

OPTIMAL JAMMER PLACEMENT IN A WIRELESS COMMUNICATION
NETWORK BY CLUSTERING

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MAHMUT ANIL ÖZCAN

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submitted by **MAHMUT ANIL ÖZCAN** in partial fulfillment of the requirements
for the degree of **Master of Science in Industrial Engineering Department, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Esra Karasakal
Head of Department, **Industrial Engineering**

Assist. Prof. Dr. Mustafa Kemal Tural
Supervisor, **Industrial Engineering, METU**

Examining Committee Members:

Prof. Dr. Sinan Gürel
Industrial Engineering, METU

Assist. Prof. Dr. Mustafa Kemal Tural
Industrial Engineering, METU

Assoc. Prof. Dr. Özlem Karsu
Industrial Engineering, Bilkent University

Assist. Prof. Dr. Sakine Batun
Industrial Engineering, METU

Assist. Prof. Dr. Özgen Karaer
Industrial Engineering, METU

Date:30.05.2023



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Name, Surname: Mahmut Anıl Özcan

Signature :

ABSTRACT

OPTIMAL JAMMER PLACEMENT IN A WIRELESS COMMUNICATION NETWORK BY CLUSTERING

Özcan, Mahmut Anıl

M.S., Department of Industrial Engineering

Supervisor: Assist. Prof. Dr. Mustafa Kemal Tural

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Wireless communication system is a communication technology that enables the wireless transmission of information such as data, sound, and image using wireless signals. The system uses radio frequencies to transmit wireless signals. Today, it is one of the most common communication tools due to its flexibility of movement, easy installation, and wide coverage. However, these systems are vulnerable to jamming attacks. The functionality of wireless communication networks can be disrupted by devices that produce unwanted signals, called jammers. However, targeting a single connection on a wireless network with the jammer may not be enough to break the communication. Since the communication traffic in the network can continue over alternative connections, the communication network should be considered as a whole, and signal jamming strategies should be developed accordingly.

This thesis deals with the problem of jammer placement to jam a wireless communication network by dividing it into disconnected clusters. There are limited number of studies on this problem in the literature. As one of the studies, Feng et al. formulate this problem as an optimal clustering problem on the graph and find the optimal solution with binary integer programming [1]. Their proposed mathematical model

finds the minimum number of homogeneous jammers required to divide the wireless network into the desired number of clusters. Jammers can only be positioned at the locations of the radios whose signals are desired to be jammed in the network. The maximum number of radios in subnets is given as input to the model.

In this thesis, the mathematical model proposed by Feng et al. [1] is considered as the base model. New models with different approaches are proposed to improve the jamming performance by eliminating the lacks of the base model. With the first proposed model, it is aimed to minimize the maximum number of radios a cluster can have by giving the number of jammers as input. The second model hierarchically minimizes the number of radios for all clusters, not just the cluster with the maximum number of radios. The optimal solutions are obtained with integer programming formulation in both models. With another proposed model in the thesis, the restriction on the position of the jammers is removed, and placement is provided in the real plane. In the final model, the variable of antenna is added to the jammers, and the problem is addressed with heterogeneous jammers for the first time in the literature. The last two proposed models obtain optimal solutions by mixed integer second-order cone programming formulation due to the real plane placement of the jammers.

In a different article [2], Feng et al. remove the placement restriction on the jammers and work on the real plane instead of the discretized plane. For this reason, the base model is adapted to the real plane by keeping the approach same to compare the developed models with the base model on the real plane in addition to the discretized plane. In this way, the developed models and the base model are compared with a comprehensive experimental design both in the discretized and real plane. In addition, the final model is compared within itself to examine the effect of using omnidirectional and directional antennas at different angles on the results.

Keywords: Jammer, Radio, Communication Link, Network, Jammer Placement, Partitioning, Graph Clustering

ÖZ

KABLOSUZ İLETİŞİM AĞINDA KÜMELEME YÖNTEMİYLE OPTİMAL JAMMER YERLEŞİMİ

Özcan, Mahmut Anıl

Yüksek Lisans, Endüstri Mühendisliği Bölümü

Tez Yöneticisi: Dr. Öğr. Üyesi. Mustafa Kemal Tural

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Kablosuz iletişim sistemi kablosuz sinyallerin kullanılarak veri, ses ve görüntü gibi bilgilerin kablosuz olarak iletilmesini sağlayan bir iletişim teknolojisidir. Bu sistem kablosuz sinyallerin iletilmesi için radyo frekanslarını kullanır. Hareket esnekliği, kolay kurulumu ve geniş kapsama alanı sebebiyle günümüzde en yaygın iletişim araçlarından biridir. Ancak, bu sistemler karıştırma saldırılarına karşı savunmasızdır. Sinyal bozucu adı verilen ve istenmeyen sinyaller üreten cihazlar ile kablosuz iletişim ağlarının işlevselliği bozulabilir. Fakat, sinyal bozucu ile kablosuz bir ağdaki tek bir bağlantıyı hedef almak iletişimin kesilmesi için yeterli olmayabilir. Ağdaki iletişim trafiği alternatif bağlantılar üzerinden devam edebileceği için iletişim ağı bir bütün olarak düşünülmeli ve buna göre sinyal bozma stratejileri geliştirilmelidir.

Bu tezde, kablosuz bir iletişim ağını bağlantısız alt ağlara bölerek bozmak için sinyal bozucuların yerleştirilmesi problemi ele alınmaktadır. Literatürde bu problem için kısıtlı sayıda çalışma bulunmaktadır. Çalışmalardan biri olarak, Feng ve arkadaşları bu problemi ağ üzerinde optimal kümeleme problemi olarak formüle ederek ikili tamsayı programlama ile optimal sonuca ulaşmaktadır [1]. Önerdikleri matematiksel model

kablosuz iletişim ağıının istenilen sayıda alt ağı bölünmesi için gereken en az türdeş sinyal bozucu sayısını bulmaktadır. Sinyal bozucular ağıda sadece sinyalleri bozulmak istenen telsizlerin konumlarına yerleştirilebilmektedir. Alt ağların sahip olabileceği azami telsiz sayısı modele girdi olarak verilmektedir.

Bu tezde, Feng ve arkadaşlarının önerdikleri matematiksel model [1] baz model olarak ele alınmaktadır. Baz modelin eksiklikleri giderilerek farklı yaklaşımlarla sinyal bozma performansının artırılması için yeni modeller önerilmektedir. Önerilen ilk model ile sinyal bozucu sayısı modele girdi olarak verilerek bir alt ağıın sahip olabileceği azami telsiz sayısının en aza indirgenmesi amaçlanmaktadır. İkinci model sadece azami sayıdaki telsize sahip olan alt ağıın değil bütün alt ağların telsiz sayılarını hiyerarşik olarak en aza indirmektedir. İki modelde de tam sayı programlama formülasyonu ile optimal sonuçlar bulunmaktadır. Tezde önerilen diğer bir model ile sinyal bozucuların konumları üzerindeki kısıtlama kaldırılarak gerçek düzlemde yerleşim sağlanmaktadır. Son modelde ise sinyal bozuculara anten eklentisi yapılarak literatürde ilk defa problem türdeş olmayan sinyal bozucular ile ele alınmaktadır. Önerilen son iki modelde sinyal bozucuların gerçek düzlemdeki yerleşimi nedeniyle karışık tamsayıli ikinci dereceden koni programlama formülasyonu ile optimal sonuçlar elde etmektedir.

Feng ve arkadaşları farklı bir makalede sinyal bozucular üzerindeki yerleşim kısıtlamasını kaldırarak ayrıklaştırmış düzlem yerine gerçek düzlemde çalıştıklarını belirtmektedirler [2]. Bu nedenle, geliştirilen modeller ile baz modeli ayrıklaştırılmış düzleme ek olarak gerçek düzlemde de karşılaştırabilmek için yaklaşım aynı tutularak baz model gerçek düzleme göre uyarlanmaktadır. Bu sayede geliştirilen modeller ile baz model ayrıklaştırılmış ve gerçek düzlemlerde kapsamlı bir deneysel tasarım ile karşılaştırılmaktadır. Ek olarak, eşyönlü ve farklı açılarda yönlü anten kullanımının sonuçlara etkisinin değerlendirilebilmesi için son model kendi içerisinde karşılaştırmaya tabi tutulmaktadır.

Anahtar Kelimeler: Jammer, Telsiz, İletişim Bağlantısı, İletişim Ağı, Jammer Yerleşimi, Bölümleme, Grafik Kümeleme



To my little bird

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ALGORITHMS

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LIST OF ABBREVIATIONS

WN	Wireless Network
BM	Base Model
BM+	Base Model Plus
MM	MinMax Model
MME	Hierarchical Extension of MinMax Model
CLE	Continuous Location Model
BCM	Base Continuous Location Model
BCM+	Base Continuous Location Model Plus
DAAM	Directional Antenna Addition Model
OA	Omnidirectional Antenna
DA	Directional Antenna
IP	Integer Programming
ILP	Integer Linear Programming
MILP	Mixed-Integer Linear Programming
MISOCP	Mixed-Integer Second-Order Cone Programming

CHAPTER 1

INTRODUCTION

A wireless network (WN) is a network of devices which use radio waves to communicate. A WN does not require any physical connection between the devices and hence provides freedom of movement and increases flexibility. WNs are often used in cases when there is no telecommunication infrastructure or user mobility is crucial (e.g., mobility of teams during a military operation). Although the WNs have more than a century of history, their use has become widespread in the last 15-20 years [3]. Today, they are among the fastest-growing technologies in the telecommunications industry. However, due to the nature of WNs, they are susceptible to jamming attacks, especially in war situations. For example, it was reported that North Korea had about 100 jamming attacks against South Korea in March 2016, and the communication systems of 962 aircraft were affected in these operations [4]. In such jamming attacks, devices called jammers are used. Jammers disrupt the existing communication by reducing the signal-to-noise ratio in the transmission of wireless signals.

Different types of jammers exist, such as proactive, reactive, and smart. A proactive jammer transmits jamming (interfering) signals independent of whether or not there is data communication in a network [5]. A reactive jammer operates jamming when signal activation occurs on a specific channel [6]. A smart jammer can quickly learn the transmission power of the user and adaptively adjust its transmission power to maximize the damaging effect [7]. In addition, jammers are varied with their antenna structures. Basically, jammers can use two types of antennas: omnidirectional antenna and directional antenna. A jammer with omnidirectional antenna transmits electromagnetic signals equally in all directions and jams in a circular pattern [8]. A jammer with directional antenna concentrates electromagnetic signals in one direc-

tion, minimizing signals going in other directions [9]. Thus, it jams in a directional pattern. Apart from the jammer type and antenna structure, another critical factor for the jamming effect is the placement of the jammers because jammers can only jam at a certain distance. This poses the problem of positioning the jammers to achieve the most effective jamming performance in a network which is related to the number of jammed signal sources and broken communication links between the sources.

Despite the enormous amount of research on optimization in telecommunication networks [10], the problem of jamming a WN has received little attention in the research community. One of the first studies in this direction is the paper of Feng et al. [1], where the authors represented the problem of jamming a WN as an optimal clustering problem on a graph and proposed an integer programming (IP) formulation for its solution. Although optimal solutions can be found with their model, analyses of the results show that important aspects of the problem are overlooked and much better jamming performances can be achieved by making some adjustments and improvements. An optimal solution of the mathematical model developed in the paper of Feng et al. [1] is displayed in Figure 1.1. This figure represents the WN by a graph with nodes corresponding to radios and edges to communication links. If there is no link between two nodes, this means that these nodes are not within the communication range. A straight line between two nodes indicates that the nodes are able to communicate. A dashed line between two nodes points to a disturbed communication by a jammer. It is assumed that jammers can be located at the nodes of the network which are the locations of the radios and can disturb the communication of radios within their jamming range.

As seen in Figure 1.1, a communication network with 40 nodes is divided into two separate subnetworks called clusters. While the radios in each cluster can communicate with each other (directly or indirectly through other radios), there is no communication between the radios in different clusters. The objective is to find the minimum number of jammers to divide the communication network into the desired number of clusters which is two for this instance. Jammers are assumed to be homogeneous, with equal transmit power and omnidirectional antennas that causes circular jamming. They are represented as hexagrams in Figure 1.1 and are placed at nodes 18 and 27. Jamming domains of them, i.e., the areas which are jammed by the jammers,

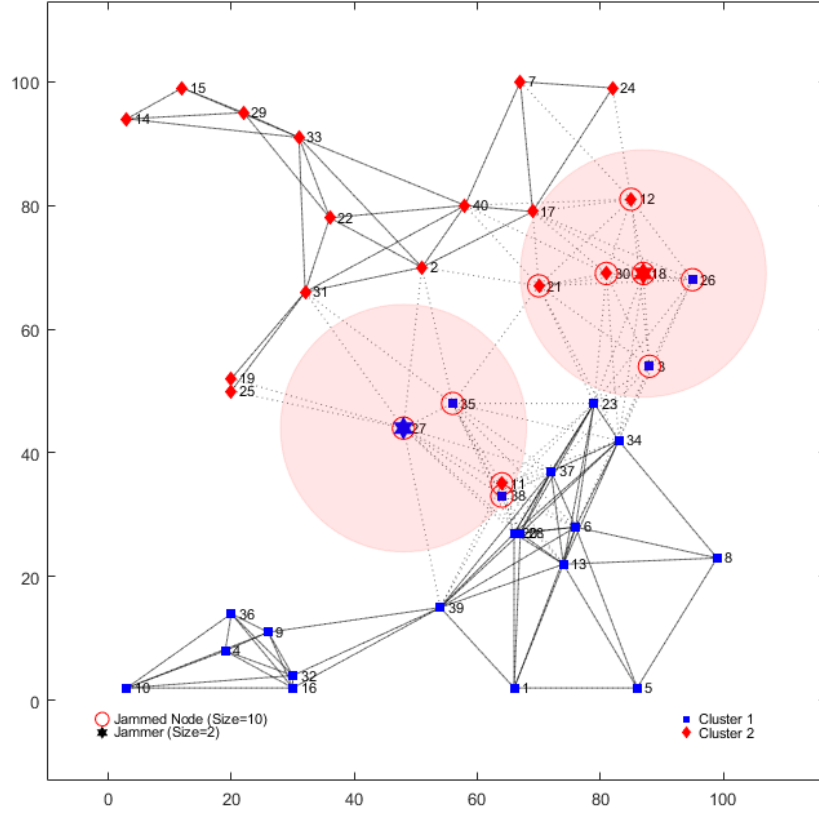


Figure 1.1: An optimal solution according to the mathematical model in the paper of Feng et al. [1]

are represented by disks. Furthermore, the jammed nodes are shown with a circle around them.

The graphical solution given in Figure 1.1 could be improved regarding several criteria that will be discussed in Section 3.1. Figure 1.2 displays an alternative solution where the number of jammed nodes and broken communication links are increased by repositioning the two jammers.

In the paper of Feng et al. [1], it is assumed that jammers can be located at the nodes of the network. This assumption is an important factor limiting the use of jammers. It negatively affects the jamming performance by reducing the efficiency of the jammers. In addition, the jammers are assumed to be homogeneous, with omnidirectional antennas that cause circular jamming, as seen in Figure 1.1. However, jamming signals in a certain direction can be vital, especially in cases such as network domain

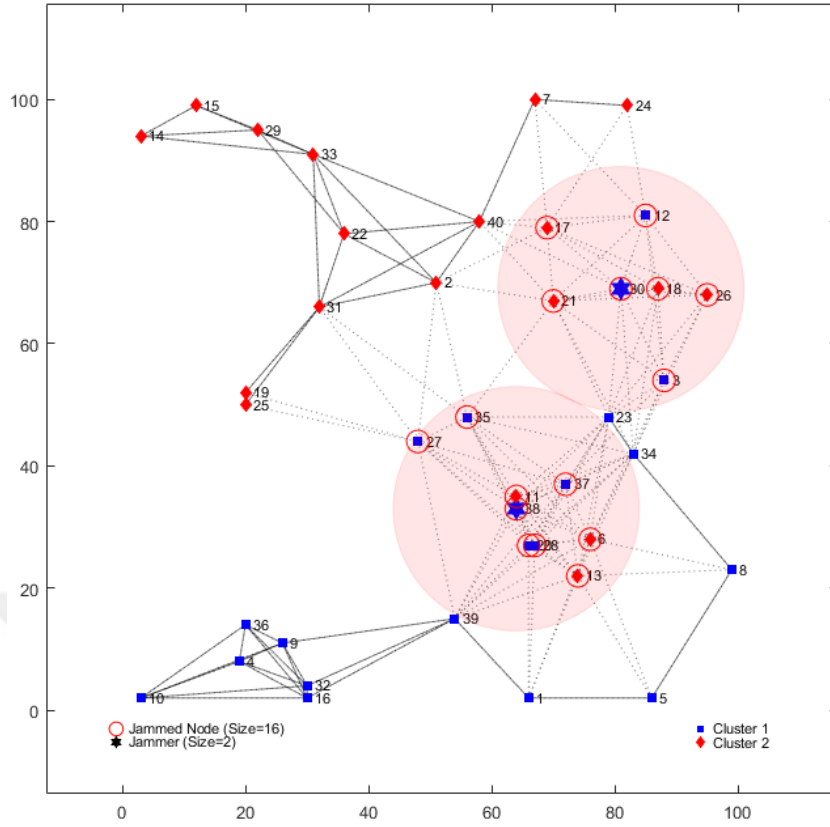


Figure 1.2: An alternative to the solution of the mathematical model in the paper of Feng et al. [1]

security and border protection. In such cases, jammers with directional antenna are generally preferred. Thanks to jammers with directional antenna, signals from only one direction are jammed, while signals from other directions are transmitted normally. Thus, there is no obstacle to the operation of friendly communication devices. In addition, jammers with directional antennas can sometimes jam more enemy radios due to their different jamming patterns. They are highly effective when enemy radios are concentrated in a certain area.

