetic radiation where he proved that electromagnetic radiation can travel through free space. Then, Marconi- known as the inventor of radio, pursued the studies and built a wireless telegraphy system using Hertzian waves. Following these successful experiments, the Italian Engineer was able to convince the English authorities of the importance of wireless communication, and this opened an opportunity for long distance communications. Soon, short wave transatlantic success has turned the media industry in broadcasting news and entertainment. This industry has evolved greatly and is continuing to evolve in an increasing pace ever since, with new areas of research available for the motivated scientists and engineers.

1.2 Military Radio Communication Systems

Today, military radio communications systems are used by armed forces to deliver audible and visual information, such that it assures a secure, distributed and a fail-safe end-to-end performance. Its QoS specifications are different than from the industrial use. Military communication equipment are designed to encrypt and decrypt transmissions, and often use different frequencies to send to other radios and to satellites. It is interesting to note that the ideas used for tactical and strategic communication mainly innovate from individuals and private companies.

As in Marconi's case, where the Italian navy has shown disinterest to radio communication, often senior officials reject the breakthrough ideas for improving communications.

For security reasons, during a conflict, the military has the tendency to hide information to themselves and seek information about the other at the same time. However communicating information always has a vulnerability which is why military forces stress on secrecy and intelligence.

The increased means in signaling and processing has allowed a continuous improvement in military radio communications, which led the carrying messages to become more complex every day.

Unlike commercial communication, military radio communication setup usually requires a robust, ad hoc, and a distributed network. These networks should operate under harsh weather and terrain conditions. An example of such a mobile network is shown in Figure 1.1 that can send voice, data and video traffic. The mobile vehicles make the backbone of the network. The members of the network consisting of land, aircraft and marines transfer signals with different radio signal powers.

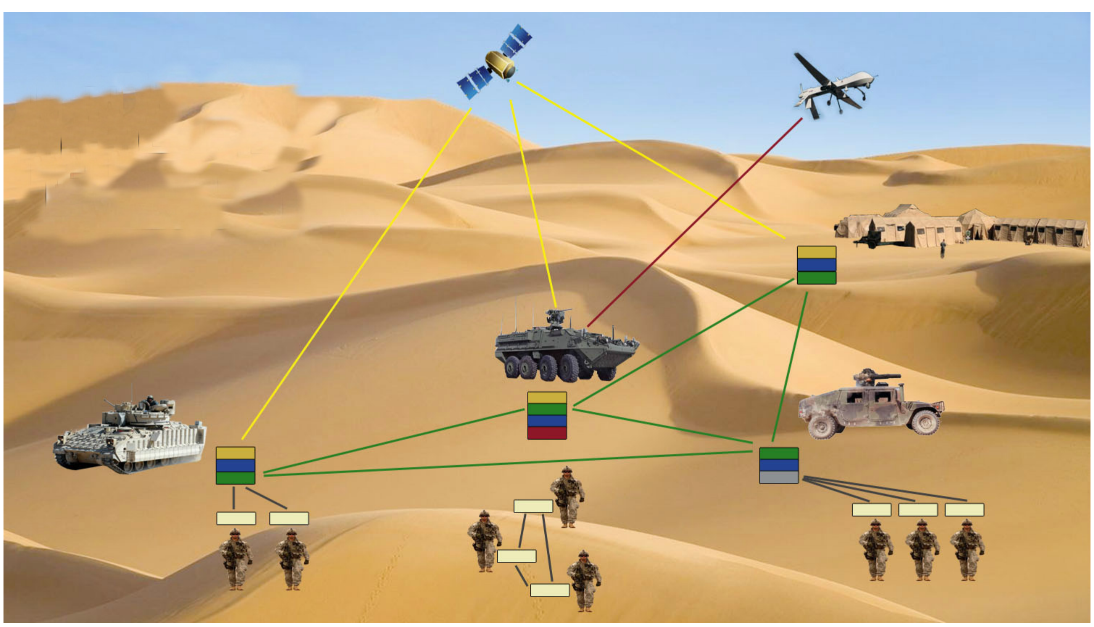

Figure 1.1: Military Communication Network

The radio communication system discussed in this thesis is considered to be ad hoc. Ad hoc networks are decentralized type of wireless network. They do not rely on a preexisting infrastructure, such as routers in wired networks or access points in managed (infrastructure) wireless networks. This means there are no base stations such as those used in cellular phones. This increases security and robustness. Otherwise, if the network relies on a fixed infrastructure, the breakdown of a single-point of failure of a fixed station can cause the network to go down.

Communication occurs by transferring signals when the users can sufficiently ensure the necessary signal-to-noise ratio threshold conditions. Jammers are used by hostile users to prevent communication by intentional emission of radio frequency to interfere signals with false noise or information. To prevent the side effects of jamming, frequency hopping is used. Frequency hopping is a method of transmitting radio signals by rapidly switching a carrier among many frequency channels, using a pseudorandom sequence known to both transmitter and the receiver. Frequency hopping will be further discussed.

1.3 Clustering

In today's world, billions of machines are connected to each other, and the increasing trend shows that this number will increase by a factor of five in less than two decades. In this case, a certain grouping schematic has to be applied. Clustering is the task of grouping a set of objects in such a way that objects in the same group named as cluster where clusters are more similar to each other than to those in other groups. In military radio communication, standalone radios are becoming insufficient in providing the required QoS. During a conflict, using centralized planning by using a main base station is inadequate in terms of using the radio spectrum and optimizing the user organization in terms of performance costs. Making a centralized network has the potential of having a single-point-of-failure, where in the case of an attack to the main base station, the majority of the infrastructure might collapse. Hence using clustering in a military radio communication has these several advantages:

1. It can be applied in a distributed manner .
2. It is power efficient.
3. It is channel efficient.
4. It can decrease interference.
5. It is scalable

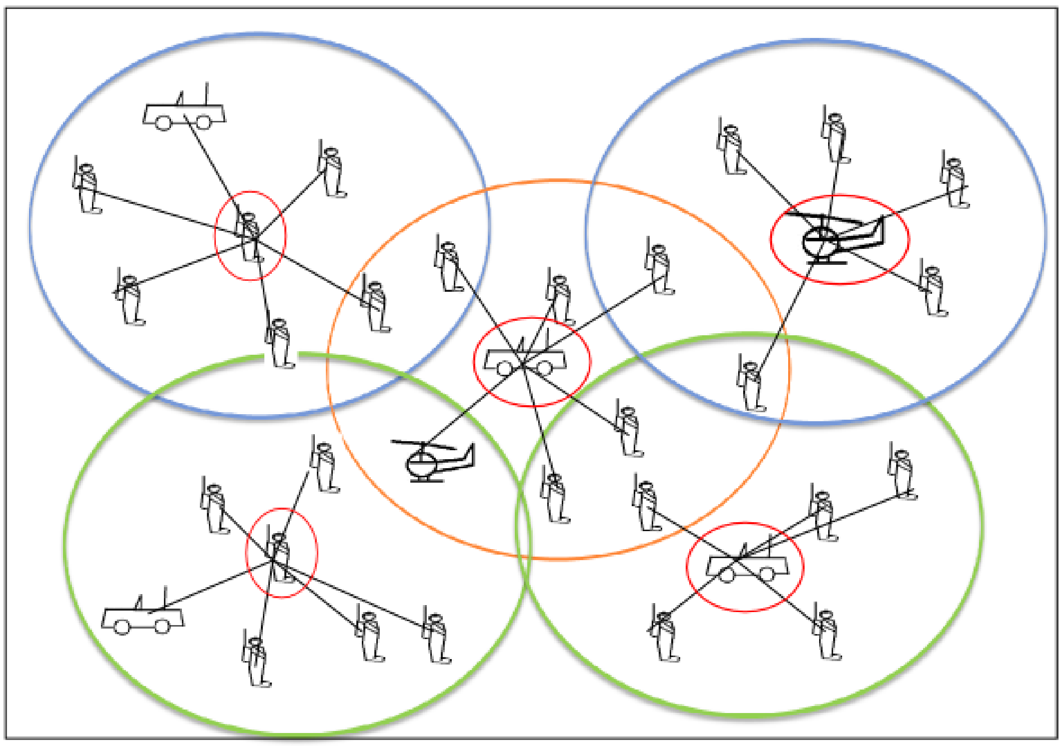

Figure 1.2: Clustering Structure

Clusters are distributed in a topology based on their location, their signal strength, closeness to other users and connectivity with respect to the general topology. Cluster architecture facilitates spatial reuse, where members of different distant clusters in the same network can be assigned with the same frequency set, and this increases the system capacity in terms of resource use. Members of the same clusters are close to each other, and they spend less energy transmitting data to each other which extends their lifetime and increases power efficiency. The information is routed over cluster heads. Cluster heads are the main member of the cluster that is responsible for synchronizing, assigning and routing transmissions in time division frames. This allows scaling even for large number of users.

A cluster formation can be seen in Figure 1.2. In this example, there are five clusterheads, and every cluster has a clusterheadmember labeled as red. The users connected to the preferred cluster given certain specifications and parameters.

1.4 Frequency Allocation

Frequency allocation is the management and regulation of spectrum of the radio frequency bands of the electromagnetic spectrum. Giving technical and economic reasons, governments allow a certain portion of the radio spectrum for users, companies, and the military to use. The scarcity of the spectrum promotes the bands to be used effectively and this advocates research on using the frequency band efficiently. Military communication frequency allocation generally takes place in the range of 30-512MHz area. Understanding the operational process in planning, managing, and employing this resource is critical to the conduct of providing the QoS and enabling a high performance.

1.4.1 Frequency Hopping

Frequency Hopping Spread Spectrum (FHSS) is a method of transmitting radio signals by rapidly switching a carrier among many frequency channels, using a pseudorandom sequence known to both transmitter and receiver. There exists slow and fast methods of frequency hopping. In slow frequency hopping, a few symbols are sent in a hopping period. In fast frequency hopping a symbol is sent in more than one hopping time. This creates frequency diversity and decreases the interference between the symbols. Though frequency hopping provides an advantage in various cases, it creates an issue of frequency allocation problem. Frequency hopping is widely used in GSM and military applications. Frequency hopping is especially important in GSM systems. The pathloss in radio signals is generally attributed to the Rayleigh Fading Model. In a case where path loss is high for a mobile node, information loss can be significant. Frequency hopping can provide frequency diversity and decrease the loss of transmission. The second advantage of frequency hopping is in the ways it can decrease interference. Without frequency hopping, the interference of other signals using the same or similar frequency can have a major impact to communication. The usage of frequency hopping can decrease interference [1]. Moreover, frequency hopping increases the resistance against cross-symbol interference. Fig. 1.3 shows how different frequencies are used in frequency-space time. The carrier frequencies change every hop such that the two close users do not interfere each other.

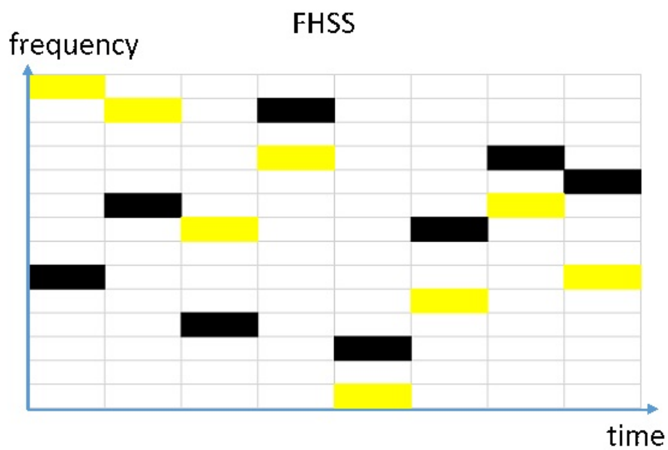

Figure 1.3: Frequency Hopping

1.5 Literature Analysis

Military tactical ad hoc networks require secure, connected, interference free, fast communication that can be deployed immediately in a distributed manner. The military tactical ad hoc network terminals communicate freely with each other via wireless links by broadcasting radio transmissions within their transmission power range. Usually this requires a multi-hop configuration where packets are routed by forwarding from source over intermediate terminals to the destination [2] [3].

Without the existence of base stations and fixed network infrastructures, careful management of the network is necessary in order to ensure entire area coverage.

Efficient communication can be supported by developing a wireless backbone architecture [4] [5] [6] [7]. Virtual backbone can be formed by building a Connected Dominating Set (CDS) . With the help of the CDS, routing is easier and can be localized to adapt quickly to network topology changes [8] [9] [10]. Routing messages are only exchanged between the backbone nodes that act as a clusterhead instead of being broadcasted to all the nodes. A clusterhead often serves as a local coordinator for its cluster, performing intra-cluster transmission arrangement, data forwarding, and other duties. Other ordinary nodes behave as a clustermember, which is a non-clusterhead node without any inter-cluster links.

It has been shown that cluster architecture guarantees basic QoS performance achievement in a MANET with a large number of mobile terminals [11]. A cluster structure, as an effective topology control means , facilitates the spatial reuse of resources to increase the system capacity. With the non-overlapping multicluster structure, two clusters may deploy the same frequency if they are not neighbouring clusters. A cluster can coordinate its transmission events effectively and decrease transmission collision, making the ad hoc network appear smaller and more stable for each mobile terminal where local changes do not need to be updated by the entire network, and information stored and processed is decreased vastly by each node [12] [13]. The clusterhead can adjust channel scheduling, perform power measurement, maintain synchronization of time division frames, and improve the spatial reuse of the time slots. This makes the clustered network scalable to large numbers of nodes [14].

In the absence of a centralized control, channel assignment in military radio sensor networks is implemented in a distributed manner. Research is being conducted on the problem of interference management in network deployments where terminals communicate using the same frequency bands and can interfere with each other. Interference of transmission signals effect the QoS of the adhoc network system, and in a tactical network packet delivery time thresholds hold vital importance. [15] [16]. Dynamic channel allocation algorithms based on the level of interference measured on each channels has been proposed to static channel allocation and random frequency hooping to reduce the co-channel interference and improve the network performance [17] [18] [19] [20]. Frequency assignment utilization based on signal-to-interference costs have been performed in the frequency assignment problem [21] [22] [23]. However, given frequency allocation schemes have not accommodated the requirements of an increasing number of higher data rate devices in a clustering environment. A new way of exploiting available spectrum in a frequency hopping clustered network has been researched in this paper to use the frequency bands opportunistically in a frequency hopping clustered network.

One of the favored frequency allocation methods in frequency hopping is simulated annealing. Similarly, this thesis will use a similar technique by creating a benchmark for one of the optimal solutions. Simulated annealing is a probabilistic meta-heuristic method for a global optimization problem by locating a global optimum given a certain function in the large search space. This method helps the testing frequency allocation of a TDMA (Time Division Multiple Access) based applications [24] by creating several frequency patterns and assigning these patterns to users. Simulated annealing has been used in GSM networks to allocate frequencies in a frequency hopping environment [22].

So far, most of the work for frequency hopping has been made for cellular networks. In cellular networks, the increase in demand leads to an insufficient frequency band and the reuse of frequency spectrum becomes important. When the frequency reuse is not optimized, the interference levels can increase high such that it decreases the performance. In frequency hopping networks, the frequency reuse can be set to minimize the interference levels, using simulated annealing [25] or by obtaining an optimal solution by MLIP.

1.6 System Model

We have selected a distributed TDMA cluster approach to supply requirements of efficient network resource control and multimedia traffic support. Deployed terminals comprises a number of N units that are distributed randomly, each equipped with a 10W and 50W cognitive radio devices. They can send voice, data and video packets to their destinations as shown in Figure 1.4. The spheres represent the users transmission range, whereas the green arrows indicate the type of packets being sent and the origin-destination pair.