As an alternative to the jammers in Figure 1.1, the jammers in Figure 1.3 are placed regardless of node locations and have different antenna structures. The solution in Figure 1.3 is more realistic and allows better jamming performance due to removing restrictions on the placement and alternative antenna structures.

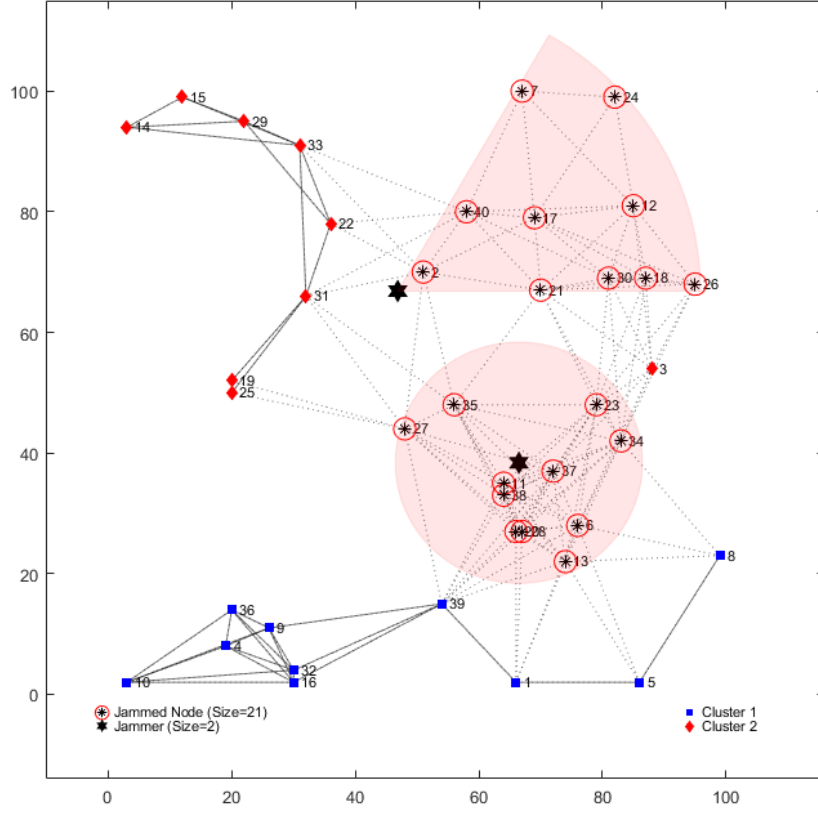


Figure 1.3: An alternative solution with heterogeneous jammers and no placement restrictions

In this thesis, the mathematical model proposed by Feng et al. [1] is taken as the base model, and several new models are developed to improve the jamming performance and offer new alternatives. Some of these consider the discrete version of the problem, where the jammers are allowed to be located only at the nodes of the WN, and are formulated as mixed-integer linear programs (MILP). We also consider continuous versions of the problem, where the jammers can be placed at any location on the plane and formulate these using mixed-integer second order cone programming (MISOCP). Finally, assuming that the jammers are not homogeneous, jammers with directional antennas are included in the problem. The mathematical models developed in this thesis are compared within themselves, with each other, and with the clustering approach of Feng et al. [1]. These comparisons show that: our approach and improvements result in significant improvements in jamming performance over that of Feng et al. [1]; using homogeneous jammers can be restrictive in some cases,

and better jamming performance can be obtained with heterogeneous jammers. The effects of the communication distance, jamming distance, number of radios, number of clusters, and field size on the jamming performance are analyzed via extensive computational experiments.

The rest of the thesis is organized as follows. In Chapter 2, a review of the related literature is provided. A detailed review of the jammer placement problem is given by touching upon the location, location set covering, network design, and clustering problems. Chapter 3 begins with the problem description and notation in Section 3.1. The optimal jammer placement problem and the common notation used in the models are introduced. In addition, the performance measures used to compare the models and the methods of finding the measures are specified. Mathematical models are presented in Section 3.2. Section 3.2.1 shows the model proposed in the study of Feng et al. [1], called Base Model. This model finds the minimum number of jammers to reach the desired number of clusters in a WN. In Section 3.2.1.1, the drawbacks of the Base Model are listed. Section 3.2.2 presents the MinMax Model, the first developed model. This model minimizes the number of nodes in the cluster with the maximum number of nodes. In Section 3.2.3, the hierarchical extension is developed to make the MinMax Model work more efficiently. With this extension, the number of nodes in all clusters is minimized hierarchically, not only in the cluster with the maximum size. By the Continuous Location Model presented in Section 3.2.4, the restriction on the jammer positions is removed, and the jammers are positioned in the real plane. In Section 3.2.5, Base Continuous Location Model, which is the adaptation of the Base Model to the real plane, is presented. In Section 3.2.6, jammers with directional antenna are included in the problem by introducing the final model, Directional Antenna Addition Model. This model addresses the optimal jammer placement problem with heterogeneous jammers for the first time in the literature.

Chapter 4 contains two sections and gives computational results. Section 4.1 in this chapter provides illustrative examples under different headings. Improvements and comparisons starting from the Base Model are presented in Section 4.1.1. The performances of the developed models in the discretized plane and the transition from the discretized plane to the real plane are explained with illustrative examples. In addition, improvements and comparisons starting from the Base Model are presented

in Section 4.1.2. The performances of the developed models in the real plane are explained with illustrative examples. Improvements and comparisons by antenna type and angle are presented in Section 4.1.3. The final model, Directional Antenna Addition Model, is evaluated using illustrative examples with the different jamming angle values and jammer combinations. Section 4.2 in Chapter 4 provides experimental results under different headings. Section 4.2.1 provides comparative tables with a large number of results for the developed models. The results in these tables are analyzed and interpreted. Section 4.2.2 shows the comparative tables of the final model with a large number of results in different combinations. The tables are subject to comprehensive evaluation. The effects of the parameters used in the models on the results are examined in Section 4.2.3. The results from the models are interpreted with line graphs for different parameter values. Conclusion and some future research directions are provided in Chapter 5.



CHAPTER 2

LITERATURE REVIEW

This thesis studies the problem of locating jammers in a WN by formulating it as a clustering problem as done in [1]. For this purpose, it is necessary to determine where to place the jammers in order to divide the network into clusters that cannot communicate with each other. Placement of jammers in a WN removes some of the edges of the network and the jamming performance is evaluated based on how the nodes communicate in the resulting network. The nodes that are in the jamming domain of the jammers (i.e., that are covered) become ineffective, and therefore covering as many nodes as possible is one of the performance criterion in the evaluation of the jamming performance. The problem studied in this thesis is therefore related to network design and covering problems in addition to graph clustering problems. Our literature review mainly focuses on studies that consider the jammer placement problem. On the other hand, the related literature about location, location set covering, network design, and graph clustering problems are also touched upon without going into the details. We start with a general literature review about the related problems and continue with studies that focus on the jammer placement problems.

The location and location set covering problems have been among the main research interests in the field of Operations Research. The location problem was first addressed in the early 1900s when Weber and Friedrich [11] aimed to minimize the total distance between a warehouse and customers. Hakimi [12] studied the problems of locating multiple base stations in a communication network and police stations in a highway system. Thus, the optimal location in a network was discussed for the first time. Toregas et al. [13] introduced the location set covering problem, which aims to find the minimum number of facilities and their locations to cover all the demand points.

Like the location and location covering problem, network design problem has been widely discussed in the literature. Magnanti and Wong [14] and Minoux [15], who did the fundamental studies on this problem, emphasized the importance of choosing the connections to be activated between facilities or users. On the other hand, Daskin et al. [16] dealt with network design and location problems as a whole and introduced the uncapacitated facility location/network design problem. This problem involved choosing a location among alternative facilities in the network without changing the network configuration instead of determining a new facility location. Later, Melkote and Daskin [17, 18] solved an example containing 40 nodes and 160 links, identifying polynomially solvable cases of this problem.

The history of graph clustering problems is not as old as the other problems we discussed since graph clustering emerged with the development of the telecommunications industry. One of the first studies on graph clustering was done in [19], where the authors aim to divide a communication network into non-disjoint clusters and determine the location of the satellite station in each cluster. Inter-cluster communication minimization was chosen as a clustering criterion to improve the service quality. In the same year, Van Dongen [20] introduced the Markov clustering method, which divides the nodes into subsets by simulating the stochastic flow in graphs. In both of these studies, a node in the network could be in different clusters simultaneously. Bertsimas and Shioda [21] aim to prevent overlap between clusters by partitioning the nodes of a network into disjoint subsets via hyperplanes using integer programming (IP). Saglam et al. [22] proposed an MILP formulation that aims to obtain equally compact clusters by minimizing the maximum radius of the resulting clusters.

So far, basic studies on location, location set covering, network design, and graph clustering problems have been discussed as they are related to the jammer placement problem. Now, studies focusing on jammer placement problems, especially in wireless networks, will be discussed in more detail. The study of Wood et al. [23] was the first to deal with the jammer placement problem, and a mapping detection approach was developed. This approach provided feedback about the jammer areas and the jamming nodes to the base station. However, this study did not consider the jamming placement problem in a network with communication links. Unlike Wood et al. [23], Liu et al. [24] discussed the jammer placement problem together with a

wireless network. They proposed a localization algorithm that estimates the jammer location by considering the signal changes in the radios. They addressed the problem of finding the location of the jammers that already exist in a wireless network. That is, this study did not include anything related to new placement of jammers. The first study on the problem of optimal jammer placement in a communication network was done by Commander et al. [25]. The study introduced the “Wireless Network Jamming Problem” to determine the optimal number and locations for a set of jammers for neutralizing a wireless communication network. They developed several mathematical programming formulations based on covering the communication nodes. The optimal number of jammers has been found to jam all communication nodes in a given network. In a study by Feng et al. [26], a different approach was introduced, aiming to partition a wireless network instead of node covering. They considered the problem of the optimal number of jammers needed to divide a wireless network into a specific number of disconnected subnetworks. They did not use a mathematical model as a solution approach to this problem but resorted to heuristic methods such as NCut Greedy Search and Harmony Search. Afterward, Feng et al. [1] formulated the same problem as an optimal clustering problem on a graph and showed that the clustering problem could be solved with a mathematical model. They compared the results from the mathematical model with those from the NCut Greedy Search and Harmony Search methods. Then, they argued that the heuristic methods had suboptimal results but worked more computationally efficiently than the mathematical model. Two years later, they developed a different method called multilevel graph cut [27]. They showed by graphical comparisons that the new method is the most computationally efficient compared to the previous ones. However, they accepted that the results of the new heuristic method are also suboptimal. Feng et al. [2] improved the mathematical model used in previous studies by developing techniques to find optimal jammer placements in the real plane. They presented an algorithm that finds a set of candidate jammer locations (CJLs) in the real plane based on finding the minimum covering disks in a depth priority search over the network. Then, these CJLs were integrated into the previous mathematical model to find optimal jammer placements.

Unlike the ones mentioned so far, there are also studies in the literature that deal with the jammer placement problem for defensive purposes. In these studies, jammers are placed to protect a particular area from the enemy. The paper published by Arkin et al. [28] aimed to protect the privacy of wireless communication in the region close to the enemy border. The jammers aim to reduce the channel quality of the hostile listener and preserve the legitimate channel quality within the facility. A “ $(1 + \epsilon)$ -Approximation Scheme” was used to find the minimum number of jammers for this aim. Sankararaman et al. [29] set out for the same purpose but used mathematical models to create a virtual barrier around the critical facility with the optimal jammer placement. They desired to reduce the effect of eavesdropping devices below a certain threshold level without affecting the network performance within the facility. For this reason, they used integer linear programming (ILP) to optimize power consumption and the number of jammers.

The thesis of Shankar [30] is one of the few studies in which defensive and attacking purposes are considered simultaneously. In this thesis, two different optimization problems were studied. Firstly, the optimal choice of links for communication in a network was discussed. It was aimed to maximize the utility of delivered network communication traffic. Secondly, the optimal interruption of communication in the network has been studied. Another study dealing with the jamming placement problem in two dimensions was done by Vadlamani et al. [31]. They model the problem as a bi-level attacker-defender mixed integer program. While the attacker tries to keep the balanced flow in the network at the maximum level, the defender tries to do the opposite. Finally, unlike all these studies, Gezici et al. [32] deals with the jammer placement problem from a purely technical electronic point of view. In this article, a model is developed to find the optimal jammer location to work with the best performance over different scenarios. The performance of the jammer was evaluated with performance metrics based on signal measurements, and it is aimed to increase these metrics. In the study, several target nodes and a jammer node are used without mentioning any placement in the network.

CHAPTER 3

PROBLEM DESCRIPTION, NOTATION, AND MATHEMATICAL MODELS

3.1 Problem Description and Notation

In this study, we consider the optimal jammer placement problem in a wireless communication network by clustering. The communication network consists of radios distributed in a two-dimensional plane. The radios are assumed to be homogeneous and have equal transmit power, omnidirectional antennas, and noise figure. They can communicate directly if they are within communication distance of each other. Radios that cannot communicate directly with each other can also communicate indirectly through others. Unlike radios, it is assumed that all jammers in this study are not homogeneous because they have either an omnidirectional or directional antenna. All jammers used in the models in Sections 3.2.1, 3.2.2, 3.2.3, 3.2.4, and 3.2.5 have an omnidirectional antenna. The directional antenna addition is included with the model in Section 3.2.6. When jammers have omnidirectional antennas, their jamming domain is circular due to equal transmit power. When jammers have a directional antenna, their jamming domain is directional depending on the jamming angle. In these domains, both the transmitting and receiving signals of the radios are jammed. The radios in the jamming domain are defined as jammed radios and cannot communicate with other radios. All direct and indirect communication links of jammed radios are cut off, and these links are defined as cut links. In this study, two different versions are presented for the location of jammers in the network, as discrete and continuous placement. First, it is assumed that each jammer can be placed at the location of the radios in the network. Second, it is assumed that the jammers can be in any position on the continuous/real plane without limitation. Both versions try to find the optimal jammer placement that divides the communication network into the desired number

of discrete subnetworks. These subnetworks, called clusters, cannot communicate with each other.

The communication network is represented by a graph $G = (V, E)$ with vertices/nodes (V) corresponding to radios and edges (E) to communication links. The edges are determined according to d_o , which represents the communication distance between radios. If the distance between two radios is less than or equal to the communication distance, there is an edge between them. Unlike d_o , d_j represents the distance equal to the jamming radius of a jammer. Indices $i/\hat{i}$ are used to indicate radios and index k to indicate clusters. In addition, the total number of radios equals n_r , and the desired number of clusters equals n_c . The set of radios (V) is defined from 1 to n_r . However, the set of clusters (C) is defined from 0 to n_c since the jammed radios are assigned to cluster 0. While C has $n_c + 1$ clusters, the network is actually divided into n_c clusters.

In this thesis, several different mathematical models are proposed for the studied problem. The following notation is common to all mathematical models.

Indices:

$i, \hat{i}$: radios or nodes (1,..., n_r)

k : clusters (0,..., n_c)

Sets:

V : set of radios

E : set of communication links

C : set of clusters

Parameters:

n_r : number of radios

n_c : number of clusters

d_o : communication distance

d_j : jamming distance

$G(V, E)$: communication graph

The developed mathematical models were compared both with each other and within themselves in terms of some performance criteria. One of the essential criteria that we use to measure jamming performance is Node Success Rate which is equal to the ratio of the number of jammed nodes to the total number of nodes. That is, if 20 nodes are jammed in an area with a total of 40 nodes, 50% Node Success Rate is achieved. Another criteria is the Link Success Rate, which is found by dividing the number of cut direct links by the total number of direct links. The last criteria is the Communication Success Rate. It is calculated by dividing the number of cut indirect links by the total number of indirect links. If the distance between two radios is less than d_o , these radios can communicate directly. In addition, if the distance between two radios is more than d_o but they have links over other nodes, they can communicate indirectly. In Figure 3.1, the direct and indirect links are explained through an example.

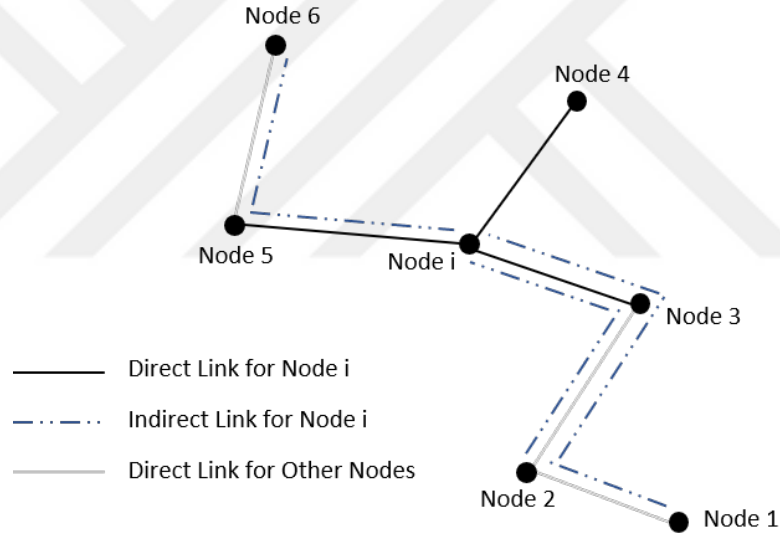


Figure 3.1: An illustrative example for the direct and indirect links of node i

As seen in the figure, node i has three direct and three indirect links. Since the distances between node i and nodes 3, 4, and 5 are less than or equal to d_o , they have an edge that indicates they can communicate directly. On the other hand, node i has a path with node 6, node 2, and node 1 via other nodes. Thanks to these paths, nodes communicate indirectly, although not directly. For a network, the total number of direct and indirect links; and the number of cut direct and indirect links after the jammer placement are computed according to Algorithm 1.

Algorithm 1: Algorithm to compute the # of links in a network

```
1  $dir \leftarrow 0;$ 
2  $ind \leftarrow 0;$ 
3 for  $i = 1 \rightarrow n_r$  do
4   for  $\hat{i} = 1 \rightarrow n_r$  do
5     if  $\exists E$  between node  $i$  and  $\hat{i}$  ( $E$  is edge) then
6        $dir \leftarrow dir + 1;$ 
7     else
8       if  $\exists P$  between node  $i$  and  $\hat{i}$  ( $P$  is path) then
9          $ind \leftarrow ind + 1;$ 
10      end
11    end
12  end
13 end
14 Run the Model;
15  $cdir \leftarrow 0;$ 
16  $cind \leftarrow 0;$ 
17 for  $\forall i \notin \text{Cluster } 0$  do
18   for  $\forall \hat{i} \notin \text{Cluster } 0$  do
19     if  $\exists E$  between node  $i$  and  $\hat{i}$  ( $E$  is edge) then
20        $cdir \leftarrow cdir + 1;$ 
21     else
22       if  $\exists P$  between node  $i$  and  $\hat{i}$  ( $P$  is path) then
23          $cind \leftarrow cind + 1;$ 
24       end
25     end
26   end
27 end
28 Total # of Direct Links  $\leftarrow dir;$ 
29 Total # of Indirect Links  $\leftarrow ind;$ 
30 # of Cut Direct Links  $\leftarrow dir - cdir;$ 
31 # of Cut Indirect Links  $\leftarrow ind - cind;$ 
```

3.2 Mathematical Models

3.2.1 Base Model

This mathematical model was proposed in the study of Feng et al. [1]. The model aims to find the minimum number of jammers needed to divide a communication network into the desired number of clusters. The jammers have an omnidirectional antenna and can be placed at the radio locations in the network. If a jammer is positioned at node i , p_i takes the value 1. Otherwise, this value is equal to 0. The number of clusters is given as input to the model, and the maximum number of nodes in clusters is limited. Notation of f_k is used for this limitation. Assigning a node to a cluster is determined by the $t_i^{(k)}$ variable. If node i is assigned to cluster k , $t_i^{(k)}$ takes the value 1. Otherwise, this value is equal to 0. $t_i^{(0)}$ (cluster 0) is defined as a jammed cluster. Jammed nodes and jammer(s) are assigned to this cluster. All clusters except cluster 0 are unjammed clusters, and unjammed nodes are assigned to these clusters.

In addition to the communication graph mentioned in Section 3.1, $G_j = (V, E_j)$, called the jamming graph, is included in the model. V still represents the same nodes, but links are represented by E_j , which are now determined by d_j instead of d_o . In other words, links are formed between all possible jammer locations and the nodes within the jamming distance of these locations. δ is an adjacency matrix showing which nodes are jammed from a given node. If an $arc(i, \hat{i})$ is in the set of E_j , the value of $\delta_{i\hat{i}}$ is 1. Otherwise, this value equals 0.

In addition to the common notation in Section 3.1, the following notation is used.

Sets:

E_j : set of jamming links

Parameters:

f_k : maximum number of nodes in cluster k

$G_j(V, E_j)$: jamming graph

$$\delta_{i\hat{i}} = \begin{cases} 1, & \text{if } arc(i, \hat{i}) \in E_j \\ 0, & \text{otherwise} \end{cases}$$

Decision Variables:

$$t_i^{(k)} = \begin{cases} 1, & \text{if node } i \in \text{cluster } k \\ 0, & \text{otherwise} \end{cases}$$

$$p_i = \begin{cases} 1, & \text{if a jammer is positioned at node } i \\ 0, & \text{otherwise} \end{cases}$$

The following is the Base Model proposed in the study of [1].

$$\min \sum_{i=1}^{n_r} p_i \quad (3.1)$$

s.t.

$$\sum_{k=1}^{n_c} t_i^{(k)} = 1 \quad \forall i \in V \quad (3.2)$$

$$\sum_{i \in V} p_i \geq 1 \quad (3.3)$$

$$\sum_{i \in V} t_i^{(k)} \geq 1 \quad \forall k \in C \quad (3.4)$$

$$\sum_{i \in V} t_i^{(k)} \leq f_k \quad \forall k \in C \quad (3.5)$$

$$\sum_{i \in V} t_i^{(k)} \leq \sum_{i \in V} t_i^{(k-1)} \quad \forall k \in C \setminus \{0, 1\} \quad (3.6)$$

$$t_i^{(0)} \leq \sum_{i \in V} p_i \delta_{ii} \quad \forall i \in V \quad (3.7)$$

$$t_i^{(k)} - t_i^{(k)} \leq t_i^{(0)} + t_i^{(0)} \quad \forall (i, i) \in E, \forall k \in C \quad (3.8)$$

$$p_i \leq t_i^{(0)} \quad \forall i \in V \quad (3.9)$$

$$p_i, t_i^{(k)} \in \{0, 1\} \quad \forall i \in V, \forall k \in C \quad (3.10)$$

The objective function (3.1) minimizes the number of jammers positioned at the nodes. According to constraint (3.3), at least one jammer must be positioned in the network. Constraints (3.4) and (3.5) define the lower and upper limits of the number of nodes in the clusters. Constraint (3.2) ensures that a node is assigned to exactly one cluster. Constraint (3.6) orders the clusters from largest to smallest according to their sizes. Constraint (3.7) determines the nodes that will not be in the jammed cluster. The nodes outside the jamming domain are never assigned to the jammed cluster. Constraint (3.8) ensures no communication between clusters. With this constraint, it

is only stated that the clusters are completely separate from each other. This does not mean that there is communication between all nodes within each cluster. Constraint (3.9) provides that the node identified as the jammer is assigned to the jammed cluster. Constraint (3.10) is binary restriction.

3.2.1.1 Drawbacks of the Base Model

The Base Model has several drawbacks listed below.

- Constraint (3.2) ensures that a node is assigned to exactly one cluster. However, since cluster 0, described as a jammed cluster, is not considered in this constraint, a node can be assigned to both the jammed cluster and a different cluster. Therefore, the number of communicating nodes in the clusters cannot be exactly determined.
- Constraint (3.5) defines the upper limits of the number of nodes in the cluster. However, since f_k is given to the model as a parameter, it can be restrictive or permissive for the jamming performance. The selected f_k values may adversely affect the number of jammed nodes or cut links. Determining the f_k values required for the best jamming performance is difficult.
- Constraint (3.7) determines the nodes that will not be in the jammed cluster. The nodes outside the jamming domain are never assigned to the jammed cluster. However, the constraint does not guarantee that the nodes inside the jamming domain will be assigned to the jammed cluster. That is, the value of $t_i^{(k)}$ is forced to be 0 but not forced to take the value 1. Consequently, the incorrect result may appear that the nodes are not jammed, even though they are actually jammed.

3.2.2 MinMax Model

In this mathematical model, we take a new approach to the Base Model, and we believe that we will achieve better results regarding the performance criteria defined in Section 3.1. With the Base Model, the minimum number of jammers is found to divide the network into the desired number of clusters. However, more nodes can be jammed, and more direct and indirect links can be broken under the same conditions. For this, we minimize the maximum number of nodes in a cluster in this model. Thanks to this objective, the model produces more efficient results by trying to jam as many nodes as possible. In parallel, more direct and indirect links are broken. In addition, almost all nodes are prevented from being assigned to a single cluster by keeping the number of nodes in the clusters close to each other. Thus, the communication network is properly divided into the desired number of clusters. In addition to all these, it aims to obtain clearer and more consistent results by improving some constraints mentioned in Section 3.2.1.

Unlike the Base Model, the number of jammers is taken as input in the MinMax Model. For this, the parameter of n_j , which specifies the number of jammers, has been added. Since the number of nodes in the clusters is no longer given as input to the model, the f_k parameters have been removed. The z decision variable, which indicates the maximum number of nodes in a cluster, has been added instead.

Except for these changes, the notation is the same as the Base Model. The new notation is as follows.

Parameters:

n_j : number of jammers

Decision Variables:

z : the maximum number of nodes in a cluster

The MinMax Model is defined as follows.

$$\min \quad z \quad (3.11)$$

s.t.

$$(3.4, 3.6-3.10)$$

$$\sum_{k \in C} t_i^{(k)} = 1 \quad \forall i \in V \quad (3.12)$$

$$\sum_{i \in V} p_i = n_j \quad (3.13)$$

$$\sum_{i \in V} t_i^{(k)} \leq z \quad \forall k \in C \setminus \{0\} \quad (3.14)$$

$$t_i^{(0)} \geq p_i \delta_{ii} \quad \forall (i, \hat{i}) \in E_j \quad (3.15)$$

Constraints (3.4,3.6-3.10) in Base Model also exist in MinMax Model. The lower limit of the number of nodes in a cluster is determined with constraint (3.4). Clusters are sorted with constraint (3.6). Nodes not assigned to the jammed cluster are determined with constraint (3.7). Communication between clusters is not allowed with constraint (3.8). The jammer nodes are assigned to the jammed cluster with constraint (3.9). Constraint (3.10) is binary restriction.

The objective function (3.11) minimizes the maximum number of nodes in a cluster. For this, constraint (3.14) ensures that the number of nodes in each cluster is less than or equal to z . That is, z equals the number of nodes in the cluster with the maximum number of nodes. Constraint (3.13) fixes the number of jammers. A small but significant change has been made in constraint (3.12) compared to the Base Model. The constraint (3.2) in the Base Model assigns nodes to unjammed clusters ($k \neq 0$), not including the jammed cluster ($k = 0$). A node can exist in any unjammed cluster and jammed cluster at the same time. By making improvements with constraint (3.12), we ensure that if a node is assigned to a jammed cluster, it does not exist in any unjammed cluster. Thus, we can adequately determine the number of nodes in the clusters. Finally, the constraint (3.7) could not guarantee that the jammed node is always assigned to the jammed cluster. In the MinMax Model, constraint (3.15) guarantees that the jammed node is assigned to the jammed cluster.

3.2.3 Hierarchical Extension of MinMax Model

In this model, we add a new extension to MinMax Model. In Section 3.2, MinMax Model was mentioned in detail. The objective of the model was to minimize the number of nodes in the cluster with the maximum number of nodes. After MinMax Model is run, only the size of the cluster with the maximum number of nodes is minimized. With this extension, we aim to run the model hierarchically by fixing the number of nodes in the cluster with the maximum number of nodes each time. The following algorithm is the explanation of this extension.

Algorithm 2: The working algorithm of Hierarchical Extension

```

1  $x \leftarrow$  number of clusters to be divided;
2  $k \leftarrow 1$ ;
3 while  $x > 1$  do
4   run MinMax Model;
5    $r \leftarrow$  the result after running ;
6   add the constraint of “# of nodes in cluster  $k = r$ ” to the model ;
7    $x \leftarrow x-1, k \leftarrow k+1$  ;
8 end
```

Remark. # of nodes in cluster $i \geq$ # of nodes in cluster $i-1$ (Constraint (3.6))

Thus, it is expected that the performance of the model will increase since all clusters are taken into account, not just the cluster with the maximum number of nodes.

The parameter of ε_k has been added to MinMax Model. Moreover, the decision variable of z has been arranged as z_k to make a distinction for each cluster. The additional notation is as follows. All other notation is the same as Section 3.2.

Parameters:

ε_k : regulated small number for cluster k

Decision Variables:

z_k : the maximum number of nodes in cluster k

The mathematical model of the hierarchical extension is as follows.

$$\min \sum_{k=1}^{n_c} \varepsilon_k z_k \quad (3.16)$$

s.t.

$$(3.4, 3.6-3.10, 3.12, 3.13, 3.15)$$

$$\sum_{i \in V} t_i^{(k)} \leq z_k \quad \forall k \in C \setminus \{0\} \quad (3.17)$$

Except for the objective function (3.11) and constraint (3.14), the inequalities in the MinMax Model are also available in the hierarchical extension. In MinMax Model, constraint (3.14) indicates that the number of nodes in all clusters is less than z . This constraint has been updated in the hierarchical extension as constraint (3.17), which ensures that the number of nodes in cluster k is smaller than or equal to z_k . Objective function (3.16) minimizes the sum of the results obtained by multiplying z_k by ε_k . The values of ε_k are determined by the equations (3.18) and (3.19) to preserve the hierarchical structure.

$$\varepsilon_1 = 1 \quad (3.18)$$

$$\varepsilon_k(n_c + k + 1) = \varepsilon_{(k-1)}k \quad \forall k \in C \setminus \{0, 1\} \quad (3.19)$$

Equation (3.19) is formed using the following formulations.

In order for the mathematical model to provide Algorithm (2), each value of ε_k must be greater than the value of $\varepsilon_{k+1}z_{k+1} + \varepsilon_{k+2}z_{k+2} + \dots + \varepsilon_{n_c}z_{n_c}$ that follows it hierarchically in the objective function (3.16). Accordingly, the values of ε_k should conform with equation (3.20).

$$\sum_{k=a+1}^{n_c} \varepsilon_k z_k < \varepsilon_a \quad (3.20)$$

Equation (3.20) is formed for ε_a . Likewise, the following equation occurs for ε_{a-1} .

$$\sum_{k=a}^{n_c} \varepsilon_k z_k < \varepsilon_{a-1} \quad (3.21)$$

The following result emerges as a result of subtracting equation (3.20) from equation (3.21). After some calculations, equation (3.22) is obtained.

$$\sum_{k=a}^{n_c} \varepsilon_k z_k - \sum_{k=a+1}^{n_c} \varepsilon_k z_k < \varepsilon_{a-1} - \varepsilon_a \quad \text{from Eqns.(3.20) and (3.21)}$$

$$\varepsilon_a z_a < \varepsilon_{a-1} - \varepsilon_a \quad (3.22)$$

Since the maximum value of z_a is $\frac{n_r}{a}$;

$$\varepsilon_a \frac{n_r}{a} < \varepsilon_{a-1} - \varepsilon_a$$

$$\varepsilon_a \frac{n_r + a}{a} < \varepsilon_{a-1}$$

$$\varepsilon_a \frac{n_r + a + 1}{a} = \varepsilon_{a-1} \quad (3.23)$$

As a result, equation (3.23) is obtained. This equation is valid for all k except 0 and 1. As the initial value, ε_1 is set to 1, and the model determines the values of ε_k according to equations (3.18) and (3.19) to minimize the values of z_k one by one. With this extension, we think that the distribution of the number of nodes between clusters will be more regular, and we will achieve better performance.

3.2.4 Continuous Location Model

All models shown so far work on a discretized plane. Since jammers can only be positioned at the location of radios in the communication network, their placement is restricted. In this model, called the Continuous Location Model, we work on the real plane by completely removing this restriction. In this way, we provide a realistic placement and performance that is at least as good as in the discretized plane by eliminating an important restriction. While doing this, we still aim to minimize the maximum number of nodes in the clusters hierarchically, as mentioned in Section 3.2.3. Consequently; we are moving the Hierarchical Extension of MinMax Model to the real plane.

In this model, the index of ℓ corresponds to jammers that have an omnidirectional antenna, and the set of jammers (J) is defined from 1 to n_j . x_ℓ and y_ℓ are determined as decision variables to find the x and y coordinates of the jammers in the real plane,

respectively. In addition, the x and y coordinates of radio i are indicated by a_i and b_i , respectively. The parameter of M_i equals the maximum distance between node i and other nodes. It is calculated separately for each node and included in the model. The adjacency matrix (δ_{ii}) is not included, instead the $h_{i\ell}$ decision variable is defined in this model. If node i is jammed by jammer ℓ , $h_{i\ell}$ takes the value 1. Otherwise, it is equal to 0. The decision variable of $t_i^{(k)}$ defined in Section 3.2.1, the parameter of n_j defined in Section 3.2, and the parameter of ε_k and the decision variable of z_k defined in Section 3.2.3 are also included in this model.