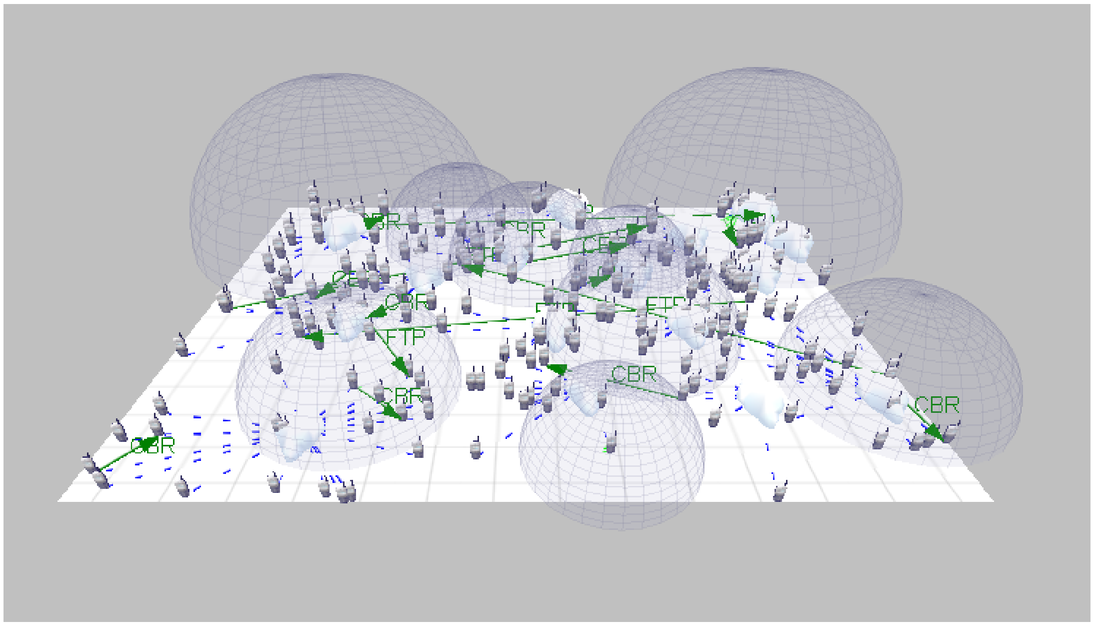

Figure 1.4: System Topology.

In the simulations, we consider around 200 nodes distributed in a rectangular area of 12×16 km^2. We assume that each node knows its neighbors based on a neighbor discovery process. We consider a frequency hopping network , where each device can tune only on a single channel in a single slot period, and can both transmit and receive in that channel. Channel loss is calculated with respect to the distance and frequency, by using Rayleigh Fading Model and location advantage $[-10dB, +10dB]$ in accordance to the node position. Via clustering, the whole population of nodes is grouped into clusters,as shown in Figure 1.5 . Each clusterhead, labeled red, acts as a regional broadcast node, and as a local coordinator to enhance channel throughput. Time-division scheduling is enforced within a cluster, where clustermembers transmit their packages via clusterheads using the allocated set of frequencies at their reserved time slots. The network does not permit two clustermembers of the same cluster to transmit packets over to the clusterhead at the same time *slot*, however multiple transmissions can be accomplished in a single time *frame*. Resource management is made by dynamic slot and frequency reservations. Spatial reuse of time and frequency slots is facilitated across the clusters. This allows distant clustermembers to use the same frequency bands at the same time. The main idea is to provide a feasible interconnected clustering algorithm that is stable, excludes single points

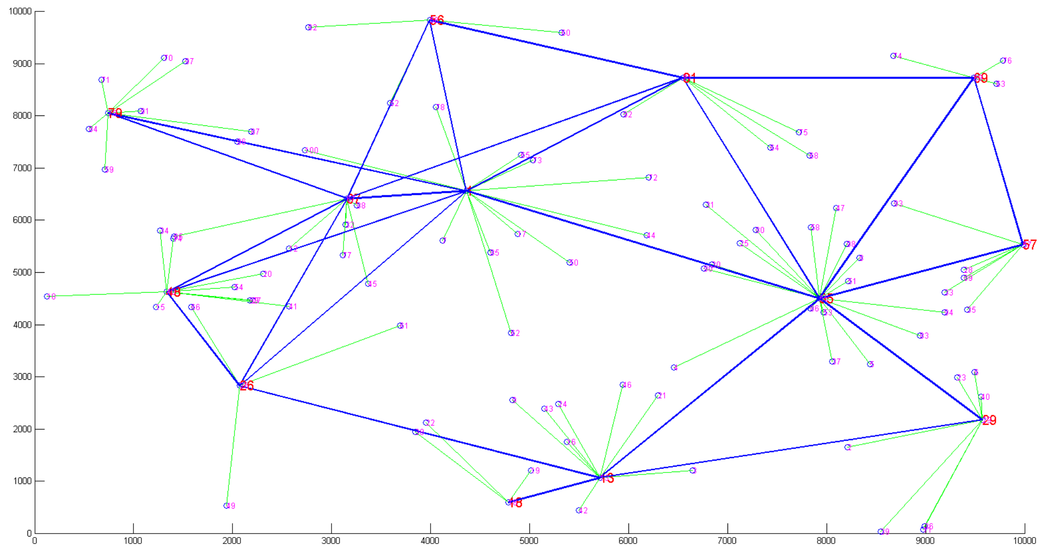

Figure 1.5: Connected Distributed Clustering Topology.

of failure on heavily loaded traffic and is easy on topological changes. At this stage node mobility is not considered that makes clustering more challenging since the node membership will dynamically change, forcing clusters to evolve over time. However, our proposed clustering algorithm can be modified to support mobility and cluster maintenance. The model supports various applications in a tactical military ad hoc network, including voice, command and control, ftp and video.

We represent the ad hoc wireless network by a directed graph $G(V)$. Each node $v \in V = 1, ..., n$ symbolizes a terminal with (possibly varying) circular transmission range $R_t(v)$ and a carrier sensing range $R_h(v)$. The graph connectivity is given by a connectivity matrix A. The adjacency matrix $A \in G(V, E)$ is a matrix with rows and columns labeled by the graph vertices V, where the matrix entry $a_{v,u}$ is 1 or 0 if nodes v and u are unidirectionally connected or not. An edge (v, u) is bidirectional if both $a_{u,v}$ and $a_{v,u} = 1$ are 1.

Each node v transmits with a rate $r_{v,u}$ to its neighbor $u \in N_e(v)$. The available transmission bit rate $r_{v,u}$ is determined through the link condition depending on the transmission power, distance between the node v and u and the resulting loss rate on that link resulting from interference. Our model includes the effects of interference therefore the transmission bit rates are not fixed.

1.7 Motivation

Today's modern military has access to real-time data with technologies such as data networking, GPS, real-time video feeds from UAVs, and satellite intelligence. However, supplying this information to the users of the fighters at the edge of the network is still an issue. Making real-time voice, data and streaming video to a user at the edges of a network is a challenging task. Providing a firm networking infrastructure in place on the battlefield is crucial. By producing protocols that can be implemented to clustered groups to decrease interference, increase routing performance and connectivity will help mobile soldiers to obtain high-performance to deliver the information they need. Hence this thesis is motivated to find solutions for military radio communication such that

- The proposed clustering and frequency allocation algorithms are distributed.
- Frequency reuse efficiency is maximized.
- Sufficient transmission takes place in the worst case scenario.
- Traffic is routed in the given delay parameters.

1.8 Thesis Contents and Contributions

This research is supported jointly by the Turkish Ministry of Science, Industry and Technology and Aselsan Inc., through SANTEZ program, project No. 1538.STZ-2012.2.

A conference paper for MILCOM 2015 on frequency allocation and clustering for tactical radio networks has been written and has been accepted.

In this thesis, I will first propose a connected clustering scheme by forming a virtual backbone of a CDS with different transmission ranges in order to maximize throughput cost of the network. The first scheme is called optimal static clustering. The optimal cluster placement that maximizes the total throughput by formulating a centralized clustering problem as a mixed linear integer programming (MLIP)is determined. Then, in the second scheme, named distributed clustering algorithm, a distributed clustering algorithm that satisfies the connectivity constraint using a marking process where the cluster formation is amenable to distributed implementation is proposed. When the network is deployed randomly such that clusterheads are concentrated in a particular part of the network forming an unbalanced cluster formation some portion of the network may become unreachable or if the resulting distribution of the clusterheads in multi-hop communication, the nodes closer to the clusterhead are under a heavy load as all the traffic is routed from different areas of the network to the clusterhead through the clustermembers [26]. For this reason, a local and dynamic clustering algorithm that is applicable for TDMA-based load balanced wireless ad hoc networks and that is adaptable to topology changes will be proposed. Furthermore, the clusters may overlap, which creates undesirable interference effects. To minimize the effects of interference, we first propose a global centralized frequency hop set allocation scheme, and then formulate a distributed algorithm that allocates available frequencies to minimize the potential interference caused in the network. To the best of our knowledge, no clustering approach in terms of connectivity constraint and interference effect among neighbouring links for frequency hopping tactical ad hoc networks have been previously proposed in the literature in the context of optimal integer programming. These schemes are tested in TDMA-based computer simulation environment. Numerical results reveal that the distributively implementable algorithms are close to the centralized ones, in terms of transmission rate performance.

This thesis is organized as follows. Section 2 describes the optimal and local algorithmic model of the distributed connected clustering problem. Section 3 presents the optimal and local algorithms for the distributed frequency hop set assignment problem. Section 4 describes the routing considerations and describes the network traffic. Numerical results are given in Section 5, with a conclusion drawn in Section 6.

2. CLUSTERING

Clustering objective is set in order to facilitate meeting the application requirements, where sensitivity to data latency, intra and inter-cluster connectivity and the length of the data routing paths are considered as criteria for CH selection and node grouping. A cluster structure, as an effective topology control means , facilitates the spatial reuse of resources to increase the system capacity. A cluster can coordinate its transmission events effectively and decrease transmission collision, making the ad hoc network appear smaller and more stable for each mobile terminal where local changes do not need to be updated by the entire network, and information stored and processed is decreased vastly by each node. This vastly decreases the overheads used and allows more information to be sent in the data packets. To this end, an optimal MLIP-based clustering that maximizes network throughput will be considered. Then our proposed algorithm that provides strong connectivity with a load balanced property will be explained. The MLIP clustering and the algorithms are described below:

2.1 Optimal Static Clustering

The optimal static clustering that maximizes the network throughput between the clusterhead and its members will be the benchmark for our proposed distributed clustering algorithm. The objective function is defined in (2.1) , where x_{ji} represents the connectivity of node i to node j (clusterhead), where 1 denotes connected or 0 not connected. c_{ji} is the total throughput of node i to node j. Binary vector I_j indicated whether node j is selected as clusterhead or not. Constraints are put to obtain a global unique solution; (2.2) enforces each node to connect to a single clusterhead, (2.3) tells that cluster members can connect only to clusterheads, (2.4) sets the maximum number of clusterheads, (2.5) sets the maximum number of cluster members in a single cluster.

$$\max_{x,I}(\sum_{i\in\mathcal{V}}\sum_{j\in\mathcal{V}} x_{ji}c_{ji}) \tag{2.1}$$

$$\sum_{j\in\mathcal{V}} x_{ji} = 1, \forall i \in \mathcal{V} \tag{2.2}$$

$$I_j \geq x_{ji}, \forall i, j \in \mathcal{V} \tag{2.3}$$

$$I_{max} \geq \sum_{j\in\mathcal{V}} I_j \tag{2.4}$$

$$N_{max} \geq \sum_{i\in\mathcal{V}} x_{ji}, \forall j \in \mathcal{V} \tag{2.5}$$

In our previous examinations, clusters were not assigned to have full connectivity. It is important that there should be at least one route from any edge node to another. For this we need to have a connected graph. This can be obtained by ensuring a connected dominating set. To form a connected dominating set, we need several more constraints. The *adjacency matrix* $A = (a_{ij})$, of G is a $N \times N$ binary matrix, where $a_{ij} = 1$ if there is an bidirectional edge linking nodes i and j in $\mathcal{E}$ and 0 otherwise. We guarantee that all clustermembers have an adjacent clusterhead in Equation (2.6). The capacity for $i = j$ of c_{ij} is equal in Equation (2.6) and does not impact on the throughput maximization. We also define a $flowmatrix$, $F = (f_{ij})$, where f_{ij} represents the flow from node i to node j. A connected subgraph should be able to send flow from a source node to any other nodes using clusterhead as intermediate nodes. Constraint (2.7) makes sure that the source node produces sufficient flow to supply at least one unit of flow to all other clusterheads. Constraint (2.8) ensures each clusterhead uses at least one unit of flow. Flow is positive and can travel along a valid edge shown in (2.9) and (2.10). Note that we initiate flow from node 1. Node 1 is the initiator node in the distributed environment.

$$I_i + \sum_{j \in \mathcal{V}} a_{ij} I_j \geq 1, \forall i \tag{2.6}$$

$$\sum_{j \in \mathcal{V}/1} f_{1j} - \sum_{j \in \mathcal{V}/1} f_{j1} = N - 1 \ , \tag{2.7}$$

$$\sum_{j \in \mathcal{V}} f_{ji} - \sum_{j \in \mathcal{V}} f_{ij} \geq I_i \ , \forall i/1 \tag{2.8}$$

$$0 \leq f_{1,j} \leq n a_{1j}(I_1 + I_j) \ , \forall j \neq 1 \tag{2.9}$$

$$0 \leq f_{i,j} \leq n a_{ij}(I_i + I_j) \ , \forall i, j \neq 1 \tag{2.10}$$

The identified problem for the given constraints has been solved by using the tools of GAMS and MATLAB.

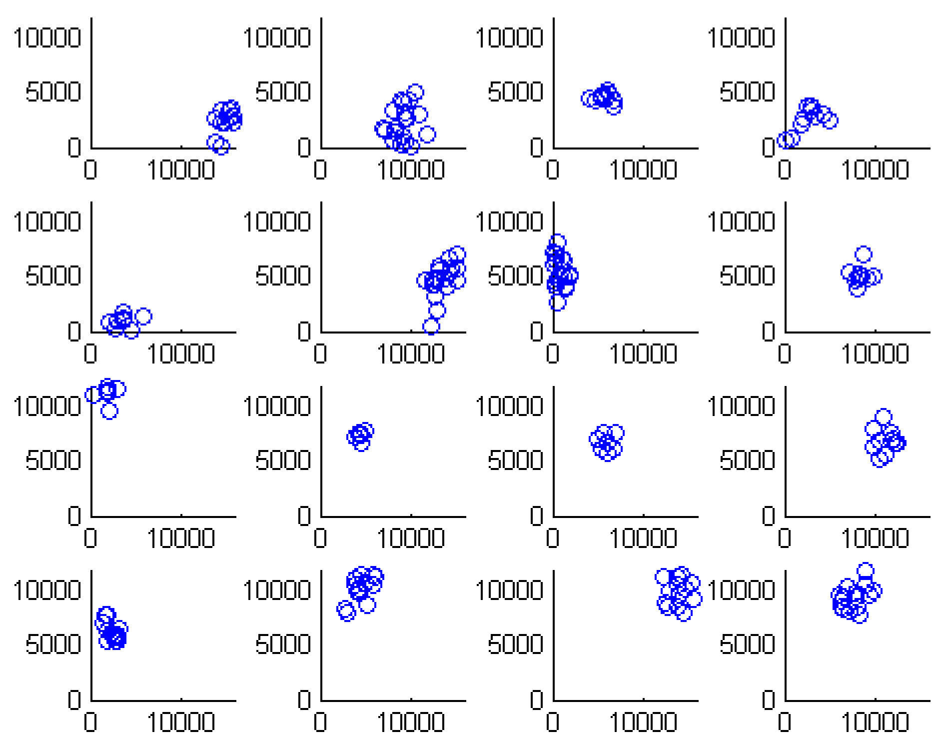

Figure 2.1: Cluster Structure Obtained From Optimization Problem

The best clustering optimization problem actually varies based on factors affecting on data rates, interference, routing and hop counts. In this solution we maximize only the data rates. In the local sense it might not be practical. For instance, if two close users that are communicating with each other get assigned to different clusters, their end-to-end delay will increase. A topology that might give a lesser total throughput can be more efficient in special cases in terms of traffic delay. Nevertheless, this benchmark serves well. It will assign close users together, and this will prevent high interference levels. A solution example is shown in Figure 2.1. Each graph indicates a cluster, and shows the assigned members in the topological area. Clearly, the radios close to each other are assigned together.

A CDS provides a guaranteed connection of clusterhead members for a given SNR threshold. This ensures a distributed hierarchical setup decreasing the interference levels. Indeed a CDS is ensured, however, there can be still a single-point-of-failure. The topology and this algorithm usually picks clusterheads such that the connectivity is either a mesh network, or there is at least two paths for clusterheads as seen in Figure 2.2. This notion will be further investigated as a future work.