The new notation is as follows.

Indices:

ℓ : jammers have omnidirectional antenna (1,..., n_j)

Sets:

J : set of jammers

Parameters:

M_i : the maximum distance between node i and other nodes

a_i : x coordinate of node i

b_i : y coordinate of node i

Decision Variables:

$$h_{i\ell} = \begin{cases} 1, & \text{if node } i \text{ is jammed by jammer } \ell \\ 0, & \text{otherwise} \end{cases}$$

x_ℓ : x coordinate of jammer ℓ

y_ℓ : y coordinate of jammer ℓ

The Continuous Location Model is defined as follows.

$$\min \sum_{k=1}^{n_c} \varepsilon_k z_k \quad (3.16)$$

s.t.

$$(3.4, 3.6, 3.8, 3.10, 3.12, 3.17)$$

$$\left\| \begin{pmatrix} x_\ell - a_i \\ y_\ell - b_i \end{pmatrix} \right\| \leq d_j + (M_i - d_j)(1 - h_{i\ell}) \quad \forall i \in V, \forall \ell \in J \quad (3.24)$$

$$\sum_{\ell \in J} h_{i\ell} \geq t_i^{(0)} \quad \forall i \in V \quad (3.25)$$

$$x_{\ell-1} \leq x_\ell \quad \forall \ell \in J \setminus \{1\} \quad (3.26)$$

$$x_\ell \geq \min_i \{a_i\} \quad \forall \ell \in J \quad (3.27)$$

$$x_\ell \leq \max_i \{a_i\} \quad \forall \ell \in J \quad (3.28)$$

$$y_\ell \geq \min_i \{b_i\} \quad \forall \ell \in J \quad (3.29)$$

$$y_\ell \leq \max_i \{b_i\} \quad \forall \ell \in J \quad (3.30)$$

$$h_{i\ell} \in \{0, 1\} \quad \forall i \in V, \forall \ell \in J \quad (3.31)$$

In this model, the aim is still to minimize the number of nodes in the clusters hierarchically, so objective function (3.16) and constraint (3.17) are the same as the hierarchical extension. The constraints (3.4, 3.6, 3.8, 3.10, 3.12) used in previous models are also used in this model. With the newly added constraint (3.24), when the Euclidean distance between the jammer ℓ and the radio i is greater than the jamming distance (the node i is not jammed by jammer ℓ), $h_{i\ell}$ must take the value 0 to ensure inequality. Thus, if a node is not jammed by any jammer, that node is not assigned to the jammed cluster with constraint (3.25). On the other hand, if a node is jammed, the model assigns the node to the jammed cluster to reduce the number of nodes in unjammed clusters because of the objective function. Constraint (3.26) sorts the jammers by their x coordinates to reduce the symmetry and make the branch and bound size smaller. Constraints (3.27, 3.28, 3.29, 3.30) limits the jammer coordinates. These constraints define the coordinates of the jammers so that they are not beyond the outermost nodes. Constraint (3.31) is binary restriction.

3.2.5 Base Continuous Location Model

In this model, called the Base Continuous Location Model, we adapt the approach in the Base Model to the real plane. Jammers only positioned at radio locations in the Base Model can now be positioned anywhere on the real plane. Minor changes and additions have been made to the Continuous Location Model to achieve this. In Section 3.2.4, it was explained that the Continuous Location Model is obtained by moving the hierarchical minmax approach to the real plane. Similarly, this model is obtained by moving the base approach mentioned in Section 3.2.1 to the real plane.

Feng et al., who proposed the Base Model, also proposed the real plane version of the model in another paper [2]. In their study, they find the optimal jammer placement by choosing candidate jammer locations. We find the optimal jammer placement with this model, different from the work of Feng et al. [2]. However, the approaches are the same, although the models are different. In this way, the minmax and base approaches can be compared on the real plane regarding the performance criteria.

The parameter of ε_k and the decision variable of z_k used in the Continuous Location Model are not included in this model. Instead of z_k , the maximum number of nodes in clusters is determined by the parameter of f_k , which is also used in the Base Model. Since the model must find the coordinates of the jammers, the index ℓ is still used. However, since it is aimed to minimize the number of jammers and the number of jammers is not given to the model as an input, an additional decision variable, λ_ℓ , is defined. This decision variable determines whether the positioned jammer is real or dummy. If a real jammer is positioned, λ_ℓ takes the value 1. Otherwise, it is equal to 0. If a jammer is positioned as a dummy, it does not jam any node. Another change has been made in the parameter of n_j , which specifies the number of jammers. Since the number of jammers will be an output of this model, the maximum number of jammers that can be used, indicated by the parameter of m_j , is now given to the model as input. Other notation is the same as the Continuous Location Model in Section 3.2.4, and common notation is valid here as well.

The new notation is as follows.

Indices:

ℓ : jammers have omnidirectional antenna (1,..., m_j)

Parameters:

m_j : maximum number of jammers

f_k : maximum number of nodes in cluster k

Decision Variables:

$$\lambda_\ell = \begin{cases} 1, & \text{if a real jammer assigned to } \ell \\ 0, & \text{if a dummy jammer assigned to } \ell \end{cases}$$

The Base Continuous Location Model is defined as follows.

$$\min \sum_{\ell=1}^{m_j} \lambda_\ell \quad (3.32)$$

s.t.

(3.2, 3.4-3.6, 3.8, 3.10, 3.24-3.31)

$$\sum_{\ell=1}^{m_j} \lambda_\ell \geq 1 \quad (3.33)$$

$$\lambda_\ell \geq h_{i\ell} \quad \forall i \in V, \forall \ell \in J \quad (3.34)$$

$$\lambda_{\ell-1} \geq \lambda_\ell \quad \forall \ell \in J \setminus \{1\} \quad (3.35)$$

$$\lambda_\ell \in \{0, 1\} \quad \forall \ell \in J \quad (3.36)$$

Constraints (3.2, 3.4-3.6, 3.8, 3.10, 3.24-3.31) used in previous models are also used in this model. Explanations of these constraints are given in previous sections. Differently, the objective function (3.32) minimizes the sum of λ_ℓ . It equals the number of used jammers since dummy jammers take the value 0. Constraint (3.34) ensures that a dummy jammer ℓ cannot jam any node since all $h_{i\ell}$ will take the value 0. If the jammer is real, the restriction on $h_{i\ell}$ is removed. Nodes in the jamming domain of the real jammer can take the value of 1. Otherwise, they can take the value of 0. Constraint (3.33) enforces the use of at least one jammer. Constraint (3.35) make sure that the real jammers have the lowest indices to reduce the symmetry. Constraint (3.36) is binary restriction.

3.2.6 Directional Antenna Addition Model

In all of the models studied so far, the jammers had an omnidirectional antenna that caused circular jamming. However, jammers with directional antenna that perform directional jamming instead of circular jamming also exist. Directional jamming means jamming in a fixed direction only at a certain angle. This angle depends on the characteristics of the directional antenna and is usually equal to 60° , 90° , or 120° . If the attack direction of the enemy is clear, the jamming of friendly radios can be prevented by using jammers with directional antenna. In addition, the jamming angle is inversely proportional to the jamming distance, so the jamming distance decreases as the angle increases. For this reason, the jamming distance of jammers with directional antenna is greater than that of jammers with omnidirectional antenna. In special cases, enemy radios farther away can be jammed due to directional antennas. In this section, we reach our final model by adding directional antenna addition to the Hierarchical Extension of MinMax Model. The jammers are no longer homogeneous in this model since there are two types of jammers with omnidirectional and directional antennas. Except for the variety of jammers, all concepts are the same as the Hierarchical Extension of MinMax Model. However, since this model is the final model, all notations and the entire model will be included in this section, even if used in previous models, to avoid disrupting the integrity. The explanations for the notation and constraints found in the previous models will be kept short.

Since changes involving radios and clusters have not been made, these and related notations are the same. Firstly, radios are represented by i or $\hat{i}$ and the set of radios by V . The total number of radios in the set V equals n_r . The radios communicate with each other when the distance between them is less than d_o . The set of communication links between radios is indicated by E . A communication graph, represented by $G(V, E)$, is created on a 2-dimensional plane according to V and E . The x and y coordinates of the radio i in this graph are indicated by a_i and b_i , respectively. Also, the maximum distance between node i and other nodes is M_i . Secondly, clusters are represented by k and the set of clusters by C . The total number of unjammed clusters in the set C equals n_c . Jammed cluster, $k = 0$, is also included in the set C . The decision variable of z_k and the parameter of ε_k exist for the hierarchical structure

between clusters. z_k is the maximum number of nodes in cluster k . ε_k is a regulated small number for cluster k , and its formulation is specified in equation (3.23). Finally, assigning radio i to cluster k is again determined by $t_i^{(k)}$.

Since two types of jammers are used in this model, the jammer and related notation differ from previous models. In previous models, ℓ represented jammer with omnidirectional antenna, and jammer discrimination was not made. In this model, ℓ again represents jammers with omnidirectional antenna. In addition, $\vec{\ell}$ has been added to represent jammers with directional antenna. Anymore, $n_{\vec{j}}$ is the number of jammers with directional antenna while n_j is for jammers with omnidirectional antenna. The set formed by ℓ and $\vec{\ell}$ are represented as J and $\vec{J}$, respectively. x_ℓ and y_ℓ are the x and y coordinates of the jammer ℓ , respectively. $x_{\vec{\ell}}$ and $y_{\vec{\ell}}$ are the x and y coordinates of the jammer $\vec{\ell}$, respectively. Since the jamming distances of the jammers change according to the antennas, these are represented in two different ways as d_j and $d_{\vec{j}}$. d_j is for omnidirectional antennas while $d_{\vec{j}}$ is for directional antennas.

Jammers with omnidirectional antennas jam 360° , while jammers with directional antenna can jam at different angles. Therefore, a parameter for angle is needed. θ is used for the jamming angle of the directional antenna. Through dividing 360° by this parameter, the number of directional antenna directions represented by $n_{\vec{j}}$ is determined. The directions of the directional antenna are represented by ρ , and the ρ forms the set of Q . For instance, the number of antenna directions is 6 for $\theta = 60^\circ$; that is, the jammer can be positioned to jam in six different directions. Two unit vectors called lines are used to determine a direction exactly. The x and y coordinates (direction coordinates) of the first line used for the direction ρ are represented by ∇_ρ^1 and ∇_ρ^2 , respectively. The x and y coordinates (direction coordinates) of the second line used for the direction ρ are represented by ∇_ρ^3 and ∇_ρ^4 , respectively. These representations are visualized in Figure 3.2.

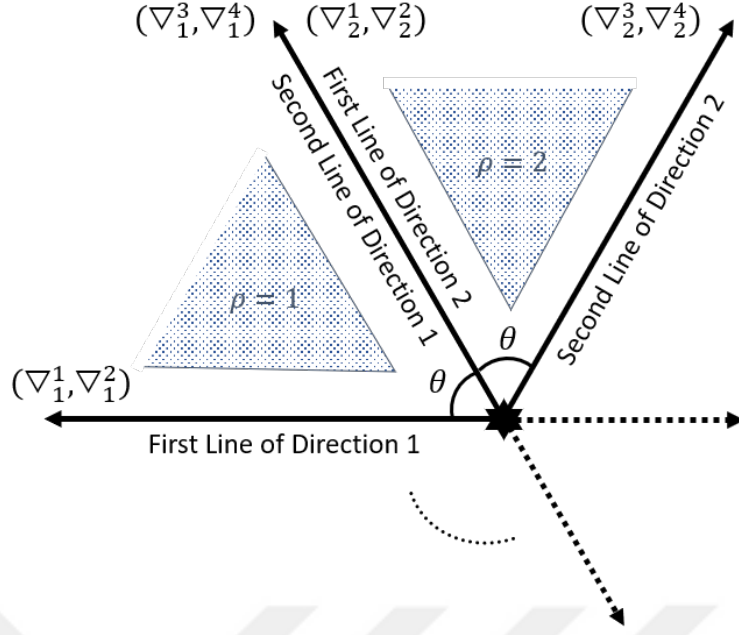


Figure 3.2: Angle, directions, direction coordinates, and direction lines of directional antenna

(∇_1^1, ∇_1^2) is always $(-1, 0)$, and the direction coordinates of other lines change according to θ . The following equations show the method of calculating the direction coordinates of the lines.

$$\nabla_1^1 = -1 \quad (3.37)$$

$$\nabla_1^2 = 0 \quad (3.38)$$

$$\nabla_\rho^3 = \nabla_\rho^2 \cos(90 - \theta) + \nabla_\rho^1 \sin(90 - \theta) \quad \forall \rho \in Q \quad (3.39)$$

$$\nabla_\rho^4 = \nabla_\rho^2 \sin(90 - \theta) + \nabla_\rho^1 \cos(90 - \theta) \quad \forall \rho \in Q \quad (3.40)$$

$$\nabla_{(\rho+1)}^1 = \nabla_\rho^3 \quad \forall \rho \in Q \setminus \{n_q\} \quad (3.41)$$

$$\nabla_{(\rho+1)}^2 = \nabla_\rho^4 \quad \forall \rho \in Q \setminus \{n_q\} \quad (3.42)$$

If the distance between a jammer with omnidirectional antenna and a radio is less than d_j , this jammer jams the radio. Only the distance determines whether jamming occurs for an omnidirectional antenna. If node i is jammed by jammer ℓ , $h_{i\ell}$ takes the value 1. Otherwise, it is equal to 0. Since the situation differs for a jammer with directional antenna, three different decision variable requirements arise. First, $u_{\vec{\ell}\rho}$ is used to determine the direction of the jammer antenna. If antenna of jammer $\vec{\ell}$ is positioned

in the direction ρ , $u_{\vec{\ell}\rho}$ takes the value 1. Otherwise, it is equal to 0. Second, $b_{i\vec{\ell}}$ is used to determine whether the distance between the jammer with directional antenna and the radio is greater or less than $d_{\vec{j}}$. If the distance between node i and jammer $\vec{\ell}$ is at most $d_{\vec{j}}$, $b_{i\vec{\ell}}$ takes the value 1. Otherwise, it is equal to 0. Finally, $s_{i\vec{\ell}\rho}$ determines if a radio is jammed. If node i is jammed by jammer $\vec{\ell}$ in the direction ρ , $s_{i\vec{\ell}\rho}$ takes the value 1. Otherwise, it is equal to 0.

The notation for Directional Antenna Addition Model is as follows.

Indices:

$i, \hat{i}$: radios or nodes $(1, \dots, n_r)$

k : clusters $(0, \dots, n_c)$

ℓ : jammers with omnidirectional antenna $(1, \dots, n_j)$

$\vec{\ell}$: jammers with directional antenna $(1, \dots, n_{\vec{j}})$

ρ : directions of jammer antenna $(1, \dots, n_q)$

Sets:

V : set of radios

E : set of communication links

C : set of clusters

J : set of jammers with omnidirectional antenna

$\vec{J}$: set of jammers with directional antenna

Q : set of directions

Parameters:

n_r : number of radios

n_c : number of clusters

n_j : number of jammers with omnidirectional antenna

$n_{\vec{j}}$: number of jammers with directional antenna

n_q : number of directions $(360^\circ / \theta)$

θ : jamming angle of directional antenna $(360^\circ / n_q)$

d_o : communication distance

d_j : jamming distance (omnidirectional antenna)

$d_{\vec{j}}$: jamming distance (directional antenna)

a_i : x coordinate of node i

b_i : y coordinate of node i

∇_ρ^1 : x coordinate of the direction ρ for the first line

∇_ρ^2 : y coordinate of the direction ρ for the first line

∇_ρ^3 : x coordinate of the direction ρ for the second line

∇_ρ^4 : y coordinate of the direction ρ for the second line

ε_k : regulated small number for cluster k

M_i : the maximum distance between node i and other nodes

$M'_{i\rho}$: the big number used to find out if node i is in the direction ρ

$G(V, E)$: communication graph

Decision Variables:

$$t_i^{(k)} = \begin{cases} 1, & \text{node } i \in \text{cluster } k \\ 0, & \text{otherwise} \end{cases}$$

$$h_{i\ell} = \begin{cases} 1, & \text{if node } i \text{ is jammed by jammer } \ell \\ 0, & \text{otherwise} \end{cases}$$

$$b_{i\vec{\ell}} = \begin{cases} 1, & \text{if the distance between node } i \text{ and jammer } \vec{\ell} \text{ is at most } d_{\vec{\ell}} \\ 0, & \text{otherwise} \end{cases}$$

$$u_{\vec{\ell}\rho} = \begin{cases} 1, & \text{if antenna of jammer } \vec{\ell} \text{ is positioned in the direction } \rho \\ 0, & \text{otherwise} \end{cases}$$

$$s_{i\vec{\ell}\rho} = \begin{cases} 1, & \text{if node } i \text{ is jammed by jammer } \vec{\ell} \text{ in the direction } \rho \\ 0, & \text{otherwise} \end{cases}$$

x_ℓ : x coordinate of jammer ℓ

y_ℓ : y coordinate of jammer ℓ

$x_{\vec{\ell}}$: x coordinate of jammer $\vec{\ell}$

$y_{\vec{\ell}}$: y coordinate of jammer $\vec{\ell}$

z_k : the maximum number of nodes in cluster k

The Directional Antenna Addition Model is defined as follows.