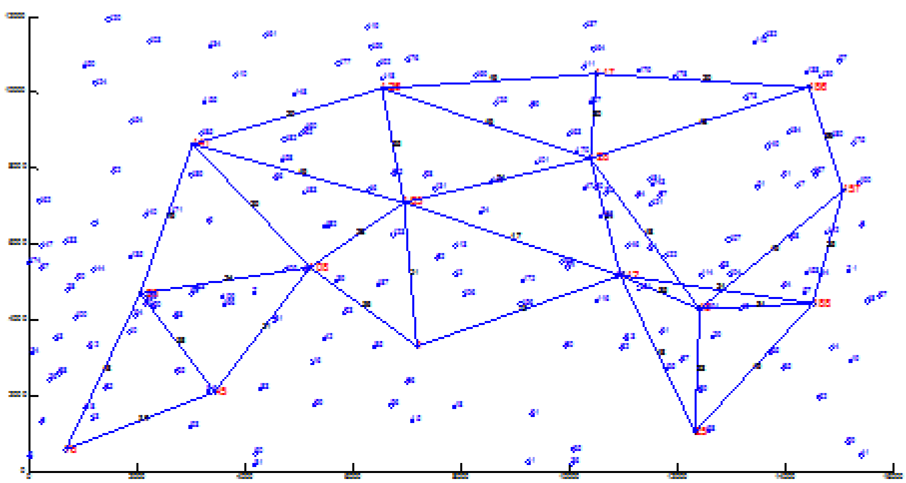

Figure 2.2: Cluster Structure Obtained From Optimization Problem

2.2 Distributed Clustering Algorithm

The distributed clustering algorithm has been formulated to work for ad hoc distributed networks. Similar to optimal static clustering, the distributed clustering algorithm attempts to formulate a infrastructure that ensures a CDS. A common virtual backbone building algorithm consists of constructing a Minimal Independent Set (MIS) by initiating a spanning tree then connecting the left over nodes to complete connectivity [27]. All nodes in MIS set are colored black and other nodes are colored gray. In the second phase, all black nodes are connected by finding a gray node w that is a clustermember of v in and a neighbor of the clusterhead u and color this node blue. Our approach in our algorithm aims to completely connect all nodes by growing a dominating set that locally maximizes throughput and checks the cluster density with respect to other elected clusterheads (backbone nodes). The load balancing throughput maximization in connected clustering algorithm has not been studied in other literature CDS algorithms.

The Distributed Clustering Algorithm (DCA) has two phases. Initially all nodes are colored white. The first phase is to initiate the clustering from an initiator node (without loss of generality, node 1) , which is typically a 50W node. The initiator node is marked black, and its neighbors (such that $a_{1i} = a_{i1}$) are marked gray (Lines 2-6). In the second phase, we will change some grey nodes to black according to a certain rule. A gray node becomes a potential CH if it has at least one white neighbor (Lines 8-12). The potential clusterheads in the set $\mathcal{CH}_{pot}$ broadcast their status and these gray nodes are elected as the clusterhead if it is the only node broadcasting itself as a potential CH or if it has the highest total rate C_i to their white neighbors, among other potential CHs (Lines 13-15). In a protocol, this can be coordinated by the initiator node. If a gray node is elected as a CH it performs two tasks. Firstly, it connects the white neighbors and marks them gray (Lines 16-20). Secondly, it checks the density of neighbor clusters and transfers nodes from denser populated clusters if it is able to provide better rates/SNR (Lines 21-28). In a protocol this can be achieved by a clustermember measuring received SNR and sending a connection request to the CH having fewer nodes and providing the best SNR. This will balance CH loads and improve the overall throughput. Note that interference, i.e. the signtal to noise interference (SINR) levels are not included in the process of swapping nodes between newly elected clusterheads. The process of election of CHs from the gray nodes continues until all white nodes are colored black or grey.

Algorithm 1 : Distributed Clustering Algorithm (DCA)

Initialize $\mathcal{W} = \mathcal{N}$, $\mathcal{G}, \mathcal{B}, \mathcal{CH}_{pot} = \emptyset, ch_i = 0 \forall i \in \mathcal{N}$
First Phase:
for $\forall i$ s.t. $a_{1i} = a_{i1} = 1$ **do**
    $\mathcal{G} = \mathcal{G} \cup i$
    $ch_i = 1$
    $N_1^{user} = N_1^{user} + 1$
end for
Second Phase:
while $\exists i \in \mathcal{G}, j \in \mathcal{W} s.t. a_{ij} = a_{ji} = 1$ **do**
    for $\forall i \in \mathcal{G}$ **do**
        if $\exists j$ s.t. $a_{ij} = a_{ji} = 1$ and $j \in \mathcal{W}$ **then**
            $\mathcal{CH}^{pot} = \mathcal{CH}^{pot} \cup i$
        end if
    end for
    Calculate $C_i = \sum_{j \in \mathcal{W}} c_{ij} a_{ij} a_{ji}, \forall i \in \mathcal{CH}_{pot}$
    $i^* = \arg\max_{i \in \mathcal{CH}_{pot}} \{C_i\}$
    $\mathcal{B} = \mathcal{B} \cup i^*$
    for $\forall j \in \mathcal{W}$ and $a_{ji^*} \times a_{i^*j} = 1$ **do**
        $\mathcal{G} = \mathcal{G} \cup j$
        $ch_j = i^*$
        $N_{i^*}^{user} = N_{i^*}^{user} + 1$
    end for
    for $\forall k \in \mathcal{G}$ **do**
        if $SNR_{i^*,k} > SNR_{ch_k,k}$ **then**
            if $N_{i^*}^{user} < N_{ch_k}^{user}$ **then**
                $N_{i^*}^{user} = N_{i^*}^{user} + 1$
                $N_{ch_k}^{user} = N_{ch_k}^{user} - 1$
                $ch_k = i^*$
            end if
        end if
    end for
end while

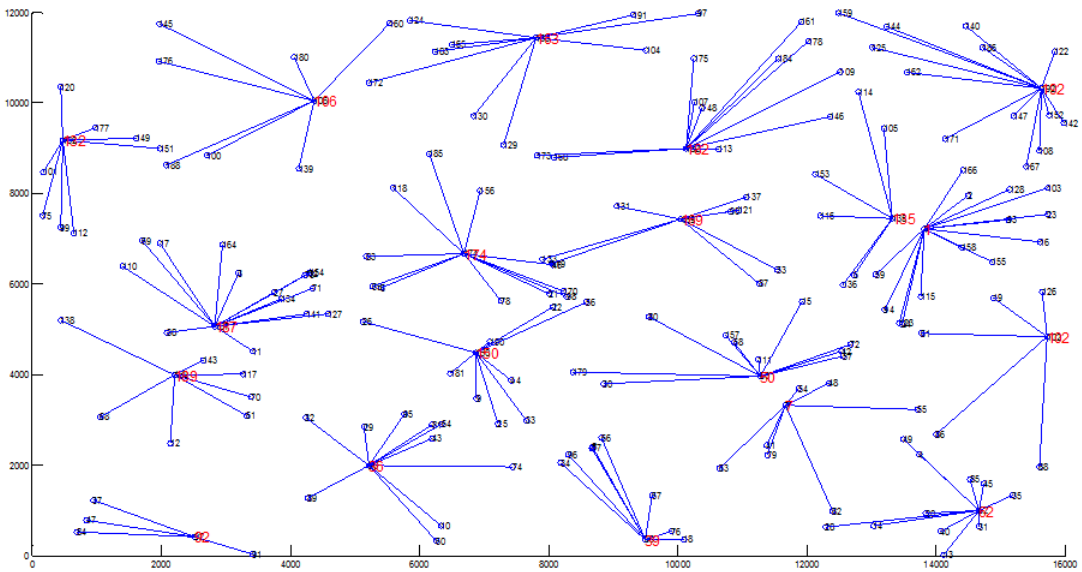

Figure 2.3: Distributed Clustering Algorithm Structure

An example of the clustering structure created by a distributed clustering algorithm is shown in Figure 2.3. Just like the optimal clustering algorithm, the clustering is formed by neighbors close to each other. This shows a positive effect in terms of throughput maximization.

2.3 Comparison of Static Clustering Algorithm to Distributed Clustering Algorithm

This section will compare the static optimal clustering algorithm as a benchmark to the proposed distributed clustering algorithm in terms of performance metrics of hop count and throughput maximization.

The global static maximization parameter aimed to maximize the total troughput of the network. The first performance parametric for distributed algorithm is to compare the equation (2.11)

$$(\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}} x_{ji}c_{ji}) \tag{2.11}$$

Table 2.1: Simulation Parameters: Clustering Algorithm Comparison

Parameter	**Description**	**Value**
f_{min}	Lowest Frequency Level	108 MHz
f_{max}	Highest Frequency Level	225 MHz
W	Frequency Bandwdith	1 MHz
N_0	Noise Spectral Density	-173.5 dBm
N	Radio Unit Count	192
P	Radio Transmission Power	10-50 Watt
I_{max}	Cluster Count	20 for OSC, varying for DCA
	Area km^2	12x16 km^2
	Simulation Count	10

2.3.1 Simulation Parameters

Parameters within the two algorithms are equal. However, in distributed algorithm, the cluster count varies depending on the topology. To give a more reliable result, the throughput will be normalized by dividing the total throughput value by the amount of originated cluster count. The simulation parameters are given in Table' 2.1. In distributed algorithm, we want to stress on connectivity, and there are certain cases when there are edge users left over at the end of the clustering iteration. Our algorithm attempts to load balance this situation by providing loaded cluster members to newly formed clusters. However, at extreme cases it is inevitable that there exists isolated clusters with one or two members.

2.3.2 Results

The algorithms were run for 10 different topologies. The total network throughput comparison is given in Table 2.2.

It can be concluded that the suggested DCA clustering algorithm is sufficiently strong in obtaining a high throughput with respect to our proposed benchmark.

Table 2.2: Simulation Result: Total Network Throughput of OSC and DCA

Simulation #	OSC Throughput	DCA Throughput	Performance
1	9,19E+08	9,17E+08	0,996
2	1,16E+09	1,16E+09	0,995
3	1,03E+09	1,01E+09	0,980
4	1,34E+09	1,25E+09	0,930
5	1,14E+09	1,13E+09	0,992
6	1,40E+09	1,39E+09	0,991
7	1,57E+09	1,55E+09	0,987
8	1,24E+09	1,24E+09	0,996
9	1,20E+09	1,13E+09	0,940
10	1,51E+09	1,42E+09	0,938

90% of the simulations were above the 0.95 performance rate. This is graphically represented in Figure 2.4.

It should be noted that OCA has a fixed 20 clusters per algorithm while DCA had a varying cluster count shown in Table 2.3. This constraint was normalized by obtaining the total throughput per cluster. Edge clusters decrease the rate for some of the DCA performance in comparison to OSC shown in Figure 2.5.

Next, the second important metric in terms of network performance is the hop-count. Hop is one portion of the path between source and destination. Data packets pass through their clusterheads, and other clusterheads as gateways on the way. Each time packets are passed to the next device, a hop occurs. The hop count refers to the number of intermediate users through which data must pass between source and destination, rather than flowing directly over a single broadcast. In a wireless network, the hop-count by itself is not used for determining the optimum network path, as it does not take into consideration the speed, load, reliability, or latency of any particular hop, but merely the total count. Nevertheless, in terms of clustering and comparison of DCA and OSC, it is an important performance metric to show how much loaded the system can get. Since we are using a TDMA approach, the hop-count will be of use.

We first observe the total throughput performance of the proposed and benchmark clustering schemes. Total throughput is measured as the sum of throughput from each node to its respective CH. The total throughput in Fig 2.4 shows that the

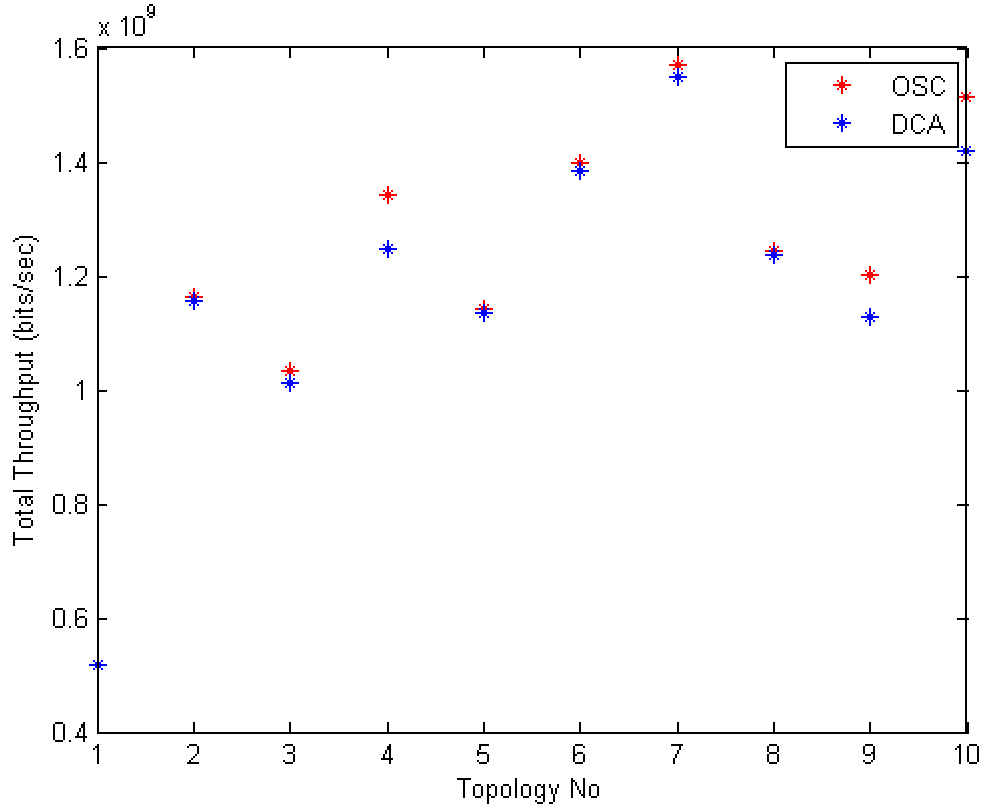

Figure 2.4: DCA OCA Total Throughput Performance

proposed clustering algorithm is in the 5% range of the MILP-based solution. The hop-performance of the distributed clustering have been carried out by testing the average hop count of the entire network for every pair of nodes. Fig 2.6 shows that our Distributed Clustering Algorithm hop-count performance is in the 5% range of the proposed benchmark algorithm.