$$\min \sum_{k=1}^{n_c} \varepsilon_k z_k \quad (3.43)$$

s.t.

$$\sum_{k \in C} t_i^{(k)} = 1 \quad \forall i \in V \quad (3.44)$$

$$\sum_{i \in V} t_i^{(k)} \geq 1 \quad \forall k \in C \quad (3.45)$$

$$\sum_{i \in V} t_i^{(k)} \leq z_k \quad \forall k \in C \setminus \{0\} \quad (3.46)$$

$$\sum_{i \in V} t_i^{(k)} \leq \sum_{i \in V} t_i^{(k-1)} \quad \forall k \in C \setminus \{0, 1\} \quad (3.47)$$

$$t_i^{(k)} - t_i^{(k-1)} \leq t_i^{(0)} + t_i^{(0)} \quad \forall (i, \hat{i}) \in E, \forall k \in C \quad (3.48)$$

$$\left\| \begin{pmatrix} x_\ell - a_i \\ y_\ell - b_i \end{pmatrix} \right\| \leq d_j + (M_i - d_j) (1 - h_{i\ell}) \quad \forall i \in V, \forall \ell \in J \quad (3.49)$$

$$\left\| \begin{pmatrix} x_{\vec{\ell}} - a_i \\ y_{\vec{\ell}} - b_i \end{pmatrix} \right\| \leq d_{\vec{j}} + (M_i - d_{\vec{j}}) (1 - b_{i\vec{\ell}}) \quad \forall i \in V, \forall \vec{\ell} \in \vec{J} \quad (3.50)$$

$$\begin{aligned} -\nabla_\rho^2 a_i + \nabla_\rho^1 b_i &\leq -\nabla_\rho^2 x_{\vec{\ell}} + \nabla_\rho^1 y_{\vec{\ell}} \\ &\quad - M'_{i\rho} (1 - u_{\vec{\ell}\rho}) + 2M'_{i\rho} (1 - s_{i\vec{\ell}\rho}) \end{aligned} \quad \forall i \in V, \forall \vec{\ell} \in \vec{J}, \forall \rho \in Q \quad (3.51)$$

$$\begin{aligned} \nabla_\rho^4 a_i - \nabla_\rho^3 b_i &\leq \nabla_\rho^4 x_{\vec{\ell}} - \nabla_\rho^3 y_{\vec{\ell}} \\ &\quad - M'_{i\rho} (1 - u_{\vec{\ell}\rho}) + 2M'_{i\rho} (1 - s_{i\vec{\ell}\rho}) \end{aligned} \quad \forall i \in V, \forall \vec{\ell} \in \vec{J}, \forall \rho \in Q \quad (3.52)$$

$$b_{i\vec{\ell}} \geq \sum_{\rho \in Q} s_{i\vec{\ell}\rho} \quad \forall i \in V, \forall \vec{\ell} \in \vec{J} \quad (3.53)$$

$$\sum_{\ell \in J} h_{i\ell} + \sum_{\vec{\ell} \in \vec{J}} \sum_{\rho \in Q} s_{i\vec{\ell}\rho} \geq t_i^{(0)} \quad \forall i \in V \quad (3.54)$$

$$\sum_{\rho \in Q} u_{\vec{\ell}\rho} = 1 \quad \forall \vec{\ell} \in \vec{J} \quad (3.55)$$

$$x_{\ell-1} \leq x_\ell \quad \forall \ell \in J \setminus \{1\} \quad (3.56)$$

$$x_{\vec{\ell}-1} \leq x_{\vec{\ell}} \quad \forall \vec{\ell} \in \vec{J} \setminus \{1\} \quad (3.57)$$

$$x_\ell \geq \min_i \{a_i\} \quad \forall \ell \in J \quad (3.58)$$

$$x_\ell \leq \max_i \{a_i\} \quad \forall \ell \in J \quad (3.59)$$

$$y_\ell \geq \min_i \{b_i\} \quad \forall \ell \in J \quad (3.60)$$

$$y_\ell \leq \max_i \{b_i\} \quad \forall \ell \in J \quad (3.61)$$

$$x_{\vec{\ell}} \geq \min_i \{a_i\} \quad \forall \vec{\ell} \in \vec{J} \quad (3.62)$$

$$x_{\vec{\ell}} \leq \max_i \{a_i\} \quad \forall \vec{\ell} \in \vec{J} \quad (3.63)$$

$$y_{\vec{\ell}} \geq \min_i \{b_i\} \quad \forall \vec{\ell} \in \vec{J} \quad (3.64)$$

$$y_{\vec{\ell}} \leq \max_i \{b_i\} \quad \forall \vec{\ell} \in \vec{J} \quad (3.65)$$

$$t_i^{(k)}, h_{i\ell} \in \{0, 1\} \quad \forall i \in V, \forall k \in C, \forall \ell \in J \quad (3.66)$$

$$b_{i\vec{\ell}}, u_{\vec{\ell}\rho}, s_{i\vec{\ell}\rho} \in \{0, 1\} \quad \forall i \in V, \forall \vec{\ell} \in \vec{J}, \forall \rho \in Q \quad (3.67)$$

Objective function (3.43) and constraints (3.44, 3.45, 3.46, 3.47, 3.48, 3.49, 3.56, 3.58, 3.59, 3.60, 3.61) were also used in previous models. The objective function (3.43) hierarchically minimizes the number of nodes in the cluster with the maximum number of nodes. Constraint (3.44) assigns nodes to one of the unjammed clusters or jammed cluster. Constraints (3.45) and (3.46) determine the lower and upper bounds of the number of nodes in the clusters. Constraint (3.47) sorts clusters according to their size. While the first cluster has the most nodes, the $(n_c - 1)^{th}$ cluster has the least. Constraint (3.48) ensures that there is no communication between nodes in different clusters. Constraint (3.49) determines whether a node is jammed by a jammer with omnidirectional antenna based on the distance between them. Constraint (3.56) sorts the jammers with omnidirectional antenna by their x coordinates to reduce the symmetry and make the branch and bound size smaller. Constraints (3.58, 3.59, 3.60, 3.61) limits coordinates of jammers with omnidirectional antenna. Constraint (3.66) is binary restriction.

Constraint (3.50), one of the newly added constraints, is very similar to the constraint (3.49) used in previous models. With this constraint, $b_{i\vec{\ell}}$ takes the value 1 if the distance between a node and a jammer with directional antenna is less than the jamming distance ($d_{\vec{j}}$). Otherwise, it is equal to 0. However, just looking at the distance is not enough for jammers with directional antenna. Therefore, only this constraint cannot determine whether a radio is jammed. It is also necessary to determine whether the radio is in the direction where the antenna of the jammer is positioned. Constraints (3.51) and (3.52) are used for direction determination. Constraint (3.51) determines which side the radio coordinates are on according to the first line of the antenna direction, and constraint (3.52) determines which side it is on according to the second line.

Constraint (3.53) ensures that a radio is not jammed when it is not within the jamming distance. With these three constraints, it is decided whether the radio is jammed or not. If the radio is between two lines in the direction of the antenna and within the jamming distance, $s_{i\vec{\ell}\rho}$ is 1. Otherwise, it is equal to 0. The following calculations are made to determine the equations used in constraints (3.51) and (3.52).

For node i with the coordinates a_i and b_i to be jammed by the jammer $\vec{\ell}$ in the direction ρ , the node should be between two lines of direction ρ as seen in Figure 3.3.

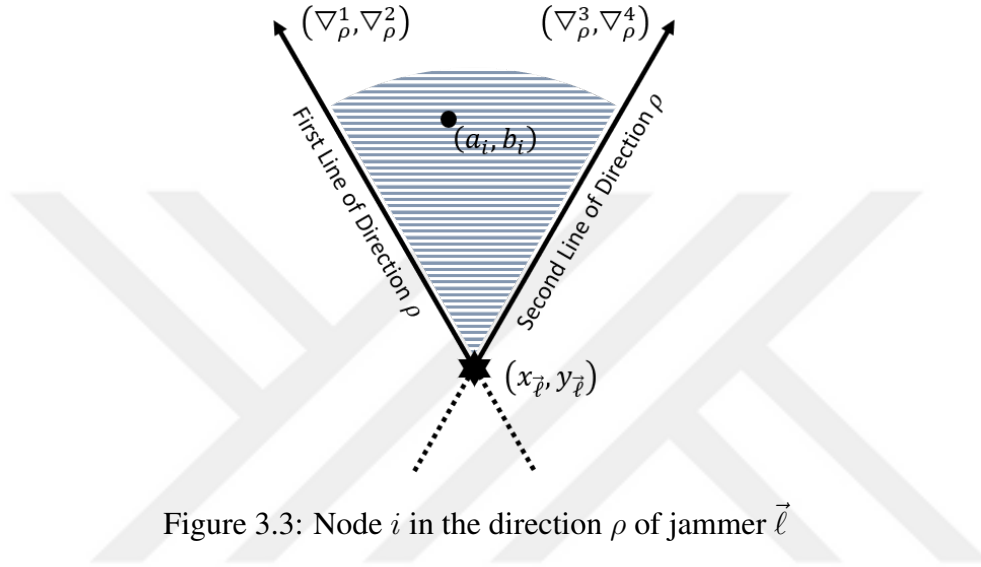


Figure 3.3: Node i in the direction ρ of jammer $\vec{\ell}$

Two separate calculations are required to determine that node i is between two lines of direction ρ . Both calculations are made using the following basic slope formula.

$$y - y_{\vec{\ell}} = m (x - x_{\vec{\ell}}) \quad (3.68)$$

The next calculation is made for the right area of the first line shown in Figure 3.4.

$$\begin{aligned} b_i - y_{\vec{\ell}} &\leq (\nabla_{\rho}^2 / \nabla_{\rho}^1) (a_i - x_{\vec{\ell}}) && \text{from Eqn.(3.68)} \\ \nabla_{\rho}^1 (b_i - y_{\vec{\ell}}) &\leq \nabla_{\rho}^2 (a_i - x_{\vec{\ell}}) \\ \nabla_{\rho}^1 b_i - \nabla_{\rho}^1 y_{\vec{\ell}} &\leq \nabla_{\rho}^2 a_i - \nabla_{\rho}^2 x_{\vec{\ell}} \\ -\nabla_{\rho}^2 a_i + \nabla_{\rho}^1 b_i &\leq -\nabla_{\rho}^2 x_{\vec{\ell}} + \nabla_{\rho}^1 y_{\vec{\ell}} \end{aligned} \quad (3.69)$$

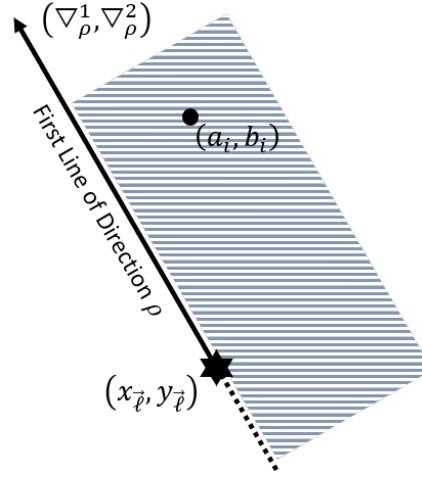


Figure 3.4: Node i on the right of the first line which indicates the direction ρ of jammer $\vec{\ell}$

The next calculation is made for the left area of the second line shown in Figure 3.5.

$$\begin{aligned}
 b_i - y_{\vec{\ell}} &\geq (\nabla_{\rho}^4 / \nabla_{\rho}^3) (a_i - x_{\vec{\ell}}) && \text{from Eqn.(3.68)} \\
 \nabla_{\rho}^3 (b_i - y_{\vec{\ell}}) &\geq \nabla_{\rho}^4 (a_i - x_{\vec{\ell}}) \\
 \nabla_{\rho}^3 b_i - \nabla_{\rho}^3 y_{\vec{\ell}} &\geq \nabla_{\rho}^4 a_i - \nabla_{\rho}^4 x_{\vec{\ell}} \\
 -\nabla_{\rho}^4 a_i + \nabla_{\rho}^3 b_i &\geq -\nabla_{\rho}^4 x_{\vec{\ell}} + \nabla_{\rho}^3 y_{\vec{\ell}} \\
 \nabla_{\rho}^4 a_i - \nabla_{\rho}^3 b_i &\leq \nabla_{\rho}^4 x_{\vec{\ell}} - \nabla_{\rho}^3 y_{\vec{\ell}} && (3.70)
 \end{aligned}$$

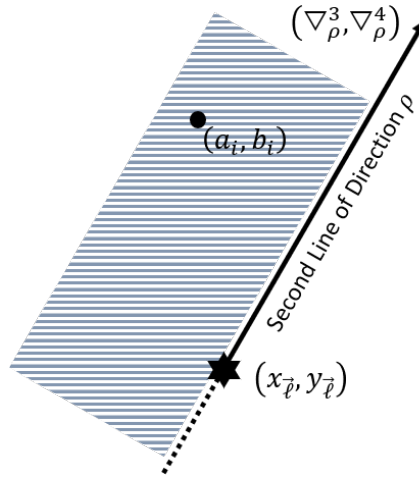


Figure 3.5: Node i on the left of the second line which indicates the direction ρ of jammer $\vec{\ell}$

When Equation (3.69) and Equation (3.70) are used together, the shaded area specified in Figure 3.3 is reached.

It is sufficient to jam a radio by at least one jammer with omnidirectional antenna or directional antenna to assign it to the jammed cluster. Constraint (3.54) provides this condition and assigns jammed nodes to the jammed cluster. Constraint (3.55) allows the jammer with directional antenna to be positioned in only one direction. Constraint (3.57) sorts the jammers with directional antenna by their x coordinates to reduce the symmetry and make the size of branch and bound tree smaller. Constraints (3.62, 3.63, 3.64, 3.65) limit coordinates of jammers with directional antenna. Constraint (3.67) is binary restriction.



CHAPTER 4

COMPUTATIONAL RESULTS

We used a computer with Intel Xeon E2246G, a 3.6 GHz processor, and 16 GB RAM in our computational experiments. We preferred to use ILOG CPLEX Optimization Studio 12.10.0, MATLAB R2022a, and Microsoft Excel Visual Basic for Applications (VBA) integrated with each other. The process of obtaining computational results is summarized in the next paragraph.

Parameters for mathematical models are calculated with MATLAB and transferred to a Microsoft Excel file. The transferred parameters are arranged automatically with VBA to be given to CPLEX. Then, the mathematical models are run by CPLEX with these parameters. The results of the models are exported to the same Microsoft Excel file, and VBA makes the results ready for MATLAB. This time, the same MATLAB code gets the results from Microsoft Excel. Then, the figures shown in Section 4.1 and the tables shown in Section 4.2 are created in MATLAB.

4.1 Illustrative Examples

In section 3.2, six models are shown, including improvement, new approach, and different additions. In this section, we share some illustrative examples to show the results we got from the models and the differences between these results. In illustrative examples, the results of the models are obtained in the same conditions to make the appropriate comparison between the models. For this reason, Base Model and Base Continuous Location Model are not presented in the same comparison. Even if the two models are run with the same parameters, it is possible to yield results with different numbers of jammers. Developed models with the minmax approach are per-

formed with the number of jammers that are the output of the base approach models so that the models give results with the same number of jammers. For this reason, the Base Model is compared with MinMax, Hierarchical Extension, and Continuous Location Models. The Base Continuous Location Model is compared with the Continuous Location Model. In addition, the final model, Directional Antenna Addition Model, is not included in comparison with other models due to its directional antenna addition and is subject to comparison within itself. So, the illustrations are given under three separate sections: Improvements Starting from Base Model, Improvements Starting from Base Continuous Location Model, and Improvements by Antenna Type and Angle. In the first and second sections, comparisons are made in accordance with the number of jammers obtained from the Base Model and Base Continuous Location Model, respectively. In the third section, Directional Antenna Addition Model is compared within itself for different combinations and parameters.

As a reminder, different shapes are used for cluster separation in the figures. Therefore, nodes are shown differently, not with a fixed representation. Jammed radios can be understood from the circles around them. Unlike nodes, jammers have a fixed representation as a hexagram. Large disks or sectors of disks indicate the jamming domain of the jammers. Another important representation in the figures is the lines. Straight lines represent active communication links, and dashed lines represent broken communication links. If a radio is jammed, all communication links of that radio are broken. In addition, summary tables are provided for the comparisons. Detailed explanations and computing algorithm of the expressions in these tables, such as direct links, indirect links, cut direct links, cut indirect links, and success rates, are mentioned in Section 3.1.

4.1.1 Improvements Starting from Base Model

This section includes illustrative examples for the Base Model, Base Model Plus, MinMax Model, Hierarchical Extension of MinMax Model, and Continuous Location Model. Starting from the Base Model, the improvement in the discrete plane and in the transition to the real plane are shown. As a reminder, the jammers used in the Base Model, MinMax Model, and Hierarchical Extension of MinMax Models

have an omnidirectional antenna and are positioned at radio locations. Therefore, these models are described as models that perform on the discretized plane. In the Continuous Location Model, jammer locations are not limited to radio locations but can be placed anywhere in the field. For this reason, this model performs on the real plane.