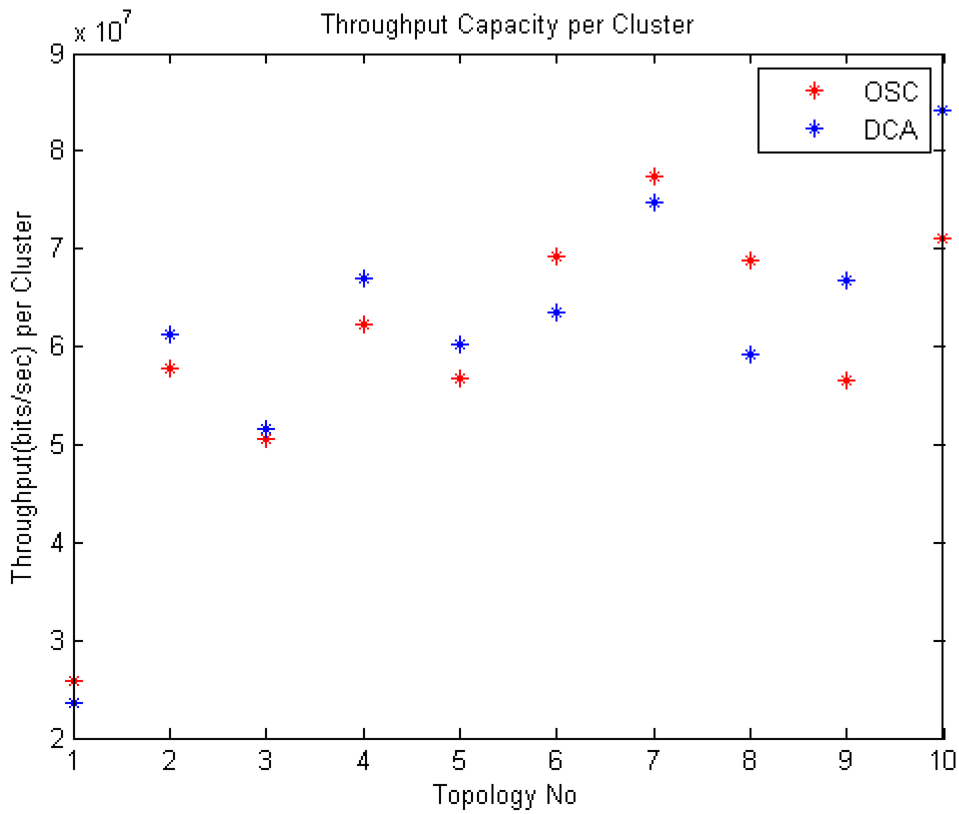

Figure 2.5: Throughout Per Cluster for OSC and DCA

Table 2.3: Simulation Result: Total Cluster Count of OSC and DCA

Simulation #	**OSC Cluster Count**	**DCA Cluster Count**
1	20	22
2	20	19
3	20	20
4	20	20
5	20	19
6	20	22
7	20	21
8	20	21
9	20	18
10	20	18

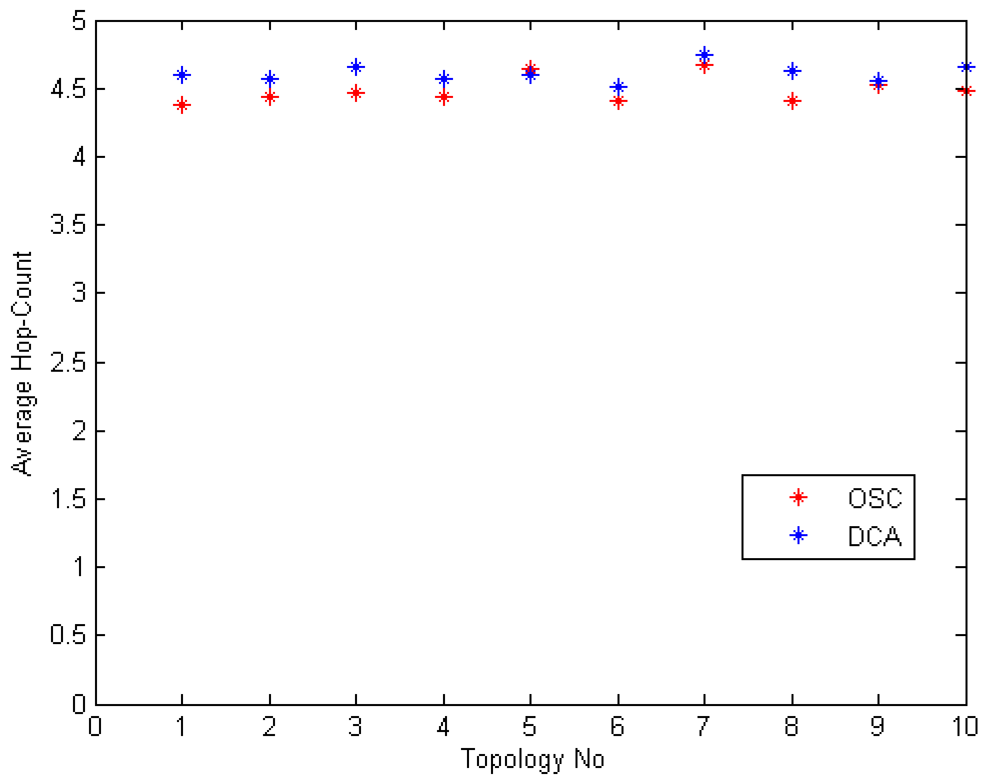

Figure 2.6: Average Hopcount for OSC and DCA

3. FREQUENCY ALLOCATION

The concepts of frequency allocation and frequency hopping were discussed previously. In this section, the algorithms used for benchmark will take place. Again, similar to the clustering chapter, one of the benchmark solution is solved by a MIQP approach on GAMS. The formulation of the two benchmark algorithms and one distributed algorithm will be shown and then the algorithms will be compared on a basic interference to noise ratio test.

3.1 System Model

N users are randomly distributed one the surface shown in Figure 3.1 ve Figure 3.2 [28]. The system is composed of up and down subnets. The blue line indicates the upper subnet where the red line shows the lower subnet in the topology in Figure 3.3. The main subnet has 8 subsubnet in it. Cycles 1-8 are include in the main lower cycle and cycles 9-16 are included in the main upper cycle. 4 of the cycles, 5/9 , 6/10, 7/11 ve 8/12 , are located in the same geographical place. In this situation, when users use the same frequency band in a close location, they create interference. The frequency band is between f_{min} and f_{max} Hz with a bandwidth of W Hz. In total, there are $N_f = (f_{max} - f_{min})/W$ amount of frequencies that can be allocated. The Additive White Gaussian noise is accepted to be N_0W Watt. The users in the system topology have P Watt transmitting power. It is accepted that channel gain is also affected by the first sideband and the second sideband during the communication of the node pairs. The further sidebands are neglected as the small coefficient does not impact the related radio communication.

The channel loss between any i and j user for the frequency f is denoted in the equation (3.1).

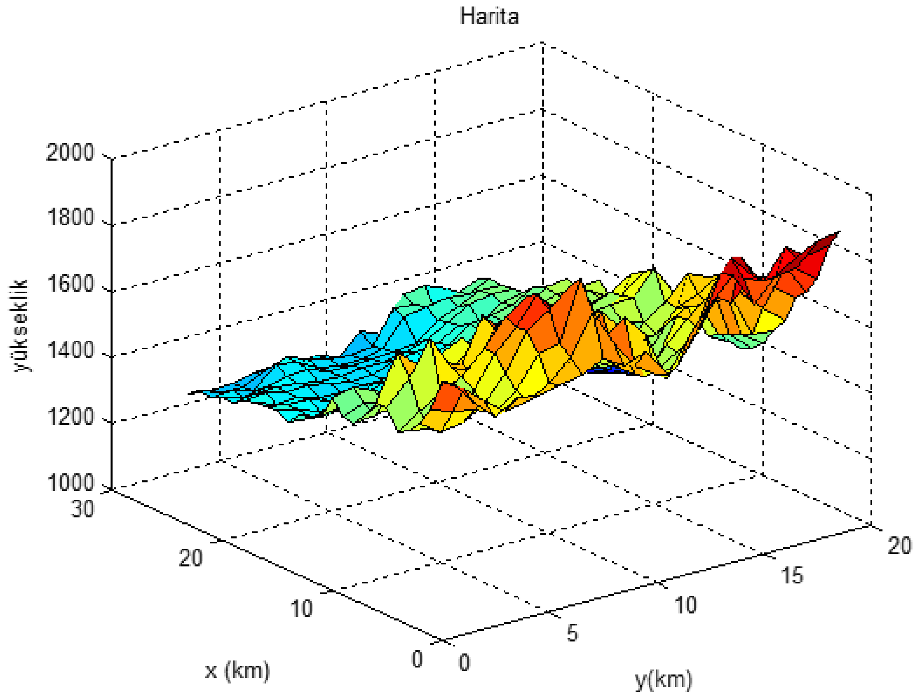

Figure 3.1: Rugged Terrain

$$h_{i,j,f} = 50 + rand[-10, 10] + rand[-10, 10] + randn \times 2 + 26 \times \log_{10}(f) + 42 \log_{10}(d_{i,j}) dB \quad (3.1)$$

The pathloss model, obtained from ASELSAN parameters, uses rand[-10,10] for the location advantage of the users that are considered to be on a rugged terrain. The shadowing pathloss effect is taken as $randn \times 2$ and the distance between the i,j users in km's is shown as $d_{i,j}$.

It has been mentioned that the interference levels are based on the same frequency, the first sideband and the second sideband. When calculating the interference levels, obtained from ASELSAN, the first sideband power coefficient is accepted as $10^{-2.5}$ and the second sideband power coefficient is accepted as 10^{-4} . The further coefficients are neglected.

The amount of frequencies assigned to a cluster was initially set to be at $N^c_{f,min} = N_c$, that is the number of users in the cluster. The frequencies assigned to a

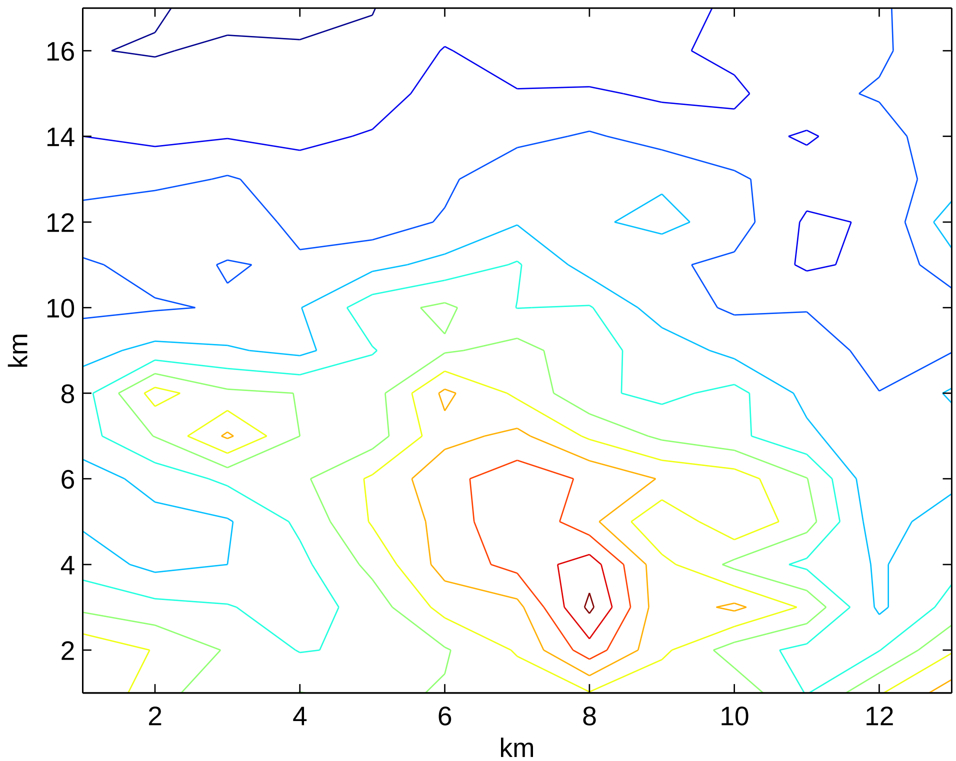

Figure 3.2: Rugged Terrain(contour line)

cluster should have at least one frequency band space in between. Since we use a TDMA structure, we will later on test by assigning little amount of frequencies per cluster and load the cluster with abundant amount of frequencies and see how this responds to the traffic simulations.

The frequencies allocated to a cluster should have at least one band space. Another constraint is that the frequency range of the allocated frequencies of a cluster should be in the range of one octave band. This aims to decrease the effect of the frequency on the channel gain. Three approaches of frequency allocation will be investigated. The first approach is a global simulated annealing approach. Frequency patterns are determined beforehand in group forms. The largest frequency pattern has a length of $\min\{N_f, \alpha \max_c\{N_c\}\}$ and the shortest frequency pattern has a length of $\min_n\{N_c\}$. The frequency pattern set is expressed as Π. If the pattern contains less number of bands than the amount of users in the cluster then that frequency set is not allocated and the pattern is discarded for

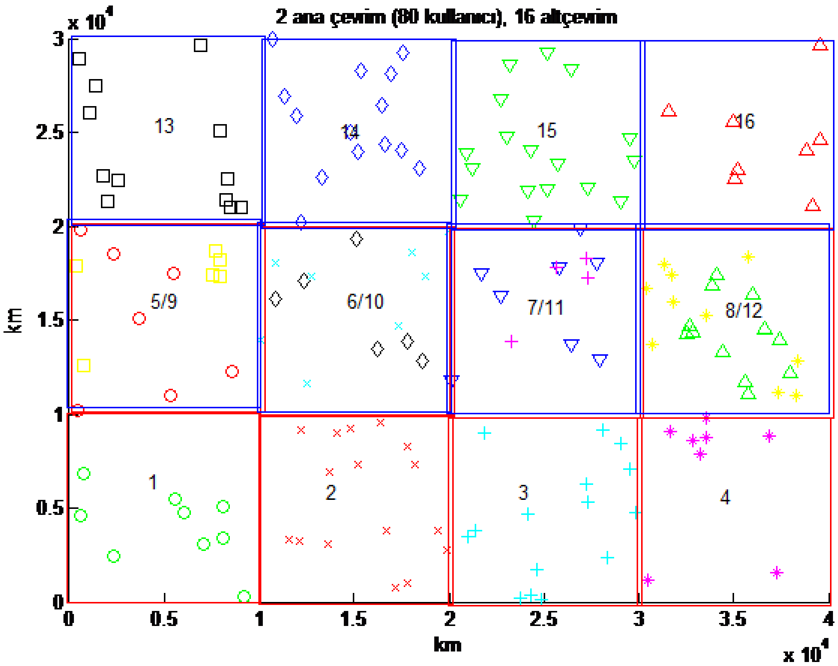

Figure 3.3: Cycle Topology

that specific cluster. Suitable patterns for the cluster c are expressed as Π_c. In this case, the user n of cluster c using channel k creates the interference+noise level expressed in the formulation in Eq (3.2).

$$I_{n,k}(\overline{\pi}) = N_o W + \sum_{c' \neq c} \frac{1}{|\pi_{c'}|} \Bigg\{ \sum_{k \in \pi_{c'}} \sum_{n' \in \mathcal{N}_{c'}} P h_{n',n,k} + \sum_{k+1 \in \pi_{c'}} \sum_{n' \in \mathcal{N}_{c'}} \beta_1 P h_{n',n,k} + \sum_{k-1 \in \pi_{c'}} \sum_{n' \in \mathcal{N}_{c'}} \beta_1 P h_{n',n,k} + \sum_{k+2 \in \pi_{c'}} \sum_{n' \in \mathcal{N}_{c'}} \beta_2 P h_{n',n,k} + \sum_{k-2 \in \pi_{c'}} \sum_{n' \in \mathcal{N}_{c'}} \beta_2 P h_{n',n,k} \Bigg\} \quad (3.2)$$

$|\pi_{c'}|$ inidcates the number of frequency bands assigned to the cluster c'. The average frequency band interference at a lowerchannel decreases as the number of frequency bands $|\pi_{c'}|$ increases. On the other hand it will increase the interference level at other channel levels. The sideband coefficient $\beta_1 = 10^{-2.5}$ and the second sideband coefficient $\beta_2 = 10^{-4}$ are set by the recommendations of ASELSAN. The total interference level of a user n is therefore the average of the whole interference level of the sum of all bands. The mean interference is expressed in Equation 3.3.

$$I_n(\overline{\pi}) = \frac{\sum_{k \in \pi_c} I_{n,k}}{|\pi_c|} \tag{3.3}$$

3.2 Centralized Frequency Allocation

The purpose of Centralized Frequency Allocation is to search and optimize the user exposed to maximum interference. The mean interference levels are taken and the the highest value is set to be minimized. The maximum of the mean user interference is expressed in Equation 3.4

$$F(\overline{\pi}) = \max_{n \in \mathcal{N}} I_n(\overline{\pi}) \tag{3.4}$$

To minimize Equation 3.4 a centralized algorithm, similar to a simulated annealing approach is proposed.

Algorithm 2 Centralized Frequency Allocation Algorithm

Initialization $\pi_c = \emptyset, \forall c = 1, \ldots, C$
for $c = 1 : C$ **do**
    Find $\pi_c^* \in \Pi_c$ pattern that minimizes $F(\overline{\pi})$ and assign the pattern to cluster c ($\pi_c = \pi_c^*$).
end for
$I_{new} = F(\overline{\pi})$
while $I_{old} \neq I_{new}$ **do**
    $I_{old} = I_{new}$
    for $c = 1 : C$ **do**
        Find $\pi_c^* \in \Pi_c$ pattern that minimizes $F(\overline{\pi})$ and assign the pattern to cluster c ($\pi_c = \pi_c^*$).
    end for
    $I_{new} = F(\overline{\pi})$
end while

The proposed algorithm for the allocation of frequency patterns is given in Algorithm 2 resembles the simulated annealing solution approach. This algorithm does not guarantee global optimum. The algorithm works in the following way. Clusters frequency sets are empty and no frequency patterns get assigned at initialization at Line 1. At each iteration, each cluster is examined to find the minimum interference making frequency pattern objective function in Equation 3.4. The frequency pattern has to be a suitable (Π_c) pattern for the cluster c. In the second phase, again the objective function sweeps through clusters 1 to C (Lines $8-10$). This searches for every cluster for a better pattern that decreases the total interference level. If it finds such a pattern, the frequency allocation and interference levels get updated. The iterations continue until no further progress and optimization can be made.

A simulation example of frequency allocation of this algorithm is shown in Table 3.1. It can be concluded that users in the same cycles of 5/9, 6/10, 7/11, and 8/12 shown in Figure 3.3 do not receive colliding frequencies. This indicates that the frequencies allocated are logical. However, this does not guarantee that the neighbor clusters do not get the same frequency band.

Table 3.1: Frequency Allocation by Centralized Frequency Allocation Algorithm

Cluster	User Count	Frequencies $(107.5 + x)$ Mhz
1	9	10 12 14 16 18 20 22 24 26
2	16	13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43
3	15	2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
4	8	1 3 5 7 9 11 13 15
5	6	17 19 21 23 25 27
6	6	1 3 5 7 9 11
7	8	30 32 34 36 38 40 42 44
8	12	19 21 23 25 27 29 31 33 35 37 39 41
9	7	2 4 6 8 10 12 14
10	8	26 28 30 32 34 36 38 40 42 44
11	4	22 24 26 28
12	10	2 4 6 8 10 12 14 16 18 20
13	12	12 14 16 18 20 22 24 26 28 30 32 34
14	14	2 4 6 8 10 12 14 16 18 20 22 24 26 28
15	17	1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33
16	8	22 24 26 28 30 32 34 36

Algorithm 2 minimizes the total frequency interference until it reaches an optimum by testing feasible Π_c patterns for every cluster. The iterations continue until no further optimization is possible and it reaches a local minimum.

This algorithm assumes a centralized implementation and assumes global knowledge of channel conditions between each pairs of nodes. This is certainly not suitable for distributed implementation, but can serve as a benchmark.

3.3 Mixed Integer Quadratic Frequency Allocation

Another suitable benchmark approach is to use mixed integer linear programming MIQP to obtain a global solution that minimizes the total interference level in the network. Similar to Simulated Annealing Algorithm, the minimization of the total interference level will increase the system performance and this will force a frequency allocation scheme where neighbor clusters assign different frequency bands to each other. The MIQP algorithm works on the basis of minimizing Eq (3.2) for every user pair i, j and every frequency f between f_{min} and f_{max}.

The global objective is hence to minimize the cost of interference. Equation (3.5) shows this objective. It takes in consideration of neighbor clusters that are stored in the array parameter xx_{ij}. If the clusters are not one hop neighbors, then it is assumed that they are far away and the interference is neglected. (Later on we will show that in case of when little amount of frequencies are allocated, xx_{ij} clusterhead neighbor parameter has to take in consideration of two-hops instead of one hop neighbors). The w_{ij} is a SNR weight parameter. The stronger SNR value between the users i and j, the more interference they will cause to each other. h_{if} is the output binary variable indicating whether the frequency f is allocated to cluster i. The sideband coefficient is $\beta_1 = 10^{-2.5}$ and the second sideband coefficient is $\beta_2 = 10^{-4}$.

$$\min_h \Big(\sum_{i\in\mathcal{C}} \quad \textstyle\sum_{j\in\mathcal{C}} \sum_{f\in\mathcal{F}} x x_{ij} w_{ij} [h_{if} h_{jf}$$
$$+\beta_1 (h_{if} h_{jf+1} + h_{if} h_{jf-1})$$
$$+\beta_2 (h_{if} h_{jf+2} + h_{if} h_{jf-2})]\Big) \tag{3.5}$$

$$\sum_{f\in\mathcal{F}} h_{if} = \sum_{n\in\mathcal{V}} x_{ni}, \qquad \forall i \in \mathcal{C} \tag{3.6}$$
$$(h_{if} + h_{if+1}) \leq \quad 1, \forall i \in \mathcal{C}, f \in \mathcal{F} \tag{3.7}$$

There are two main constraints. First of all, the number of frequencies assigned should be to the sum of the cluster members shown in Equation 3.6. Secondly, the assigned frequencies to a cluster should have at least one band in between shown in Equation 3.7.

Table 3.2: Frequency Allocation by MIQP-Based Solution

Cluster	User Count	Frequencies $(107.5 + x)$ Mhz
1	15	1 3 5 7 9 11 14 16 19 21 41 48 51 60 62
2	9	32 35 38 65 68 91 93 111 115
3	10	33 36 44 54 66 73 96 98 110 113
4	11	24 33 35 69 71 79 84 96 98 111 114
5	6	29 32 36 69 99 111
6	4	88 103 105 107
7	13	1 3 6 15 18 24 26 28 48 50 52 60 62
8	12	1 3 5 7 9 22 41 43 46 50 52 62
9	6	1 6 50 80 83 85
10	17	1 3 5 7 9 11 13 15 17 19 21 29 40 50 61 63
11	6	27 78 101 103 105 107
12	14	55 73 77 80 82 84 86 88 98 100 102 104 106 108
13	7	1 3 5 27 29 64 117
14	7	45 55 74 89 91 105 107
15	9	12 19 25 59 73 90 93 115 117
16	10	33 38 65 67 76 106 111 113 115 117
17	7	10 12 21 43 45 71 87
18	9	58 70 81 85 88 91 104 106 116
19	13	12 32 34 55 70 75 78 84 91 107 112 115 117
20	7	11 16 41 59 70 103 116

A constraint of assigning different frequencies to neighbor clusters was initially set, however it was removed latter, as the amount of frequencies have become insufficient in certain topologies when a lot of frequency bands were set per cluster. A similar table of the assigned frequencies are shown in Table 3.2. The assigned clusters can be compared with the topology assigned for these frequency sets in Figure 3.4. It is visible that same frequencies are not assigned to neighbor clusters. In fact, all first coefficient and second coefficient sidebands are avoided completely. This shows that this algorithm can be used as benchmark instead. Performance analysis will be shown in the traffic simulation chapter.

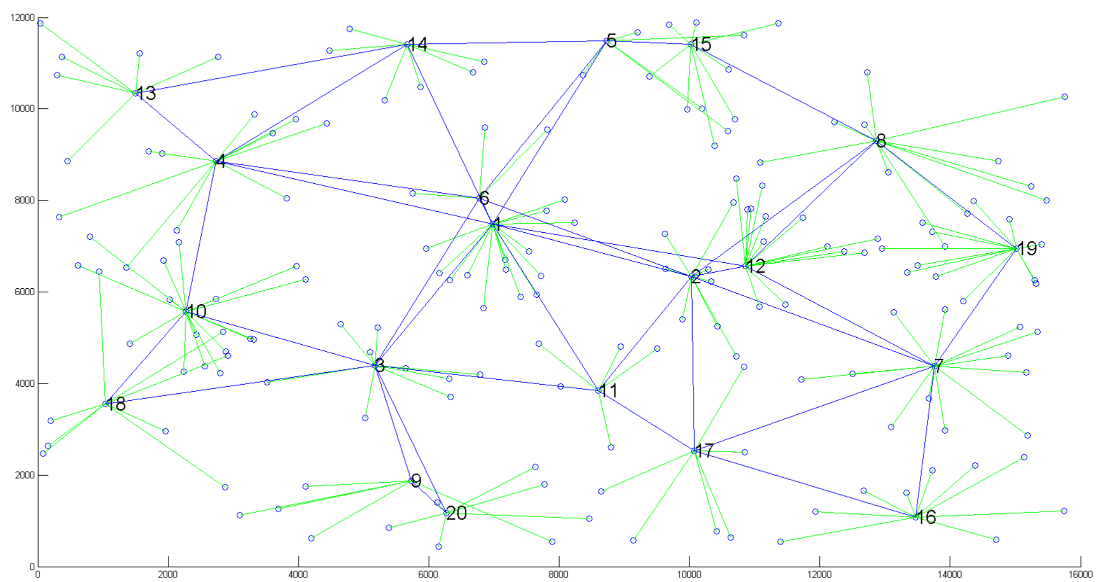

Figure 3.4: Clustering Topology for Frequency Allocation in Table 3.2

3.4 Distributed Frequency Allocation Algorithm

The distributed frequency allocation algorithm works on a marking process principle. Initially, all the clusterheads are colored white and have available frequency set $\Pi_c = \Pi$. In the first phase, the initiator node is colored black and allocates itself a set of channels π_1 (Lines 2-3). The channel set π_1 and the sideband channel set $\pi_1^{'}$ are removed from the available set of its neighbor clusterheads (Line 5); neighbor clusterheads cannot use these and adjacent (sideband) channels. In the second phase, clusterheads that have received a frequency set, marked black, checks whether they have a white neighbor -an unassigned clusterhead neighbor- that has not received a channel set (Line 10). The available channel set Π_i for every white cluster i gets updated (Line 14). A clusterhead allocates itself a set of frequency bands from its available set (Line 11). The available set gets re-updated by including side channels if there are insufficient available channels (Line 26). In a protocol implementation each CH can observe the control channels, and once one of its neighbors perform an allocation, it can start its own frequency allocation based on the allocation of neighbor CHs.

The proposed allocation algorithm is much simpler than the benchmark solution, as it does not assume full channel information, and only assumes CH neighbor information instead.

Algorithm 3 : Distributed Frequency Allocation Algorithm (DFA)

Initialize $\Pi = \{1, ..., N_f\}, \mathcal{W} = \mathcal{CH}$, $\mathcal{B} = \emptyset, \pi_c = 0 \ \forall c = \mathcal{CH}, \Pi_c = \Pi \ \forall c = \mathcal{CH}$
First Phase:
$\mathcal{B} = \mathcal{B} \cup 1$, $\mathcal{W} = \mathcal{W} \setminus 1$
allocate $\pi_1 \subseteq \Pi_1$ s.t. $|\pi_1| = N_1$
for $\forall c$ s.t. $a_{1c} = a_{c1} = 1$ **do**
    update $\Pi_c = \Pi_c - \pi_1 - \pi_1^{'}$
end for
Second Phase:
while $\exists i \in \mathcal{W}$ **do**
    for $\forall i \in \mathcal{W}$ **do**
        if $|\Pi_i| \geq N_i$ **then**
            if $\exists c \in \mathcal{B}$ s.t. $a_{ic} = a_{ci} = 1$ **then**
                allocate $\pi_i \subseteq \Pi_i$ s.t. $|\pi_i| = N_i$
                $\mathcal{B} = \mathcal{B} \cup i$, $\mathcal{W} = \mathcal{W} \setminus i$
            else
                for $\forall c \in \mathcal{CH}$ s.t $a_{ic} = a_{ci} = 1$ **do**
                    update $\Pi_c = \Pi_c - \pi_i - \pi_i^{''}$
                end for
                if $|\Pi_i| \geq N_i$ **then**
                    allocate $\pi_i \subseteq \Pi_i$ s.t. $|\pi_i| = N_i$
                    $\mathcal{B} = \mathcal{B} \cup i$, $\mathcal{W} = \mathcal{W} \setminus i$
                else
                    allocate $\pi_i \subseteq \min \Pi_{used}$ s.t. $|\pi_i| = N_i$
                end if
            end if
        end if
        for $\forall c \in \mathcal{CH}$ s.t $a_{ic} = a_{ci} = 1$ **do**
            update $\Pi_i = \Pi_i - \pi_c - \pi_c^{'}$
        end for
    end for
end while

3.5 Frequency Allocation Performance Analysis

This section explores the performance of the frequency allocation algorithms. A detailed analysis will be further put in traffic simulation results. An important notion is that the first algorithm was based on all traffic users communicating at the same time. In that case, interference is unavoidable. However, in a military application, the amount of users communicating varies. Therefore a random traffic generation will be a good way of observing the possible interference effects. The other aspect is that the system uses TDMA. This means that the collision of two same frequencies is even lower. In other words, even if the two neighbors get the same frequency, they may never use the same frequency at the same time. This effect will be studied in the continuation of the research. This section will compare the CFA (Centralized Frequency Algorithm) to DFA (Distributed Frquency Algorithm).

3.5.1 Simulation Parameters

The algorithms were compared using the parameters shown in Tabke 3.3'. A network, consisting of 192 members are allocated with 117 different channels. At least 75 channels are assigned to more than one user. The highest frequency level will be later on changed to 188 to compare the effects of using few/a lot frequencies in traffic analysis.

Table 3.3: Simulation Parametersi for Frequency Allocation Algorithms

Parameter	**Description**	**Value**
f_{min}	Lowest Frequency Level	108 Mhz
f_{max}	Highest Frequency Level	225 Mhz
W	Frequency Bandwdith	1 Mhz
N_0	Noise Spectral Density	-173.5 dBm
N	Radio Unit Count	192
P	Radio Transmission Power	10-50 Watt
I_{max}	Cluster Count	20
	Area km^2	12x16 km
	Simulation Count	10

3.5.2 Results

The algorithms were compared by searching for the worst user exposed to the highest interference level in the scenario where all users were transmitting at the same time. This would give the result for the interference to noise ratio. The noise is static and is known to be N_0W . The interference is expressed as I and the aim is to see whether the interference to noise ratio I/N_0W is similar to each other for the worst case users. The lower the ratio the better the situation. Figure 3.5 shows the ten different topology cases for the interference to noise ratio. CFA represents the centralized frequency allocation algorithm, MIQP is the solution obtained by mixed integer quadratic programming and DFA is Distributed Frequnecy Algorithm.

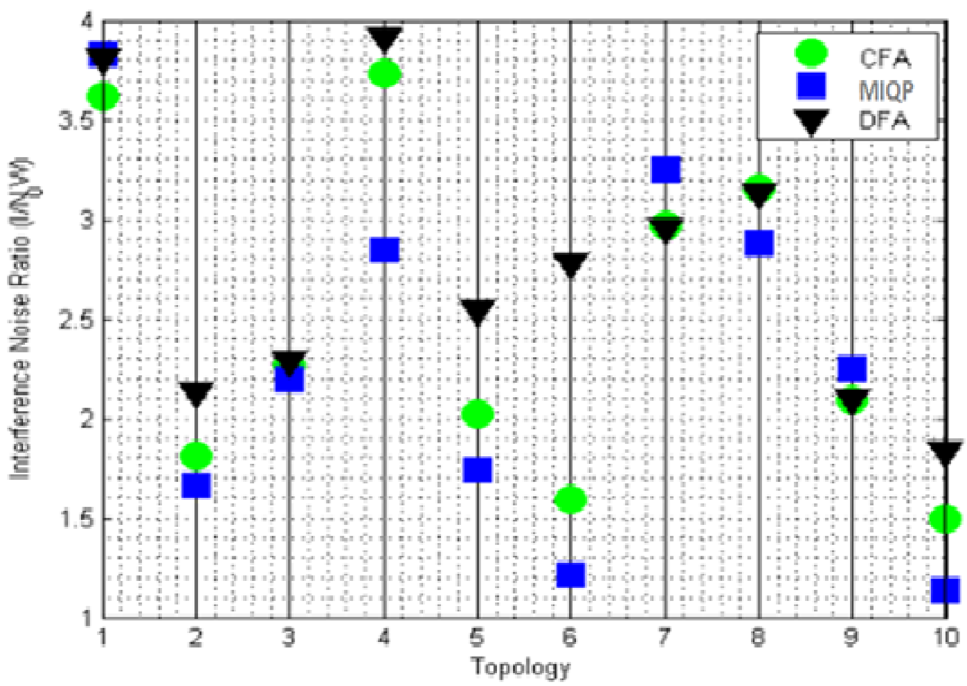

Figure 3.5: Frequency Algorithm Test

The results show that both centralized and MIQP frequency allocation results show similar results in providing the least interference for the worst case user. When the centralized frequency algorithm searches for a solution minimizing interference of the neighborhood clusters, it automatically decreases the interference of the worst case user. The results of the distributed clustering algorithm naturally gives a higher worst case interference levels. Nevertheless, it is sufficient to approve the expecetations of a lower interference level compared to a static frequency allocation. It has been seen that the levels of interference to noise ratio can raise by a factor varying from 300 to 9000 when frequency allocation is not applied and thus the benchmark and proposed dsitributed algorithms can be considered to be a positive result for minimizing the interference levels. The implementation of the frequency algorithms will be further discussed in the traffic simulation results.

4. ROUTING AND TRAFFIC

In the previous chapters, the clustering and frequency allocation formulations and algorithms were introduced. In this chapter, the proposed algorithms will be tested in a simulated environment created by MATLAB. In terms of application level, the various routing algorithms will be discussed and the latencies of the end-to-end communication will be analyzed for the different proposed scenarios.