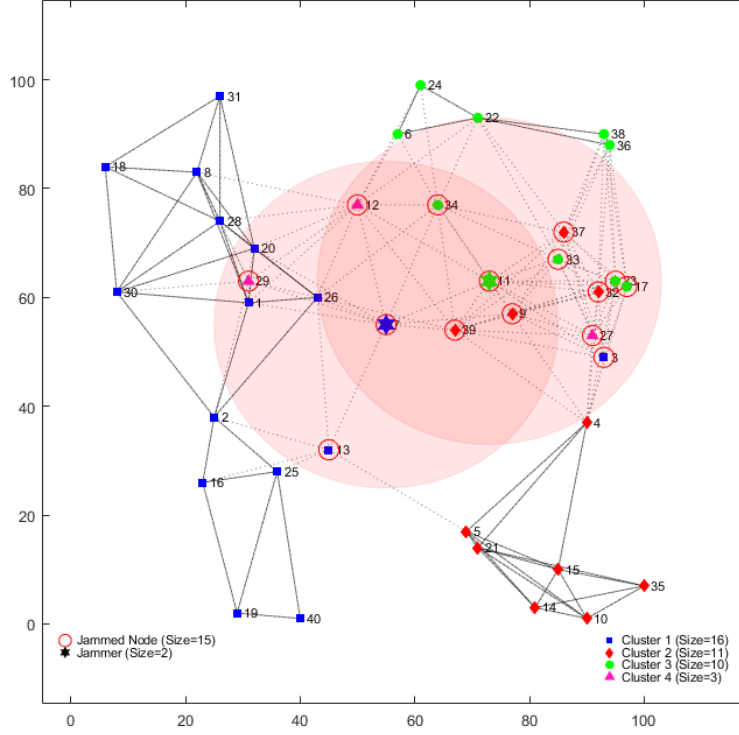


Figure 4.1: Illustrative result of Base Model for $n_r=40$, $n_c=4$, $d_o=30$, $d_j=30$

Figure 4.1 shows the result obtained by running the Base Model in an area of 100 km^2 for $n_r = 40$, $n_c = 4$, $d_o = 30$ and $d_j = 30$. As a result, two jammers are positioned at nodes 7 and 11. A total of 15 radios are jammed with this placement. However, when we look at Figure 4.1 in detail, it is seen that nodes 1, 20, and 26 are not assigned as jammed nodes even though they are in the jamming domain. This results from the drawback of constraint (3.7) mentioned in Section 3.2.1. This constraint assigns unjammed nodes to the unjammed clusters but does not guarantee that jammed nodes are assigned to the jammed cluster. To avoid this drawback, the constraint (3.15) mentioned in Section 3.2 must be in the model. By adding this constraint to the Base Model, the results obtained with the new model, Base Model Plus, are shown in Figure 4.2.

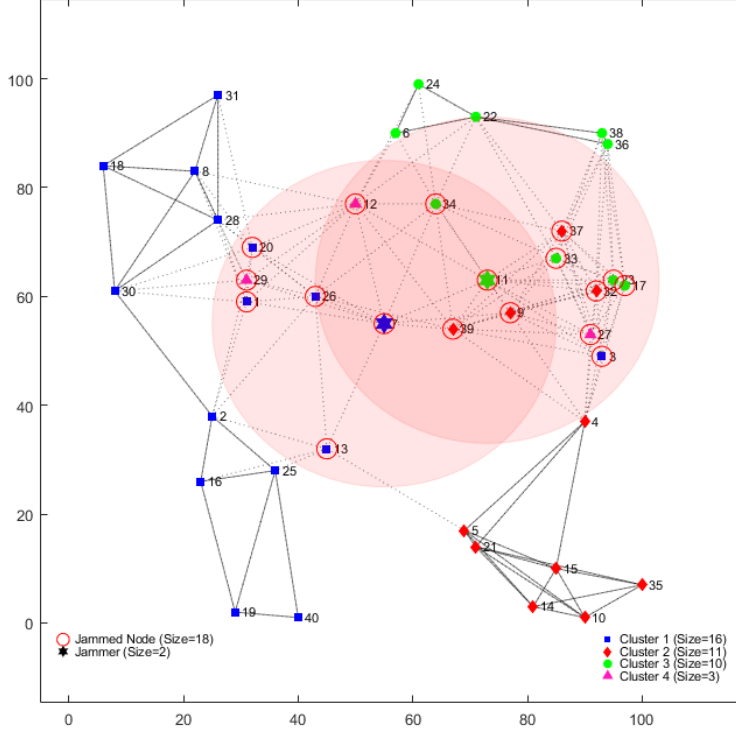


Figure 4.2: Illustrative result of Base Model Plus for $n_r=40$, $n_c=4$, $d_o=30$, $d_j=30$

As can be seen, all nodes in the jamming domain are assigned as jammed in the results of the new model. The number of jammed nodes has been increased to 18, and a circle has been added around nodes 1, 20, and 26.

In Figures 4.1 and 4.2, different shapes are used for the clusters, including square, diamond, circle, and triangle. As can be seen, the clusters cannot communicate with each other in any way. It was aimed to divide the communication network into 4 clusters, but the unjammed nodes form 3 different clusters. In this case, we can say that the network is actually divided into 3 clusters. This results from the constraint (3.2) mentioned in Section 3.2.1. Because of this constraint, nodes are assigned to both the jammed cluster and one of the unjammed clusters. As seen in the figures, all jammed nodes are included in a cluster. Since all nodes are jammed in cluster 4, indicated by the triangle, the initially desired number of clusters and the number of clusters the model gives do not match. The model can reach the desired number of clusters by assigning only one jammed node to one or more clusters. We describe this case as a drawback. Therefore, when making any comparisons, we consider the number of clusters obtained from the Base Model, called unjammed cluster, instead of the

desired number of clusters given as input to the model, called base cluster. Constraint (3.12) is used to avoid this case in the MinMax Model. The results obtained by running the MinMax Model with the same parameters are visualized in Figure 4.3. As can be seen, jammed nodes no longer belong to any cluster. Therefore, jammed nodes are represented by an asterisk with a circle outside.

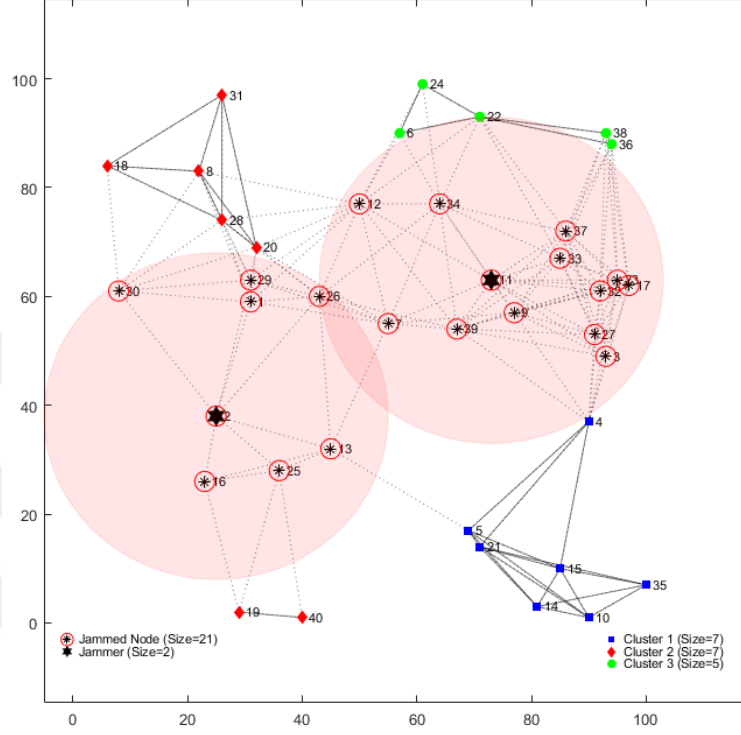


Figure 4.3: Illustrative result of MinMax Model for $n_r=40$, $n_j=2$, $n_c=3$, $d_o=30$, $d_j=30$

The number of unjammed clusters is used in the MinMax Model to make a meaningful comparison between the models. In this way, the network is divided into 3 clusters with both models. In Figure 4.3, it is seen that the nodes where the jammers are positioned have changed. The jammer, positioned at node 7 with the Base Model, is positioned at node 2 with the MinMax Model. The position of the other jammer remains the same. Three more nodes are jammed with this change. Under the same conditions, the MinMax Model uses two jammers like the Base Model but separates the communication network into 3 clusters with better performance.

In the result of Base Model, the number of nodes in the clusters was distributed imbalanced. While the number of nodes in the cluster with the maximum size was 16,

the number of nodes in the cluster with the minimum size was 3. However, the maximum number of nodes in a cluster has been reduced to 7 by providing a balanced distribution with the MinMax Model.

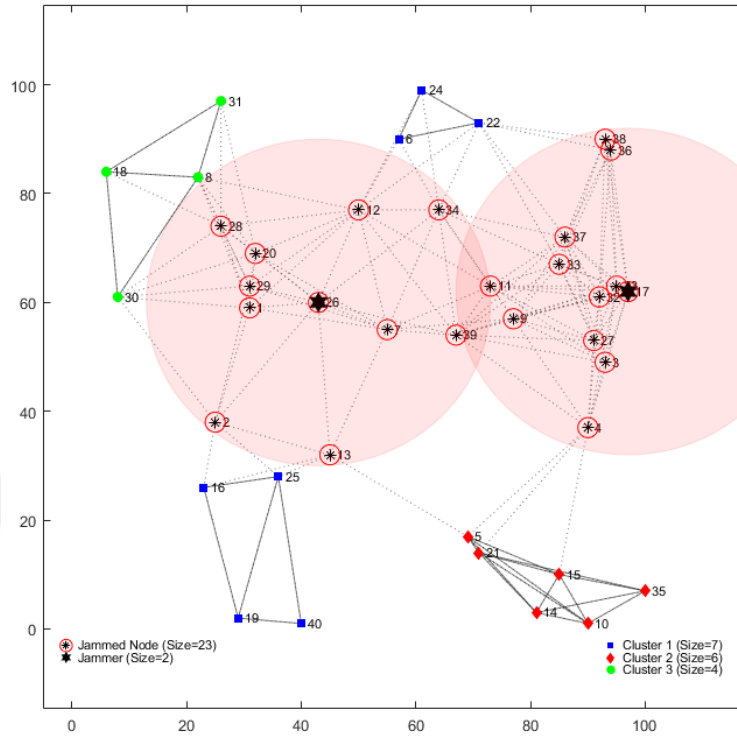


Figure 4.4: Illustrative result of Hierarchical Extension of MinMax Model for $n_r=40$, $n_j=2$, $n_c=3$, $d_o=30$, $d_j=30$

The hierarchical extension of MinMax Model was run under the same conditions to evaluate the effect on the distribution of the number of nodes in the clusters, and the result is shown in Figure 4.4. The maximum number of nodes in a cluster is still 7, but the numbers in other clusters have been minimized and have decreased due to the hierarchical structure. Jammers are positioned at different nodes (nodes 17 and 26) with this extension. As a result, 23 nodes are jammed, and the performance increase even more.

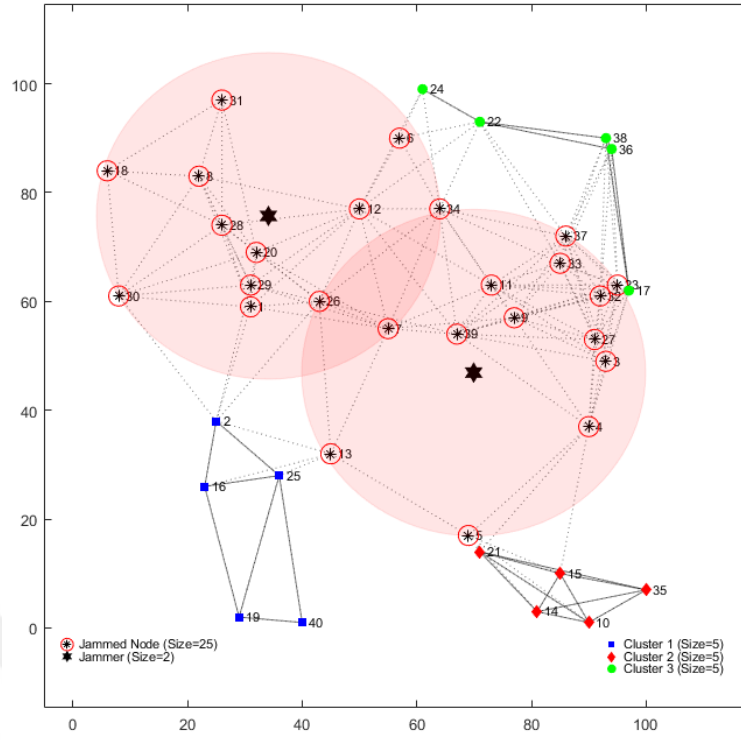


Figure 4.5: Illustrative result of Continuous Location Model for $n_r=40$, $n_j=2$, $n_c=3$, $d_o=30$, $d_j=30$

The results obtained by running the Continuous Location Model under exactly the same conditions are visualized in Figure 4.5. Two more nodes are jammed since the most significant restriction on the location of the jammers is removed. As a result, while the Base Model can jam only 15 nodes, this number has been increased to 25 with different approaches and improvements. A summary is provided in Table 4.1. In the table, Base Model, Base Model Plus, MinMax Model, Hierarchical Extension of MinMax Model, and Continuous Location Model are abbreviated as BM, BM+, MM, MME, and CLE, respectively.

Table 4.1: Summary results of the models, starting from BM

	BM	BM+	MM	MME	CLE
Total # of Nodes	40	40	40	40	40
# of Jammed Nodes	15	18	21	23	25
Node Success Rate	38%	45%	53%	58%	63%
Total # of Direct Links	160	160	160	160	160
# of Cut Direct Links	107	120	127	133	137
Link Success Rate	67%	75%	79%	83%	86%
Total # of Indirect Links	620	620	620	620	620
# of Cut Indirect Links	564	584	611	617	613
Com. Success Rate	91%	94%	98%	99%	99%

Remark.

Direct Link : The communication link between two radios with a distance less than or equal to d_o .

Indirect Link : The communication link between two radios with a distance greater than d_o but able to communicate via other radio(s).

Node Success Rate : # of Jammed Nodes / Total # of Nodes

Link Success Rate : # of Cut Direct Links / Total # of Direct Links

Com. Success Rate : # of Cut Indirect Links / Total # of Indirect Links

In addition to the improvements so far, removing the cluster number restriction also improves performance. Constraint (3.4) assigns at least one node to each cluster to reach the desired number of clusters. When this constraint is removed, the model determines the number of clusters. In this way, the n_c parameter equals the maximum number of clusters the network can be divided. Figure 4.6 shows the results of the Continuous Location Model with (on the left) and without (on the right) constraint (3.4) under the same conditions.

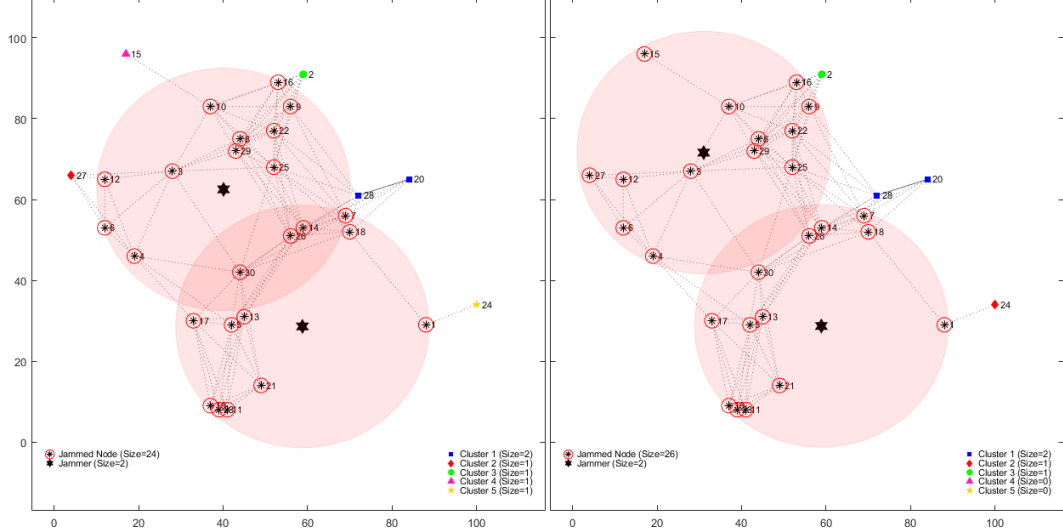


Figure 4.6: Illustrative comparison of the results for Continuous Location Model with and without constraint (3.4)

The parameter of n_c is set to 5, and the network is divided into 5 clusters in the left representation. Despite the same value of n_c , the network is divided into 3 clusters in the right representation since two clusters do not have any node. On the other hand, nodes 15 and 27 are jammed, and the number of jammed nodes increases by 2. The reason for this difference is that the models do not jam some nodes to reach the desired number of clusters, although they can jam more nodes. Since the number of clusters changes with this improvement, it is not fair to include it in the comparison. Therefore, it is not considered as a separate model. When comparing models, dividing a network into the same number of clusters is essential.