4.1 Routing

Routing is the process of selecting the paths in a network. Packets are forwarded from source to destination via choosing the next hops known as the intermediate nodes. The routing algorithms for wireless networks can be tricky when nodes are mobile that connect in a dynamic manner. During the process of communication, The mobile unit can move geographically and when it goes out of range, the clustering algorithm has to recalculate its infrastructure and routing paths once again. However, this thesis focuses on a static case, and nodes are considered to be stationary throughout the simulation process. For this reason, the Dijkistra's shortest path routing algorithm [29] is sufficient to be the routing algorithm for the traffic simulations. Dijkistra Algorithm solves the shortest path problem by assessing non-negative edge path costs, producing a shortest path tree. This table-driven algorithm is assumed to be global in our system since the infrastructure of the clustering scheme is fully connected. The cost function of the Dijkistra Algorithm is given in Equation (4.1). Based on the ASELSAN radio communication networks, a connection is accepted when the signal to noise ratio SNR is above $17dB$. Then if there is a connection the cost of transmission is $Cost_{ij} = 1/SNR_{ij}$. Otherwise the cost is accepted as $Cost_{ij} = \infty$.

$$Cost_{ij} = \begin{cases} 1/SNR_{ij}, & SNR_{ij} \geq 17dB \\ \infty, & SNR_{ij} < 17dB. \end{cases} \quad (4.1)$$

The cost (4.1) aims to make the source packets reach the destination with the minimum hops. Packet loss between the user i and user j does not occur unless the transmission signal to noise ratio is below 7dB. The higher the SNR the more packets can be sent simultaneously, and by Shannon's capacity theorem there is a reciprocality between the cost and the SNR levels of the user i and user j.

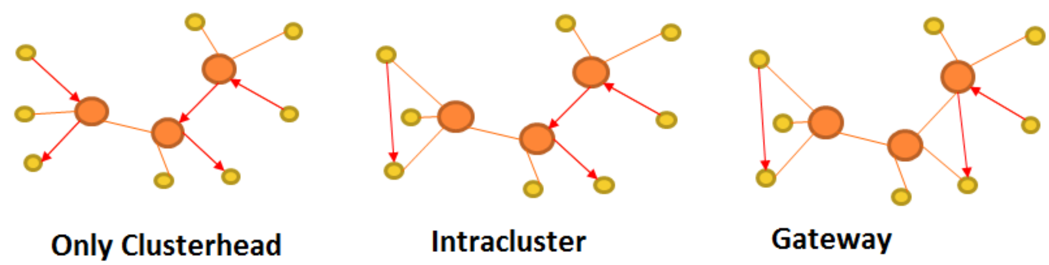

Figure 4.1: Three Routing Methods in Clustering

Additionally, there are several ways the routing can occur in a clustering network. The three types shown in Figure 4.1 are the most popular routing procedures in a clustering environment. The Type 1 routing method occurs by making the clusterheads the main routers of the system. Only the clusterhead can route information to the destination node. All inter-cluster and intra-cluster communication occurs through clusterheads. The source node has to send the information to the clusterhead in order to make a successful transmission. In Type 2 routing case, intra-cluster messages are allowed. Members inside a cluster can directly send information to each other without loading the clusterhead. The Type 3 routing option is to use gateways. This can be achieved by using inter-cluster communication where clusterheads that have a sufficient connection with a cluster member outside of its cluster can send information directly to those members outside of their cluster. This decreases the hop count and can be useful in unloading the traffic in the network more quickly. We have found from the simulations that Type2 routing is the most favourable in most of the cases in our system model and Type 1 is the least unfavourable (Results are shown in Section V). The delay performance is decreased by 66% in Type 1 routing. However, ASELSAN has indicated that Type 1 routing should be used, as their systems intend on using clustering to decrease overheads, and members will be able to transmit information only via their clusterheads. Unfortunately, this results in certain traffic, such as video to cause congestion.

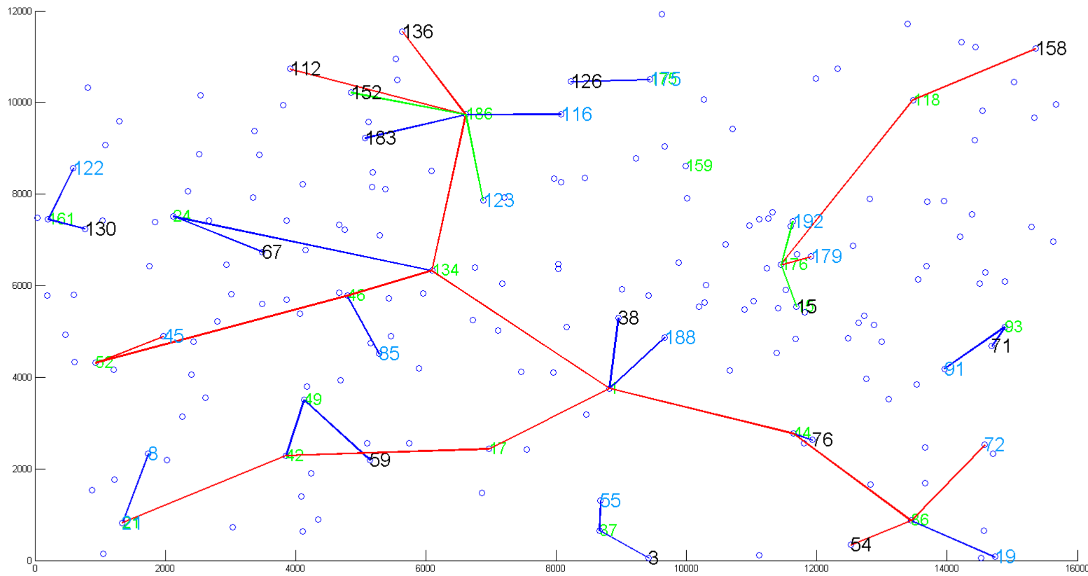

Figure 4.2: Network Traffic Example

4.2 Network Traffic

A traffic has been applied to our proposed communication system using clustering and frequency algorithms. The Military Radio Communication Systems use three main data types in their communication. These are Voice, Video and Command&Control messages. Command & Control and Voice messages have a high sensitivity towards delay and video communication requires a good amount of bandwidth to be efficient. These traffic types are generated randomly by random users between the transmitter and receiver. This requires a proper planning. An example of the network traffic is shown in Figure 4.2. The lines represent the routing and the intermediate nodes of the source-destination pairs. The red paths are command&control traffic type, the blue paths show the voice traffic type and the green path shows the video path. The source destinations are written in blue. The destination nodes are labeled as black.

The clusterheads are labeled in green. The voice messages and video packets are usually occur in a similar geographical position. Command&Control messages are sent to longer distances. Since the routing occurs through clusterheads, there are many traffic crossovers at clusterhead locations. For instance, the clusterheads 1,14,16,134,176,186 have multiple flows passing through them.

4.2.1 Adaptive TDMA

Depending on the clustering algorithm, the algorithm makes around 20 clusters with an approximate of 10 users per cluster. Each member receives a slot reservation of 1ms. A cluster member waits approximately for 10ms to make a new transmission in a classical TDMA approach. In a populated cluster, this delay increases linearly. This complicates the success rate of users sending video and command & control messages that require a certain bandwidth and low delay. This also creates a bottleneck for traffics that pass simultaneously over one clusterhead. Since control messages take place between the clusterhead and its members, the clusterheads knows the amount of active users transmitting packets to the destinations. For this reason, it can be assumed that the clusterhead can make a proper division of time for its active users such that the bandwidth is used efficiently. This becomes an adapted TDMA where the time slots are allocated only to active transmitting members and clusterheads.

An example will be sufficient to illustrate the traffic model integrated in the clustering environment. Figure 4.3 gives a sample topology where it shows the cluster structure and the members connected to it. This example is the continuation of the traffic example given in Figure 4.2. The green lines shows the members that are connected to the clusterhead. The blue line represents the connectivity of the clusterheads. The blue line also shows the main routing path of the system since most of the routing passes over the clusterheads. This is the reason of the many traffic crossovers in Figure 4.2. The cluster structure for the given example is shown in Table 4.1 which implies that the cluster size varies, and this can cause higher traffic in certain central clusters than others.

This scenario example uses 12 transmitter and receiver pairs. The cluster

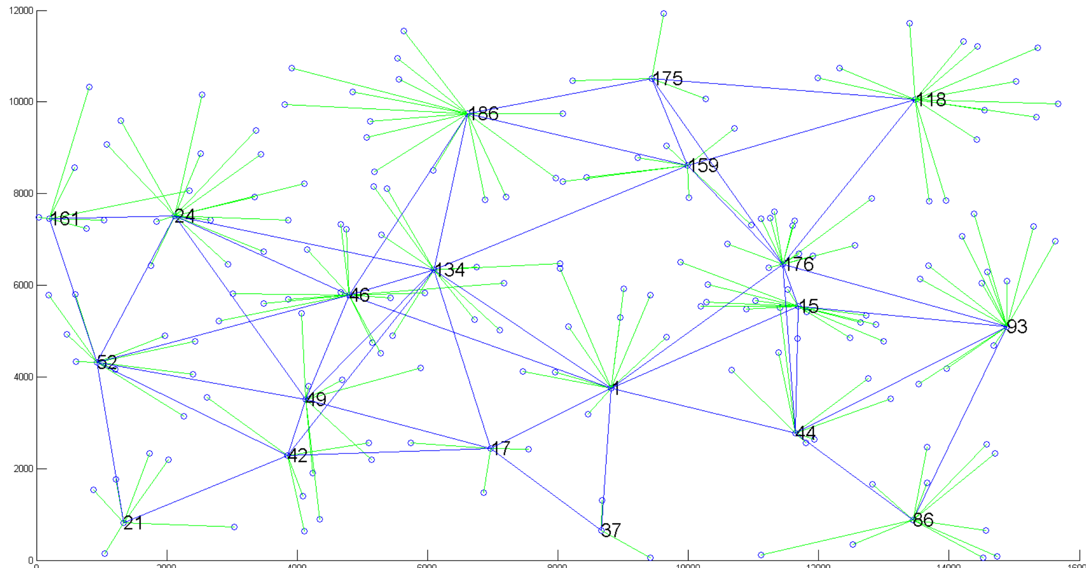

Figure 4.3: Clustering Sample

structure in Table 4.2 shows that nodes can communicate directly only if they are clusterheads. All other members have to transmit data over clusterheads. Voice traffic usually is sent in 2 hops, as it is geographically close and has to transmit the message over the clusterhead. Video communication is similarly set to geographically close locations. On the other hand command & control messages are sent in around 5 hops. This will be further simulated and analyzed in the Section V of the Simulation Results.

Table 4.1: Cluster Members in a Sample Clustering Structure

Clusterhead	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**#11**	**#12**	**#13**	**#14**	**#15**	**#16**	**#17**	**#18**	**#19**	**#20**
Clusterhead No	**1**	**176**	**134**	**44**	**17**	**24**	**186**	**118**	**42**	**93**	**46**	**86**	**159**	**37**	**15**	**52**	**21**	**175**	**49**	**161**
Member No	1 13 16 19 20 25 34 59 60 70 177	29 35 42 44 45 46 54 87 91 148 159	6 38 41 55 65 67 80 101 145 171 172	7 17 36 75 88 89	11 24 28 76 79	69 102 129 161 165	3 9 14 21 32 33 64 81 93 94 110 114 120 130 142 168 173 175	96 109 113 122 124 138 163 179	5 15 18 27 49 57 71 72 73 83	63 77 78 103 104 108 118 135 136 151 166	4 22 23 39 47 62 143	126 127 157 162 164 169 174 178	99 121 123 133 147 176 182	30 105 139 149 150 160 167	2 8 48 51 56 61 66 84	82 106 115 117 125 134 156	12 53 97 107 112 116 128 137 158 170	98 100 119 141 152 154 180 181	43 50 68 74 86 90 92 131 155	95 140 144 146
Total Number of Nodes	10	11	11	6	5	5	18	8	10	11	7	8	7	7	8	7	10	8	9	4

Table 4.2: Routing Information for the Sample Example

Source Node	Destination Node	Intermediate Nodes				
8	59	21	42	49		
85	67	46	134	24		
122	130	161				
116	183	186				
91	71	93				
19	76	86	44			
55	3	37				
175	126	126				
188	38	1				
21	54	42	17	1	44	86
45	136	52	46	134	186	
179	158	176	118			

The adaptive TDMA does the following. It reserves slots for active users only. The Table 4.3 shows the active transmitting nodes within the cluster formation.

This adapted TDMA allows clusters 4,5,6,8,9 to use make full transmission, cluster 2 (user 179 and 176), cluster 10 (user 91 and user 93) and cluster 11 (user 85 and user 46) to make transmission every 2 milliseconds. Cluster 12 members transmit every three milliseconds. This creates an advantage for active transmitting units to effectively use the channel. Clusters 15 members receive transmission and cluster number 13 is inactive. Also, clusterheads have a comparative advantage since most of traffic routing passes through them. For every new source routing over them, transmitting clusterheads take up an extra reservation on the TDMA slot. Therefore, when a lot of different traffic passes through one clusterhead, most of the reservation is covered by the clusterhead.

Table 4.3: TDMA Reservation

Clusters	Transmitting Nodes
#1	188 1
#2	179 176
#3	134
#4	44
#5	17
#6	24
#7	116 123
#8	118
#9	42
#10	91 93
#11	85 46
#12	19 86 72
#13	
#14	55 37
#15	
#16	45 52
#17	8 21
#18	175
#19	49
#20	122 161

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4.2.2 Voice

Voice data are specified in the table below. Voice communication has a high importance level in military communication systems. This type of communication requires low delay and a continuous transmission. The traffic model used is shown in Table 4.4.

Table 4.4: Voice Traffic Model

End-to-End Delay	250 ms
Jitter Tolerance(ms)	Included
Speed	19.2 Kbps
Packet Gap Type and Generation Distribution	22.5 ms
Mean Call Time	Üssel $\mu = 5min$
Mean Talking Time	1026 ms
Mean Silence Time	1171 ms
Mean Call Distribution	Üssel $\mu = 5min$
Protocol	UDP

4.2.3 Command & Control

Command & Control packets are crucial in military systems. New decisions should be instantaneously reported to the soldiers and this requires a low delay. The command & control messages show similarity to FTP traffic. The parameters used for command & control messages are shown in Table 4.5 [30].

Table 4.5: Command & Control Traffic Model

End-to-End Delay	1000 ms
Jitter Tolerance(ms)	Included
Speed	6Kbps
Packet Gap Type and Generation Distribution	FTP Exponential $\mu = 120ms$
Average Package Distribution and Package Size	Truncated Pareto $\mu = 480bmax = 720b$
Protocol	UDP

4.2.4 Video

Video communication requires a high bandwidth. Military communication uses video application nevertheless in our current system, a real time video traffic causes a lot of congestion in the network. The model we used for video traffic is an approximation to the realistic version based on the requirements of the ASELSAN for a real time video application. This requires priority. To provide the needs, the network ideally should be free of transmission. The parameters used in video model are given in Table 4.6 [31].

Table 4.6: Video Traffic Model

End-to-End Delay	1000 ms
Jitter Tolerance(ms)	Included
Speed	128-256Kbps
Average Package Distribution and Package Size	Truncated Pareto $\mu = 10Kbmax = 24Kb$
Packet Generation Gap	60 ms(10fps)
Protocol	UDP

5. TRAFFIC SIMULATION RESULTS

The simulations we have produced were used for the rugged terrain shown in Figure 3.1 that have a contour lines of Figure 3.2. The users got a location advantage between $+10dB$ and $-10dB$. The highest user in altitude received $+10dB$ and the lowest user in altitude receive $-10dB$, and the other users were got a linear distribution of location advantage depending on their altitude. Hence higher altitude users have a higher channel gain. This feature was included in certain simulations and were not used in others, for instance when we wanted to measure the effects of clustering or frequency allocation only, the random location advantage could distort the results. Furthermore, the location advantage parameter does not consider of interference caused by objects, such as the possible mountain block in between two users. Nevertheless, this modeling of location advantage is suitable for simulation purposes.

5.1 QUALNET and Clusterhead Routing

Table 5.1: Traffic Parameters for QUALNET Simulation

Parameter	**Value**
Node Count	20
Traffic Generation	10
Node Distribution	Random (Using terrain)
Mobile Nodes	None
Radio Mac Level	802.11b
Traffic Model	CBR (512bit 1000adet, eşit zamanlı)
Queue Model	FIFO
Routing Protocol	Static Routing (only clusterhead) Bellman Ford (gateway)

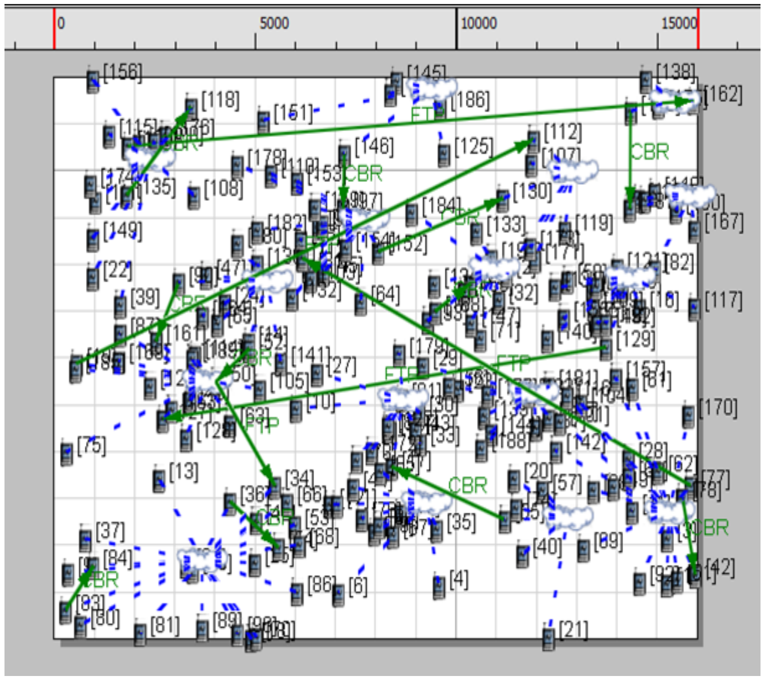

Figure 5.1: Qualnet Traffic Simulation

Initially, the effects of routing protocols for clustering environments were investigated. For this, I ran a simple simulation of 192 nodes that are communicating with each other on a 802.11b radio level. The actual MAC level of the military radio communications are different. The effects of routing over clusterheads were compared by producing 10 CBR traffics. The frequency band is fixed and the clustering nodes are obtained using MILP based solution. The topology and the traffic is crudely given in Figure 5.1. The clusters are represented in subnets that are shown as bubbles in the figure. The gateway routing simulation is done by making a Bellman Ford routing, and the clusterhead routing is made by configuring the routing to a static routing solution, i.e. all members can communicate with the clusterheads only and the clusterheads can communicate with other clusterheads. The simulation parameters are shown in Table 5.1.

The simulation was produced on Qualnet Network Simulator [32]. Results showed that Type 1 routing through only clusterheads increases the end-to-end delay. This is reflected in the results shown in Table 5.2 where, the gateway routing has been more efficient up to 60%.

Table 5.2: Results for QUALNET Traffic Simulation

Source Node	**Gateway Routing (Bellman Ford)**	**Clusterhead Routing (Static)**
135	0.0234	0.0287
152	0.0397	0.0829
90	0.0427	0.0496
55	0.0314	0.0743
166	0.0527	0.0632
78	0.0681	0.0748
52	0.0743	0.1018
36	0.0652	0.0711
168	0.0337	0.0201
83	0.0154	0.0586

Qualnet Network simulator is a powerful tool in testing network applications. However it does not support a protocol that allows frequency allocation schemes to be applied on a wireless ad hoc network. For this reason we were not able to use Qualnet efficiently for this research purpose. Instead, we formulated an environment using MATLAB.

5.2 MATLAB Traffic in Clustered and Frequency Allocated Network

The simulation takes place in an area of $12 \times 16km^2$ rugged terrain. The users emit either $10W$ or $50W$ power. The number of nodes emitting $50W$ power changes in every simulation, and the initiator node 1 always emits $50W$. At initialization, clustering is allocated either by MILP based centralized solution or by a distributed clustering algorithm. After clustering is complete, frequency allocation is made either by MILP based centralized solution or by the distributed frequency algorithm. Independent and random users are chosen that will send voice, command & control and video traffic after initialization. The routing algorithm used for this event will be Dijkstra shortest route path algorithm. The routing will occur through clusterheads only.

5.3 Simulation Scenario

The rugged terrain is divided into 12 regions of $4 \times 4km^2$ area. The amount of traffic varies from simulation to simulation based on the principles that voice traffic travels within a single region. The source and destination users are randomly chosen. Similarly, the constraint for command & control traffic is that source traffic has to travel to different region destinations. The source user and destination user are picked randomly. Video traffic requires a high bandwidth which consumes most of the channel capacity. This requires a high amount of TDMA slot reservation. Video traffic source are generated for the same or close region destinations. The amount of video traffic is considered to be a lot less than command & control or voice communication traffic. The adaptive TDMA structure allocates the reservation slots for the transmitting source members and the intermediate nodes at the start of the simulation. The frequency patterns are automatically generated based on the frequencies allocated to clusters and the frequencies are used in a subsequent order. This creates a semi random topology that would reflect a military based deployment communication as shown in Figure 4.2.

The chosen source nodes start generate traffic for a chosen period of time. One packet is 500bits. The simulation continues till the last generated packet is sent to the destination node (unless the packet is dropped). In military communication voice and command & control traffic have a high priority level. Video traffic is important too, however it can be classified as less important. For this reason, voice and command & control packets have a priority over video traffic. Command & control packets have the highest priority level. The priority level gets activated only after when traffic packets has accumulated a high delay over $50ms$ after their generation time. Besides the types of traffic, there is no priority for specific nodes in the network. The system works as a first in first out FIFO model for all packets. Priority levels helps to decrease end-to-end delays in a loaded traffic configuration. The transmission within a specified time slot is accepted to be successful if the signal to noise ratio $SINR$ is above $7dB$. The latest signal to interference noise ratio $SINR$ levels are stored in the nodes, where depending on the $SINR$ levels the following number of packets are sent:

1. 1 packet is sent if signal to noise interference level is above 7dB
2. 2 packets are sent if signal to noise interference level is above 13dB
3. 3 packets are sent if signal to noise interference level is above 17dB

If the SINR level satisfies the conditions during the transmissions the packets are sent.

Another important aspect in the simulation is the requirement of making at least 2 successful transmissions per packet. The re-transmission feature is important in military communications to make a reliable and robust transmission that will not get affected by jammers. Hence once the intermediate node receives 2 identical transmissions it accepts the packet as successful and continues to rout the packet to its destination.

5.4 Routing Simulation on MATLAB

This section will consider the three different routing schematics offered in Figure 4.1. The Type 1 routing is set to rout only through clusterheads. Type 2 routing is set such that inter-cluster communucations routs only through clusterheads and intra-cluster communication can take amongst all members. Type 3 routing allows gateway communication, such that clusterheads can directly send messages outside of their cluster to other cluster members.

5.4.1 Simulation Parameters

Table 5.19 shows the parameters used for testing the Type 1, Type 2 and Type 3 routing shown in Figure 4.1. The different routing proposals are tested for a traffic that is generated for 60 seconds. The traffic consists of 10 voice , 10 command & control and 2 video traffic. The algorithm used for frequency allocation is simulated annealing, and the clustering formulation is based on MILP solution. The first five simulations are provide in Tables 5.4,5.5 and 5.6.

Table 5.3: Traffic Simulation Parameters for Different Clusterhead Routing Types

Parameter	**Description**	**Value**
f_{min}	Lowest Frequency Level	108 MHz
f_{max}	Highest Frequency Level	225 MHz
W	Frequency Bandwdith	1 MHz
N_0	Noise Spectral Density	-173.5 dBm
N	Radio Unit Count	192
P	Radio Transmission Power	10-50 Watt
Clustering		$MILP$
Frequency Allocation		CFA
Area		$12 \times 16km^2$
Voice Traffic		10
Command & Control Traffic		10
Video Traffic		2
Traffic Duration		60000 ms (1min)

5.4.2 Simulation Results

In Type 1 routing (only clusterhead routing), simulations 1 and simulation 3 produce high delay for the video packets. All other packets are sent in the constrained time below $250ms$. The Command & Control packets receive priority when the video packets overload the network. In Type 2 routing (Intra-cluster communication is allowed), similarly simulation 1 and simulation 3 fail for video packets and succeed in others. Note that the maximum delay of Type2 is lower than Type1. Type 3 (Gateway routing) simulations has succeeded in all cases.

Table 5.4: Type 1 Routing Traffic Simulation Results

Simulation	Parameter	Traffic Type		
		Command and Control	**Voice**	**Video**
1	Mean Transfer (ms)	11	16	10430
	Mean Delay (ms)	10	16	10603
	Max Delay (ms)	39	24	32406
	Packet Number	10588	5220	17517
	Mean SINR (dB)	24	15	13
2	Mean Transfer (ms)	11	2	4
	Mean Delay (ms)	11	2	4
	Max Delay (ms)	25	3	7
	Packet Number	9415	5220	17517
	Mean SINR (dB)	11	16	18
3	Mean Transfer (ms)	32	3	6284
	Mean Delay (ms)	33	3	6284
	Max Delay (ms)	55	7	30007
	Packet Number	9312	6525	17517
	Mean SINR (dB)	15	27	12
4	Mean Transfer (ms)	5	2	3
	Mean Delay (ms)	5	2	5
	Max Delay (ms)	10	4	9
	Packet Number	11809	5220	15000
	Mean SINR (dB)	8	7	7
5	Mean Transfer (ms)	8	3	3
	Mean Delay (ms)	8	3	3
	Max Delay (ms)	16	7	5
	Packet Number	10388	5220	17517
	Mean SINR (dB)	15	13	17

Table 5.5: Type 2 Routing Traffic Simulation Results

Simulation	Parameter	Traffic Type		
		Command and Control	**Voice**	**Video**
	Mean Transfer (ms)	12	3	8830
	Mean Delay (ms)	13	3	8831
1	Max Delay (ms)	22	11	30598
	Packet Number	10588	5220	17517
	Mean SINR (dB)	20	13	8
	Mean Transfer (ms)	12	2	24
	Mean Delay (ms)	14	2	25
2	Max Delay (ms)	27	3	57
	Packet Number	9415	5220	17517
	Mean SINR (dB)	31	0	0
	Mean Transfer (ms)	5	2	9723
	Mean Delay (ms)	34	2	9724
3	Max Delay (ms)	59	12	28039
	Packet Number	16241	5220	17517
	Mean SINR (dB)	31	14	27
	Mean Transfer (ms)	9	2	32
	Mean Delay (ms)	433	2	36
4	Max Delay (ms)	3589	7	69
	Packet Number	11809	5220	15000
	Mean SINR (dB)	8	8	7
	Mean Transfer (ms)	8	2	3
	Mean Delay (ms)	9	2	3
5	Max Delay (ms)	12	5	5
	Packet Number	10388	5220	17517
	Mean SINR (dB)	21	9	18

Table 5.6: Type 3 Routing Traffic Simulation Results

Simulation	**Parameter**	**Traffic Type**		
		Command and Control	**Voice**	**Video**
1	Mean Transfer (ms)	8	2	3
	Mean Delay (ms)	9	2	2988
	Max Delay (ms)	16	5	10354
	Packet Number	10588	5220	17517
	Mean SINR (dB)	8	13	8
2	Mean Transfer (ms)	6	2	3
	Mean Delay (ms)	7	2	3
	Max Delay (ms)	12	5	5
	Packet Number	10388	5220	17517
	Mean SINR (dB)	6	12	18
3	Mean Transfer (ms)	1229	2	7
	Mean Delay (ms)	1230	2	2660
	Max Delay (ms)	6881	3	9221
	Packet Number	9415	5220	17517
	Mean SINR (dB)	6	11	7
4	Mean Transfer (ms)	4	2	3
	Mean Delay (ms)	4	2	6
	Max Delay (ms)	10	6	11
	Packet Number	11809	5220	15000
	Mean SINR (dB)	7	10	7
5	Mean Transfer (ms)	6	2	3
	Mean Delay (ms)	7	2	3
	Max Delay (ms)	12	5	5
	Paket Sayisi	10388	5220	17517
	Mean SINR (dB)	6	12	18

5.5 MILP Based Solution vs. Distributed Clustering

This simulation is intended to see the traffic performance of the two clustering algorithms that was previously discussed in Section 2. The first algorithm is centralized and obtained by using GAMS that maximizes the total throughput. The second algorithm is distributed and completes the marking process algorithm shown in Algorithm 1. The results are shown below.

5.5.1 Simulation Parameters

Table 5.7 shows the parameters used for testing the traffic results on the two different clustering algorithms discussed in Chapter 2. The different clustering algorithms are tested for a traffic that is generated for 30 seconds. The traffic consists of 4 voice , 4 command & control and 2 video traffic. The algorithm used for frequency allocation is simulated annealing. The first five simulations are provided in Tables 5.8, and 5.9.

Table 5.7: Traffic Simulation Parameters for Clustering Algorithm Comparison

Parameter	**Description**	**Value**
f_{min}	Lowest Frequency Level	108 MHz
f_{max}	Highest Frequency Level	225 MHz
W	Frequency Bandwdith	1 MHz
N_0	Noise Spectral Density	-173.5 dBm
N	Radio Unit Count	192
P	Radio Transmission Power	10-50 Watt
Clustering		$MILPvsDistributed$
Frequency Allocation		$SAFA$
Area		$12 \times 16km^2$
Voice Traffic		5
Command & Control Traffic		4
Video Traffic		2
Traffic Duration		30000 ms (30secs)

Table 5.8: MILP Based Solution Traffic Simulation Results

Simulation	Parameter	Traffic Type		
		Command and Control	**Voice**	**Video**
	Mean Transfer (ms)	7	3	2
	Mean Delay (ms)	7	4	2
1	Max Delay (ms)	12	8	3
	Packet Number	12560	6525	17517
	Mean SINR (dB)	21	10	25
	Mean Transfer (ms)	5	3	2
	Mean Delay (ms)	6	3	2
2	Max Delay (ms)	12	12	7
	Packet Number	9233	6525	17517
	Mean SINR (dB)	21	20	22
	Mean Transfer (ms)	12	3	2
	Mean Delay (ms)	14	4	3
3	Max Delay (ms)	24	13	5
	Packet Number	11549	6525	17517
	Mean SINR (dB)	21	20	25
	Mean Transfer (ms)	11	3	6
	Mean Delay (ms)	12	4	7
4	Max Delay (ms)	25	21	22
	Packet Number	11618	6525	15000
	Mean SINR (dB)	9	20	20
	Mean Transfer (ms)	8	3	5
	Mean Delay (ms)	9	4	6
5	Max Delay (ms)	14	12	20
	Packet Number	13961	6525	17517
	Mean SINR (dB)	28	20	14

5.5.2 Simulation Results

All simulations in Tables 5.8, and 5.9 have a successful transmission range below $250ms$. The traffic is low and the performance level of both clustering algorithms works well under low traffic. The distributed clustering algorithm gives a little higher delay, which results from several extra hops per transmission as seen in Figure 2.6. The clustered network works well under low traffic. The clustering algorithms make a connected network and this fulfils the demand for the delay constraint provided in tables 4.4, 4.6 4.5.

Table 5.9: Distributed Clustering Solution Traffic Simulation Results

Simulation	**Parameter**	**Traffic Type**		
		Command and Control	**Voice**	**Video**
1	Mean Transfer (ms)	17	3	2
	Mean Delay (ms)	19	3	2
	Max Delay (ms)	28	7	3
	Packet Number	15706	6525	17517
	Mean SINR (dB)	19	20	20
2	Mean Transfer (ms)	8	3	3
	Mean Delay (ms)	8	4	3
	Max Delay (ms)	16	10	5
	Packet Number	12771	6525	17517
	Mean SINR (dB)	18	20	30
3	Mean Transfer (ms)	11	3	6
	Mean Delay (ms)	12	3	8
	Max Delay (ms)	20	10	13
	Packet Number	11316	6525	17517
	Mean SINR (dB)	23	12	21
4	Mean Transfer (ms)	8	2	5
	Mean Delay (ms)	9	2	7
	Max Delay (ms)	17	10	15
	Packet Number	10688	6525	15000
	Mean SINR (dB)	19	14	18
5	Mean Transfer (ms)	7	3	3
	Mean Delay (ms)	8	4	4
	Max Delay (ms)	15	12	6
	Packet Number	9856	6525	17517
	Mean SINR (dB)	21	14	21

5.6 Frequency Allocation Traffic Simulations

This simulation is intended to see the traffic performance of the centralized MILP based solution algorithm to the distributed frequency allocation algorithm that was previously discussed in Section 3. The first algorithm is centralized and obtained by using GAMS that minimizes the total interference (Equation 3.5. The second algorithm is distributed and completes the frequency allocation by assigning frequency sets to the initiator node, and then iterating the process by a marking algorithm shown in Algorithm 3. Distributed Clustering Algorithm were used in these simulations. The results has shown that both algorithms work in a similar fashion in the traffic model simulation.