4.1.2 Improvements Starting from Base Continuous Location Model

In Section 4.1.1, the differences between approaches on the discretized plane and the effect of performing on the discretized and real plane were shown with illustrative examples. In this section, we compare the base and minmax approaches on the real plane. We examine the effect of the two approaches on the results by starting from the Base Continuous Location Model and considering the number of jammers obtained from this model. So, this section includes examples for the Base Continuous Location Model, Base Continuous Location Model Plus, and Continuous Location Model.

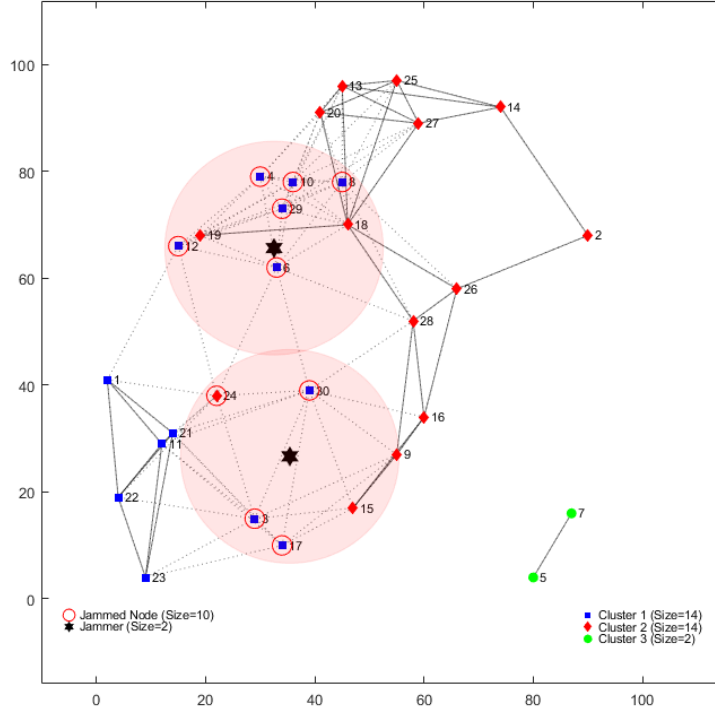


Figure 4.7: Illustrative result of Base Continuous Location Model for $n_r=30$, $n_c=3$, $m_j=5$, $d_o=30$, $d_j=20$

Figure 4.7 shows the result obtained by running the Base Continuous Location Model in an area of 100 km^2 for $n_r = 30$, $n_c = 3$, $m_j = 5$, $d_o = 30$ and $d_j = 20$. Unlike the Base Model, the parameter of m_j , which specifies the maximum number of jammers that can be used, is also given as input. Although this parameter is set as 5, the model determines 3 jammers as dummies and places 2 real jammers, as seen in Figure 4.7. These jammers are no longer positioned at node locations since they can be anywhere on the real plane. As a result, 10 nodes are jammed according to the model. However, although nodes 9, 15, 18, and 19 are in the jamming domain, they are not jammed. After this drawback in Base Continuous Location Model is fixed, the results obtained with the new model, called Base Continuous Location Model Plus, are shown in Figure 4.8.

As can be seen, all nodes in the jamming domain are assigned as jammed in the results of the new model. The number of jammed nodes has been increased to 14, and a circle has been added around nodes 9, 15, 18, and 19.

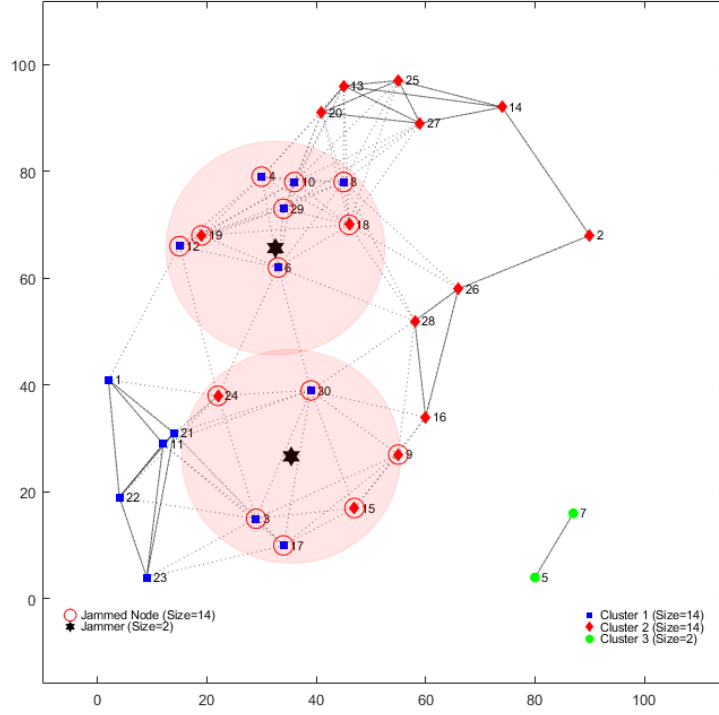


Figure 4.8: Illustrative result of Base Continuous Location Model Plus for $n_r=30$, $n_c=3$, $m_j=5$, $d_o=30$, $d_j=20$

As a result of both models, the network is divided into 3 clusters as desired despite the drawback of constraint (3.2). Since all clusters have at least one node that is not jammed, the number of base and unjammed clusters are the same. However, the difference between the number of nodes in the clusters is remarkable. Cluster 1 has 14 nodes, while cluster 3 has 2 nodes. As in the results of the Base Model, the number of nodes in the clusters was distributed imbalanced. The results obtained from the Continuous Location Model under the same conditions are shown in Figure 4.9.

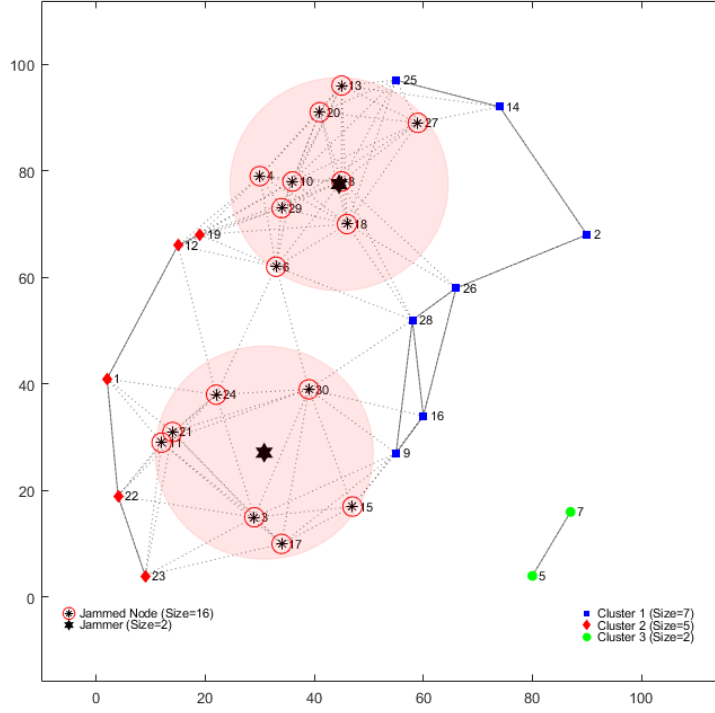


Figure 4.9: Illustrative result of Continuous Location Model for $n_r=30$, $n_j=2$, $n_c=3$, $d_o=30$, $d_j=20$

The number of jammed nodes increased by 2 to 16 because of the change in the locations of the jammers. This is a significant increase when the total number of nodes ($n_r = 30$) is considered. The representation of the jammed node is different because of the constraint (3.12), which is not included in the Base Continuous Location Model and Base Continuous Location Model Plus but is included in the Continuous Location Model. As mentioned before, jammed nodes are not assigned to unjammed clusters thanks to this constraint. The numbers of nodes in the clusters are closer to each other due to the hierarchical MinMax approach in this model. In this way, better performance is obtained in the real plane compared to the base approach under the same conditions. A summary is provided in Table 4.2. In the table, Base Continuous Location Model, Base Continuous Location Model Plus, and Continuous Location Model are abbreviated as BCM, BCM+, and CLE respectively.

Table 4.2: Summary results of the models, starting from BCM

	BCM	BCM+	CLE
Total # of Nodes	30	30	30
# of Jammed Nodes	10	14	16
Node Success Rate	33%	47%	53%
Total # of Direct Links	106	106	106
# of Cut Direct Links	71	82	93
Link Success Rate	67%	77%	88%
Total # of Indirect Links	273	273	273
# of Cut Indirect Links	219	250	254
Com. Success Rate	80%	92%	94%

4.1.3 Improvements by Antenna Type and Angle

Examples shown in Sections 4.1.1 and 4.1.2 included jammers with omnidirectional antenna. As a reminder, this type of jammer jams a 360° area by transmitting signals equally in all directions. However, using jammers with omnidirectional antenna may not always be a good option. Sometimes, jammers with directional antenna may be more appropriate since they offer more sensitive jamming than jammers with omnidirectional antenna. Depending on the location of targets, jammers with directional antennas can give different results even if they do not provide 360° coverage since they have a long jamming distance. The jamming distance of the jammers with directional antenna varies according to the jamming angle of the antenna. The jamming angle and distance are inversely proportional, and the distance decreases as the angle increases. Since directional antennas with the angle of 45° , 60° , and 90° are used in real life, results are obtained based on these three angles in this section. According to the field trials, the average effects of the angles on the jamming distance at the same power and frequency bands are shown in Table 4.3. In this study, the results are obtained by considering these ratios.

Table 4.3: Jamming distance ratios according to antenna types and angles

Antenna Type	Jamming Angle	Jamming Distance
Omnidirectional	360°	x
Directional	90°	2x
Directional	60°	2.45x
Directional	45°	2.83x

In this section, illustrative examples will be shown in three cases according to the number of jammers used. First, the effects of omnidirectional and directional antennas will be compared using only one jammer. Examples and summary results will be given according to different antenna types and jamming angles. Second, all combinations in the case of using two jammers will be considered. In addition to using homogenous jammers, examples where jammers with omnidirectional and directional antennas are used simultaneously will be included. Illustrative examples will be examined, and summary results will be shared. Finally, a few illustrative examples will be shown by using three jammers.

Case 1 (One Jammer):

All examples shown in this case are obtained by running the final model, Directional Antenna Addition Model in Section 3.2.6, at the same node coordinates for $n_r = 30$, $n_c = 2$ and $d_o = 30$ in an area of 100 km². The jamming distance (d_j) of the jammer with omnidirectional antenna is determined as 20 km. Consequently, the jamming distances (d_j) of the jammers with directional antenna are calculated as 40 km, 49 km, and 56 km for the jamming angles (θ) of 90°, 60°, and 45°, respectively, according to Table 4.3.

Figure 4.10 is obtained by using one jammer with omnidirectional antenna. In the figure, the network is divided into two separate clusters by jamming 8 nodes in total. The jammer jams the nodes in the middle of the field, which have more communication links, in order to divide the network into the desired number of subnetworks. The cluster with the most nodes, namely cluster 1, has 13 nodes.

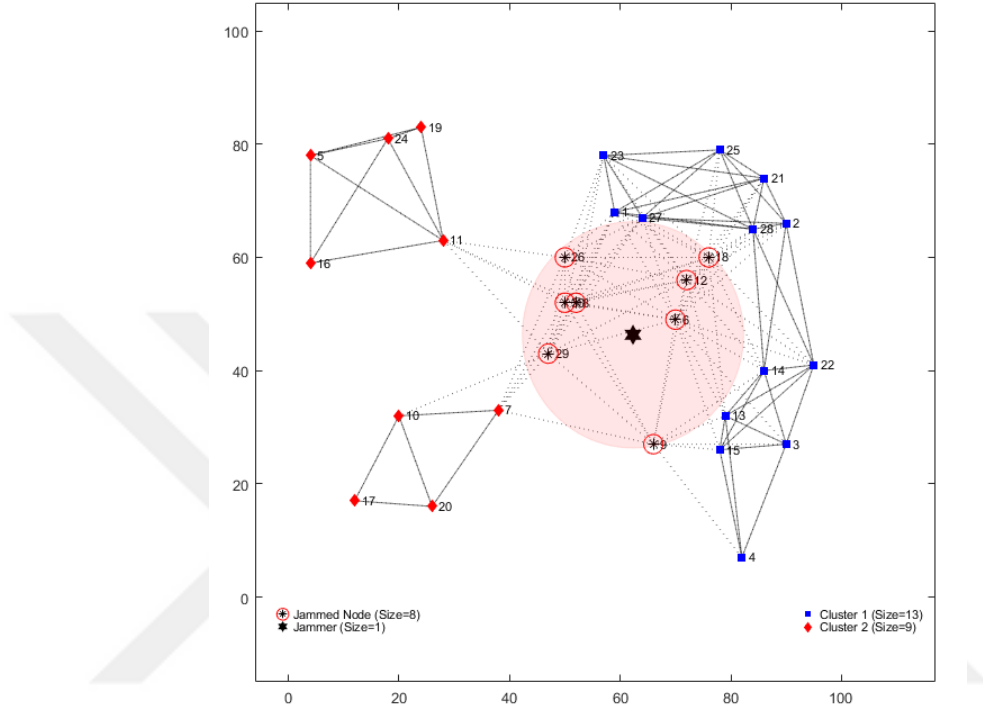


Figure 4.10: Illustrative result of DAAM for $n_r=30$, $n_c=2$, $d_o=30$, $n_j=1$, $d_j=20$

Figure 4.11 is obtained by using one jammer with 90° directional antenna. The set of jammed nodes in this figure is very similar to that in Figure 4.10. However, due to the advantage of the 90° area pattern, nodes 13 and 15 are additionally jammed. As a result, a total of 10 nodes are jammed, and the network is divided into two separate clusters. The number of nodes in cluster 1 decreases by 2 to become 11.

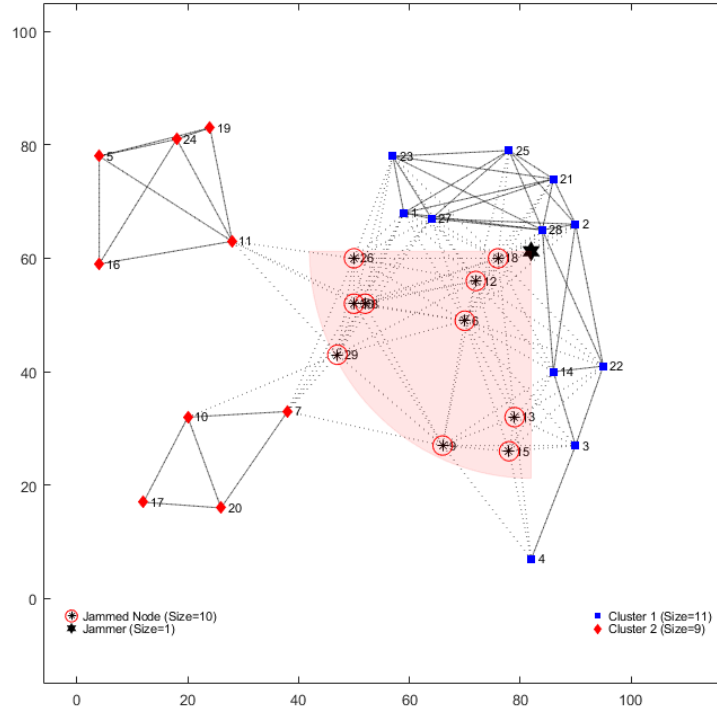


Figure 4.11: Illustrative result of DAAM for $n_r=30$, $n_c=2$, $d_o=30$, $n_j=1$, $\theta=90^\circ$, $d_j=40$

Figure 4.12 is obtained by using one jammer with 60° directional antenna. A different and more successful result is obtained compared to the result obtained with the jammer with an omnidirectional antenna. Node 29 is now out of the jamming area, and nodes 1, 2, 27, and 28 are jammed instead of this node. As a result of this difference, cluster structures change. In Figure 4.10, the set of nodes on the right side of the graph forms cluster 1, while in Figure 4.12, the set of nodes on the left side of the graph forms cluster 1. As a result, a total of 11 nodes are jammed, and the network is divided into two separate clusters. In addition, the number of nodes in the clusters is now very close to each other since the size of cluster 1 decreases by 3 to 10.