5.6.1 Algorithm Comparison

The comparison of distributed frequency allocation, centralized frequency allocation, and a static frequency allocation is shown in this section.

5.6.1.1 Simulation Parameters

The traffic configuration in the format of (Video,Command & Control, Voice) have been increased to test the system at its capacity.

Table 5.10: Traffic Simulation Parameters for Different Frequency Algorithms

Parameter	**Description**	**Value**
f_{min}	Lowest Frequency Level	108 MHz
f_{max}	Highest Frequency Level	225 MHz
Clustering Algorithm		*Distributed*
Frequency Allocation Algorithm		*All*
Voice Traffic		10-14
Command & Control Traffic		4-6
Video Traffic		2
Traffic Duration		10000 ms (10secs)

5.6.1.2 Simulation Results

Unlike in the previous simulations, the algorithms were run for 10 seconds. If the system is converging, the end-to-end delay of the traffic is constant. If there is congestion, the end-to-end delay increases linearly. Therefore, if there exists packets with end-to-end delay over 250ms, and the delay is increasing in time, the result is considered to be unsuccessful. The overall success rate is given in Table 5.11 and the first fifty simulation results are provided in Tables 5.12, 5.13, 5.14, 5.15, 5.16, 5.17.

Table 5.11: Traffic Simulation Parameters for Different Frequency Algorithms

Algorithm	**(2,4,10)**	**(2,4,11)**	**(2,4,12)**	**(2,4,13)**	**(2,4,14)**	**(2,5,10)**	**(2,6,10)**
DFA	248/300	253/300	237/300	222/300	225/300	236/300	196/300
MIQP FA	240/300	243/300	222/300	216/300	226/300	212/300	187/300
CFA	237/300	235/300	211/300	210/300	200/300	226/300	170/300
SFA	212/300	199/300	174/300	157/300	135/300	167/300	110/300

The results show that distributed frequency algorithm is a good algorithm. The Table 5.12 shows the following. Static Frequency Algorithm (SFA), where random frequencies are assigned and no constraint over avoiding same frequencies amongst neighbor clusterhoods shows the worst performance. Centralized approach (CFA algorithm and MIQP based solution) show a similar performance with MIQP being slightly better except (2,5,10) configurations. This shows that using a proper frequency allocation algorithm can change the network end-to-end performance effectively.

Table 5.12: Traffic Simulation Results for Different Frequency Algorithms of the Configuration 2 Video, 4 Command & Control, 10 Voice Source Nodes

Simulation No	MILP FA (ms)	Static FA (ms)	Distributed FA (ms)	Simulated Annealing FA (ms)
1	32	66	33	38
2	26	30	21	25
3	69	75	65	69
4	183	725	75	136
5	217	468	140	203
6	42	46	31	37
7	703	782	265	146
8	67	77	44	70
9	104	93	81	95
10	43	63	61	48
11	100	134	114	133
12	55	256	51	107
13	47	61	49	46
14	419	298	192	369
15	42	63	37	73
16	236	246	197	222
17	39	47	32	32
18	714	596	39	248
19	818	722	390	740
20	22	26	19	23
21	59	78	63	86
22	51	87	32	55
23	25	32	26	25
24	37	29	29	29
25	635	257	95	217
26	81	133	57	70
27	49	64	35	37
28	183	326	134	215
29	33	54	34	39
30	33	42	51	28
31	116	144	93	110
32	132	332	77	252
33	243	295	282	345
34	903	882	207	510
35	37	53	45	37
36	158	245	53	89
37	36	50	35	33
38	109	125	336	107
39	50	48	46	43
40	364	513	311	408
41	404	447	381	410
42	38	134	53	73
43	35	86	28	47
44	127	387	82	157
45	545	589	465	641
46	86	79	258	148
47	53	59	50	42
48	696	894	710	906
49	27	41	23	27
50	523	491	286	636

Table 5.13: Traffic Simulation Results for Different Frequency Algorithms of the Configuration 2 Video, 4 Command & Control, 11 Voice Source Nodes

Simulation No	MILP FA (ms)	Static FA (ms)	Distributed FA (ms)	Simulated Annealing FA (ms)
1	47	910	37	48
2	73	105	67	78
3	47	60	49	51
4	192	545	74	113
5	323	348	321	266
6	50	51	35	42
7	34	57	46	45
8	87	77	43	64
9	199	534	106	68
10	67	359	55	53
11	67	222	63	200
12	43	58	33	41
13	63	220	48	56
14	669	504	850	600
15	52	60	57	36
16	78	107	143	83
17	64	272	49	65
18	225	470	98	190
19	556	569	556	600
20	38	50	32	42
21	95	174	95	96
22	36	57	36	35
23	51	45	36	51
24	116	142	128	137
25	886	705	285	886
26	84	523	79	214
27	58	99	57	64
28	243	677	157	288
29	36	65	34	39
30	49	80	54	62
31	69	124	62	92
32	115	307	99	348
33	354	362	286	291
34	854	151	557	776
35	684	112	57	733
36	100	381	82	102
37	42	53	54	42
38	81	102	207	71
39	33	40	39	37
40	184	427	327	348
41	290	906	618	841
42	48	74	43	46
43	49	85	41	55
44	84	209	99	69
45	893	497	677	671
46	116	296	138	110
47	126	232	129	94
48	415	630	273	298
49	40	54	40	42
50	627	741	546	773

Table 5.14: Traffic Simulation Results for Different Frequency Algorithms of the Configuration 2 Video, 4 Command & Control, 12 Voice Source Nodes

Simulation No	MILP FA (ms)	Static FA (ms)	Distributed FA (ms)	Simulated Annealing FA (ms)
1	257	776	103	102
2	90	306	95	102
3	34	51	35	41
4	146	87	174	107
5	427	493	409	401
6	44	57	38	45
7	44	59	38	42
8	83	85	66	235
9	617	903	794	451
10	293	685	304	342
11	143	451	148	181
12	41	59	39	36
13	59	165	64	61
14	645	547	627	693
15	71	118	71	54
16	860	920	773	905
17	37	66	30	49
18	773	818	754	734
19	723	578	606	840
20	44	818	42	330
21	584	800	680	535
22	42	48	38	38
23	41	35	30	33
24	65	74	54	65
25	199	131	120	158
26	69	156	43	185
27	36	58	36	38
28	750	564	607	920
29	38	66	33	42
30	50	81	35	50
31	67	165	59	84
32	520	576	143	715
33	435	518	433	426
34	946	924	95	627
35	199	133	55	821
36	118	356	121	98
37	319	236	419	419
38	72	150	141	99
39	75	131	64	72
40	588	644	657	600
41	508	480	514	488
42	44	60	38	43
43	56	255	61	72
44	51	102	41	48
45	953	712	893	798
46	43	126	72	53
47	51	87	51	47
48	453	686	320	544
49	414	765	149	297
50	697	800	702	915

Table 5.15: Traffic Simulation Results for Different Frequency Algorithms of the Configuration 2 Video, 4 Command & Control, 13 Voice Source Nodes

Simulation No	MILP FA (ms)	Static FA (ms)	Distributed FA (ms)	Simulated Annealing FA (ms)
1	336	398	42	492
2	75	167	74	81
3	37	58	43	57
4	406	669	143	203
5	470	601	413	491
6	89	108	62	70
7	82	74	68	79
8	71	80	47	74
9	85	387	93	53
10	160	225	216	216
11	147	213	142	185
12	46	85	38	46
13	47	239	47	43
14	205	244	174	193
15	64	155	78	94
16	776	698	752	800
17	57	79	51	52
18	928	543	813	856
19	893	866	711	701
20	176	173	48	58
21	552	702	265	400
22	35	49	41	37
23	229	239	134	262
24	210	542	153	135
25	642	696	269	902
26	56	118	49	49
27	75	212	75	68
28	478	608	465	737
29	48	88	39	44
30	41	50	35	40
31	77	90	74	79
32	604	846	463	802
33	479	578	555	538
34	776	1024	936	398
35	96	489	69	366
36	262	682	259	290
37	55	93	62	49
38	75	394	82	66
39	60	87	47	52
40	409	691	449	606
41	349	346	308	349
42	46	94	41	49
43	54	132	57	69
44	97	770	72	115
45	820	588	925	881
46	35	60	37	42
47	111	406	81	79
48	878	960	597	597
49	517	772	505	528
50	414	613	414	575

Table 5.16: Traffic Simulation Results for Different Frequency Algorithms of the Configuration 2 Video, 4 Command & Control, 14 Voice Source Nodes

Simulation No	MILP FA (ms)	Static FA (ms)	Distributed FA (ms)	Simulated Annealing FA (ms)
1	54	384	46	76
2	59	459	54	60
3	56	103	47	157
4	52	117	34	65
5	430	655	363	449
6	84	162	99	88
7	64	106	65	73
8	164	119	136	222
9	74	184	82	47
10	196	261	281	176
11	119	175	134	130
12	42	186	40	43
13	60	303	57	58
14	87	71	53	58
15	140	301	91	56
16	582	820	586	566
17	111	423	67	96
18	690	996	924	749
19	565	737	419	506
20	249	307	79	133
21	219	796	241	190
22	136	510	90	155
23	39	71	42	38
24	203	486	231	166
25	724	224	346	221
26	89	159	67	94
27	52	99	48	48
28	726	199	901	888
29	41	103	41	54
30	48	84	49	50
31	569	682	453	410
32	991	894	699	818
33	585	559	472	562
34	774	344	634	792
35	85	430	81	687
36	119	164	87	124
37	53	75	50	48
38	223	806	167	331
39	64	449	53	71
40	642	734	891	643
41	749	606	622	749
42	50	123	52	49
43	47	52	38	44
44	65	437	46	70
45	925	398	699	829
46	172	974	287	215
47	50	489	72	42
48	989	152	779	770
49	493	645	262	476
50	606	810	413	760

Table 5.17: Traffic Simulation Results for Different Frequency Algorithms of the Configuration 2 Video, 5 Command & Control, 10 Voice Source Nodes

Simulation No	MILP FA (ms)	Static FA (ms)	Distributed FA (ms)	Simulated Annealing FA (ms)
1	385	780	844	175
2	57	74	49	49
3	97	150	92	118
4	170	765	83	104
5	262	379	306	248
6	122	224	62	82
7	45	64	43	50
8	79	143	53	46
9	226	539	142	81
10	137	446	62	57
11	173	360	83	111
12	113	176	53	88
13	325	690	109	215
14	557	658	857	708
15	281	308	236	202
16	62	71	119	66
17	61	401	80	65
18	227	557	161	268
19	639	615	597	620
20	24	148	21	27
21	91	166	178	78
22	44	70	39	45
23	104	192	80	150
24	224	186	223	224
25	938	769	175	471
26	236	918	113	160
27	79	92	44	54
28	617	516	441	435
29	44	61	33	40
30	99	102	64	190
31	58	229	73	61
32	339	434	88	264
33	357	484	369	350
34	930	175	638	789
35	355	453	99	93
36	137	693	157	154
37	57	101	54	40
38	77	130	128	78
39	59	56	53	47
40	585	656	549	672
41	664	722	467	657
42	44	185	41	44
43	149	256	99	195
44	139	576	68	200
45	207	254	677	422
46	77	252	101	88
47	71	88	62	46
48	502	690	443	693
49	39	68	35	30
50	260	371	134	247

Table 5.18: Traffic Simulation Results for Different Frequency Algorithms of the Configuration 2 Video, 6 Command & Control, 10 Voice Source Nodes

Simulation No	MILP FA (ms)	Static FA (ms)	Distributed FA (ms)	Simulated Annealing FA (ms)
1	875	876	824	665
2	61	212	58	53
3	55	74	47	58
4	810	232	134	274
5	711	669	671	686
6	129	776	81	399
7	51	81	53	51
8	49	192	96	77
9	881	966	397	256
10	642	923	737	585
11	183	375	329	159
12	694	866	489	636
13	171	906	249	128
14	651	708	325	743
15	740	740	776	704
16	824	569	902	133
17	41	140	33	42
18	74	147	73	78
19	543	894	681	71
20	42	237	27	49
21	630	756	476	563
22	68	94	41	39
23	58	58	44	55
24	49	67	57	58
25	465	624	356	438
26	502	538	268	226
27	49	333	55	50
28	243	910	292	788
29	82	623	78	102
30	516	415	344	36
31	155	226	70	86
32	135	289	85	195
33	353	553	368	471
34	256	735	205	267
35	130	955	215	907
36	758	619	351	596
37	122	279	80	71
38	87	601	218	86
39	93	132	72	113
40	137	290	226	207
41	360	354	302	344
42	59	147	68	120
43	221	564	249	651
44	141	508	53	192
45	877	382	370	329
46	58	197	89	49
47	79	637	94	93
48	740	745	570	817
49	913	824	800	864
50	439	601	458	486

5.6.2 Frequency Count

We tested the effects of frequencies allocated per cluster, and the effects of decreasing the frequency set from 117 to 80. The results showed that assigning few frequencies per cluster decreased the performance of our algorithms while increasing the amount of frequency per cluster resulted in a similar performance compared to assigning the same number of frequencies to clustermembers. The simulation parameters and the results are shown below.

5.6.2.1 Simulation Parameters

Table 5.19: Traffic Simulation Parameters for Different Frequency Sets

Parameter	**Description**	**Value**
f_{min}	Lowest Frequency Level	108 MHz
f_{max}	Highest Frequency Level	188 or 225 MHz
Clustering Algorithm		*Distributed*
Frequency Allocation Algorithm		$DFA/MIQP$
Voice Traffic		12
Command & Control Traffic		6
Video Traffic		2
Traffic Duration		10000 ms (1min)

5.6.2.2 Simulation Results

The results in Table 5.20 show that assigning a low amount of frequency bands produce a worse end-to-end delay performance. The probability of interference increases when insufficient frequency bands is provided. Excess frequency bands do no increase the success effectively.

Table 5.20: Success Rate for Traffic Simulation Over Different Frequency Sets

Algorithm	Frequency Bands per Cluster		
	4	20	#Cluster Size
DFA	24/50	30/50	28/50
MIQP	25/50	32/50	32/50

6. CONCLUSION

6.1 Contribution, Benefits and Ideas

This thesis work has provided a contribution for frequency hopping radio network in terms of:

1. Allocating frequency to a set of grouped users by minimizing the interference.
2. Organizing an ad hoc user group into connected clusters that maximizes their throughput rate.
3. Route the clustered and frequency allocated users by using an adaptive TDMA structure.
4. Simulate a traffic scenario and test the efficiency of the proposed algorithm in terms of realistic end-to-end delay.

The initial problem of the SANTEZ No.1538.STZ-2012.2. was to conduct a frequency allocation for subnets in a rugged terrain based on a centralized unit and general knowledge case. However, this demand required a connected infrastructure and we designed a set of proposal that enabled the use of clustering, to provide distributed algorithms that can initiate in any environment.

Clustering was added to the frequency allocation problem in the later stage. Initially users were divided into subnets at their geographical positions. This knowledge provided us a motivation to analayze and use a clustering algorithm. Clustering algortihms are distributed and suitable for ad hoc networks. This makes is possible for any initiator node, to start the distributed algorithm and form a connected dominating set that connects to all of the users. We provided an optimal solution that maximizes throughput with the clusterheads using mixed integer linear programming, and then generated a clustering algorithm based on a marking process. The results in Section II show that the distributed algorithm performs well and lies in the boundaries of the performance metrics; such as hop count, throughput optimization, load-balance and end-to-end delay. Hence the distributed clustering algorithm presents a strong case of a CDS in a MANET environment and can be used in military networks for clustering purposes.

Frequency Allocation problem has been tackled with three ways. Centralized Frequency Allocation was initially formed for subnets. Then in a clustering enviroment, mixed integer quadratic problem formulation has provided an optimal solution that allocated frequencies based on specific constraints. The results in Section III showed relatively close and low Interference to Noise ratios. Distributed Frequency Algorithm has shown itself to be an effective distributed algorithm for allocating channels in a connected clustering environment. The end-to-end delay saving for this method is clear, especially when the traffic is dense and multiple users are communicating simultaneously.

6.2 Possible Future Work

This work can have a continuation and the future work may include:

- Forming a dynamic network frequency allocation problem.
- Creating a distributed routing algorithm.
- Optimizing the routing and clustering problem as a single entity.
- Forming a protocol from the algorithms.
- Proposing the clustering algorithms for device-2-device and machine-2-machine communication.

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