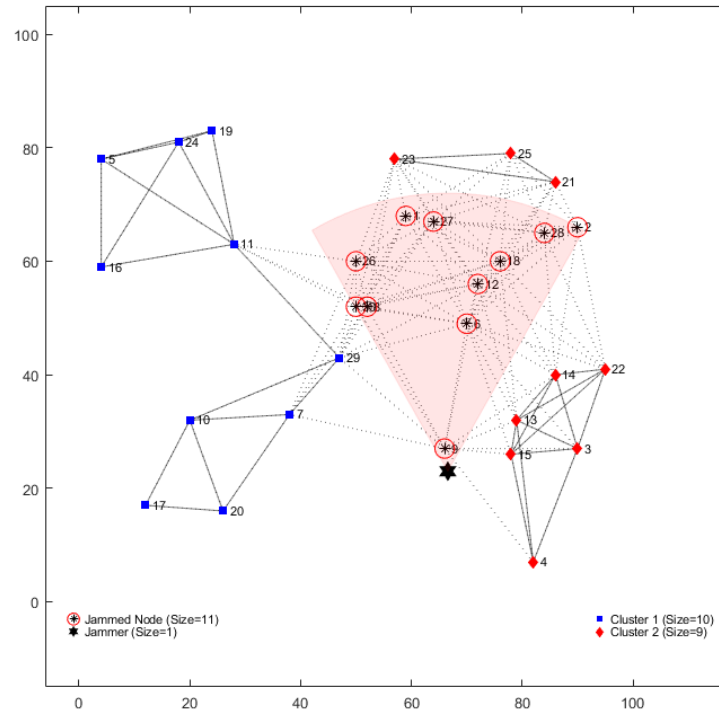


Figure 4.12: Illustrative result of DAAM for $n_r=30$, $n_c=2$, $d_o=30$, $n_j=1$, $\theta=60^\circ$, $d_j=49$

Figure 4.13 is obtained by using one jammer with 45° directional antenna. Compared to Figure 4.10, nodes 2 and 28 are jammed instead of node 9 in this figure. This causes the formation of a different cluster structure. In Figure 4.10, the network is divided into two separate subnetworks as right and left, while it is divided as up and down in Figure 4.13. As a result, the number of nodes in the clusters is very close to each other, and cluster 1 has 11 nodes. By jamming a total of 9 nodes, the success rate increases compared to the omnidirectional antenna, as in other directional antennas.

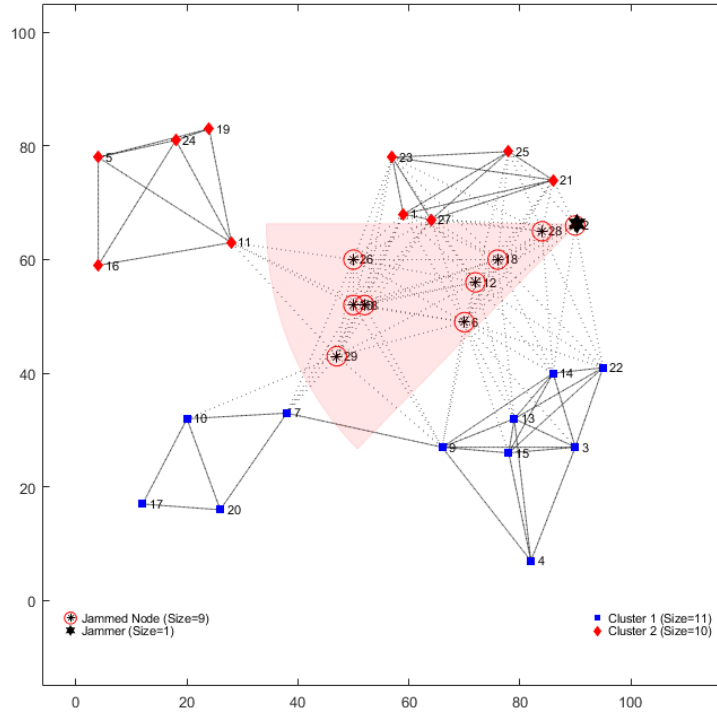


Figure 4.13: Illustrative result of DAAM for $n_r=30$, $n_c=2$, $d_o=30$, $n_j=1$, $\theta=45^\circ$, $d_j=56$

As the illustrative examples show, using the directional antenna for one jammer can affect the results by changing the cluster structures. The summary of the results in the figures is provided in Table 4.4.

Table 4.4: Summary results of DAAM for one jammer

	Omnidir. Antenna	Directional Antenna		
		90°	60°	45°
Total # of Nodes	30	30	30	30
# of Jammed Nodes	8	10	11	9
Node Success Rate	27%	33%	37%	30%
Total # of Direct Links	131	131	131	131
# of Cut Direct Links	81	90	98	88
Link Success Rate	62%	69%	75%	67%
Total # of Indirect Links	304	304	304	304
# of Cut Indirect Links	260	274	274	272
Com. Success Rate	86%	90%	90%	89%

Case 2 (Two Jammers):

All examples shown in this case are obtained by running the final model, Directional Antenna Addition Model in Section 3.2.6, at the same node coordinates for $n_r = 30$, $n_c = 3$ and $d_o = 30$ in an area of 100 km^2 . Same as in Case 1, the jamming distance (d_j) of the jammer with omnidirectional antenna is determined as 20 km. In the same way, the jamming distances (d_j) of the jammers with directional antenna are calculated as 40 km, 49 km, and 56 km for the jamming angles (θ) of 90° , 60° , and 45° , respectively according to Table 4.3.

Figure 4.14 is obtained by using two jammers with omnidirectional antenna. The network is divided into three clusters as desired, and a total of 14 nodes are jammed. In addition, nodes 16 and 21 become disconnected, meaning they cannot communicate with any node even though they are not jammed. Cluster 1, the cluster with the highest number of nodes, has 6 nodes. The other two clusters have 5 nodes.

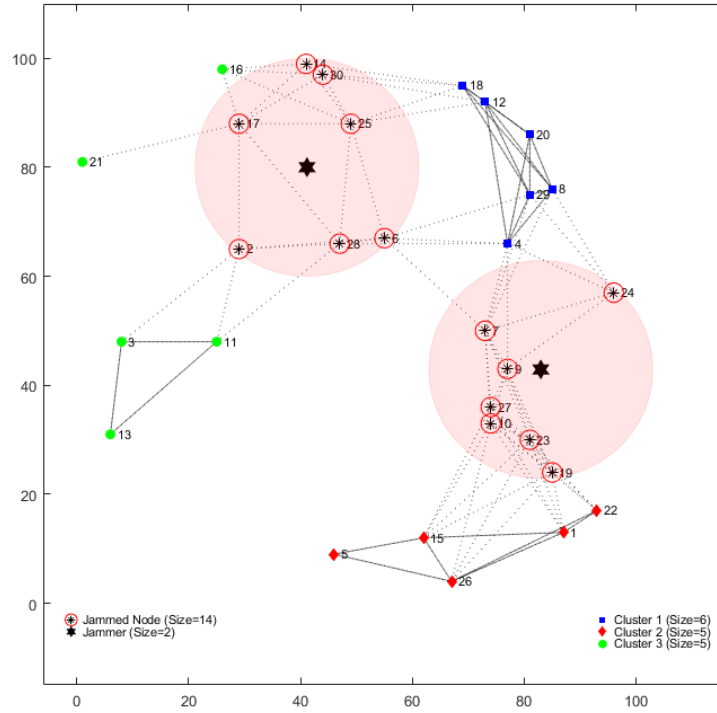


Figure 4.14: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=2$, $d_j=20$

Figure 4.15 is obtained by using one jammer with omnidirectional antenna and one with 90° directional antenna. The cluster structures and the set of jammed nodes in this figure are very similar to Figure 4.14. There is a slight change in the position of the jammer on the right. Node 4 is jammed instead of node 19 with this change. On the left, the set of nodes jammed by the jammer with omnidirectional antenna is jammed this time by the jammer with directional antenna. However, node 16 is also jammed due to the advantage of the 90° area pattern. Therefore, the total number of jammed nodes is 15.

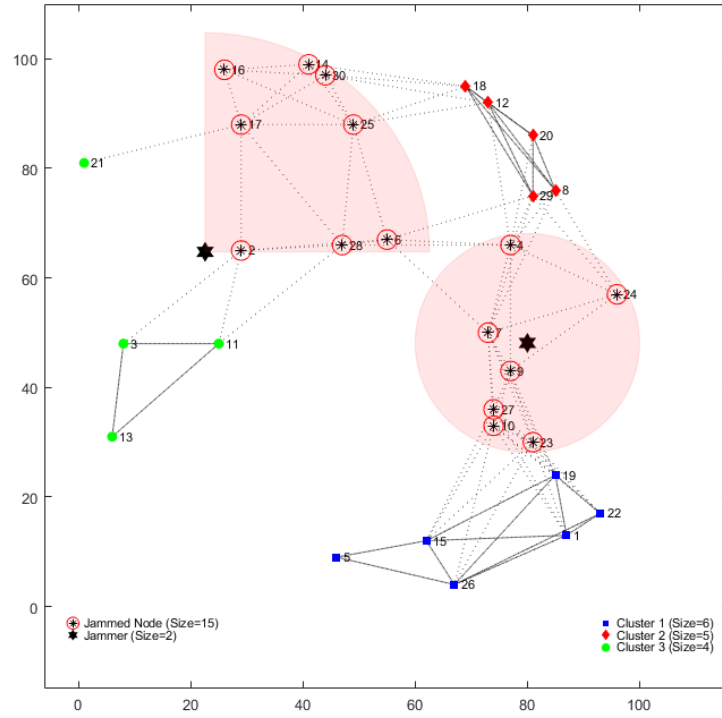


Figure 4.15: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=1$, $d_j=20$, $n_{\bar{j}}=1$, $\theta=90^\circ$, $d_{\bar{j}}=40$

Figure 4.16 is obtained by using one jammer with omnidirectional antenna and one with 60° directional antenna. The position of the jammer with the omnidirectional antenna on the right in Figure 4.14 changes slightly. Nodes 1 and 22 are now jammed instead of node 24 due to this change. Instead of the jammer with the omnidirectional antenna on the left, the jammer with the directional antenna is now used, and nodes 18 and 12 are jammed instead of node 2. Compared to circular jamming, the 60° area pattern increases the number of jammed nodes by jamming nodes 12 and 17 at the border. Thus, the total number of jammed nodes becomes 16 without any change related to disconnected nodes. Additionally, the number of nodes in cluster 1 and cluster 3 decreases by 1.

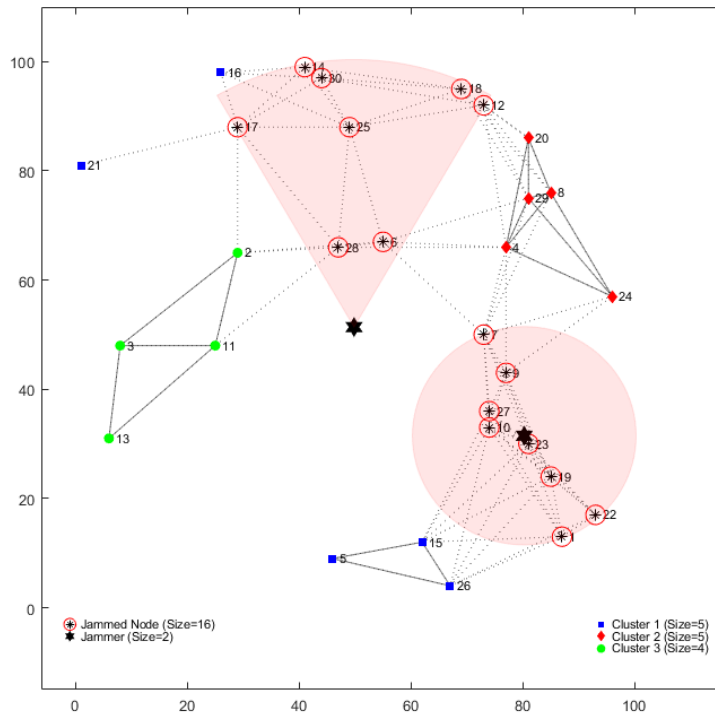


Figure 4.16: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=1$, $d_j=20$, $n_{\bar{j}}=1$, $\theta=60^\circ$, $d_{\bar{j}}=49$

Figure 4.17 is obtained by using one jammer with omnidirectional antenna and one with 45° directional antenna. Contrary to previous results obtained with 60° and 90° , the jammer with omnidirectional antenna is used on the left side, and the jammer with directional antenna is used on the right. Due to the long jamming distance caused by the low jamming angle, node 6 is jammed by the jammer with directional antenna. For this reason, the jammer with omnidirectional antenna on the left jams node 16 with a slight change in its position. Also, the linear positioning of nodes 6, 7, 9, 10, 19, 23, and 27 is advantageous for the directional antenna. Thus, the jammer with directional antenna jams 10 nodes simultaneously. As a result, a successful result is obtained as the number of jammed nodes is 17 and disconnected nodes is 2. In addition, the number of nodes in each cluster decreases by 1 compared to the result in Figure 4.14.

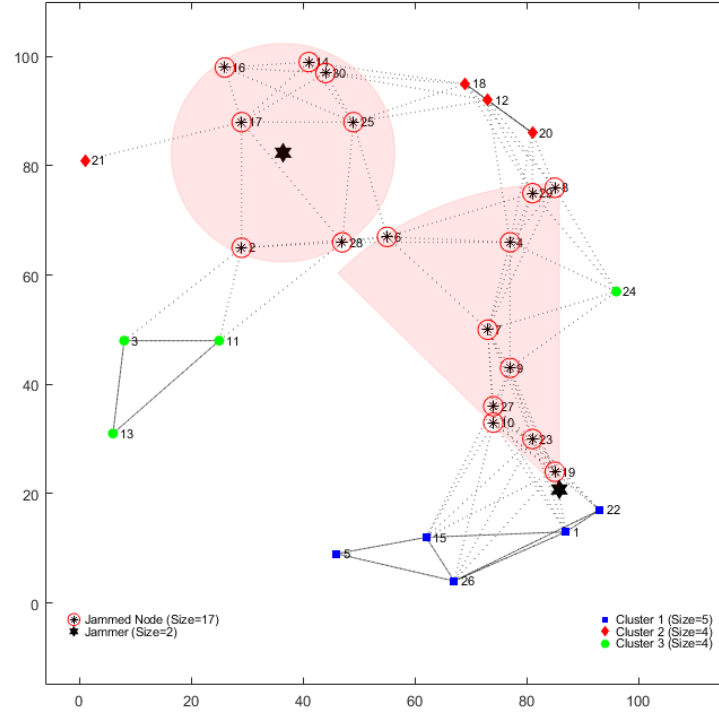


Figure 4.17: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=1$, $d_j=20$, $n_{\bar{j}}=1$, $\theta=45^\circ$, $d_{\bar{j}}=56$

Figure 4.18 is obtained by using two jammers with 90° directional antenna. The resulting cluster structures and the set of jammed nodes are very similar to Figure 4.14. The nodes jammed by the jammer with omnidirectional antenna on the right in Figure 4.14 are also jammed by the jammer with the directional antenna in this figure. The only difference is that node 16 is included in the set of jammed nodes on the left due to the advantage of the angle pattern. The total number of jammed nodes is 16, and the results are the same as in Figure 4.15.

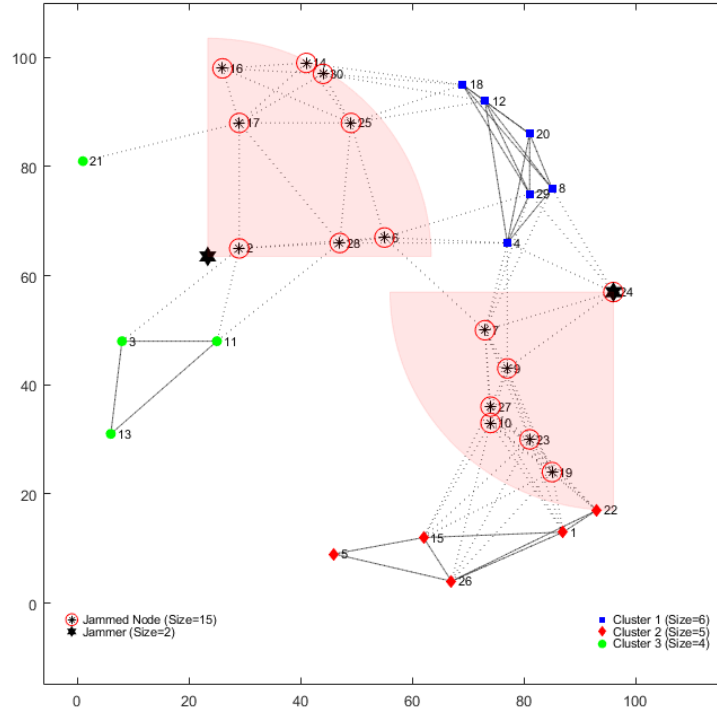


Figure 4.18: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=2$, $\theta=90^\circ$, $d_j=40$

Figure 4.19 is obtained by using two jammers with 60° directional antenna. The most successful result among the two jammer alternatives is achieved with this combination. The jammer with the directional antenna on the right almost jams a cluster. While 7 nodes are jammed with the jammer with omnidirectional antenna in Figure 4.14, 10 nodes are jammed here. Moreover, node 5 becomes disconnected. In addition, compared to the jammer with the omnidirectional antenna on the left in Figure 4.14, the jammer with the directional antenna here jams an extra node. The disconnected state of nodes 16 and 21 is also preserved. As a result, 18 nodes are jammed, and 3 nodes are disconnected with two 60° directional antenna jammers. Considering that any node in cluster 3 lacks communication, an additional cluster is jammed here compared to other results.

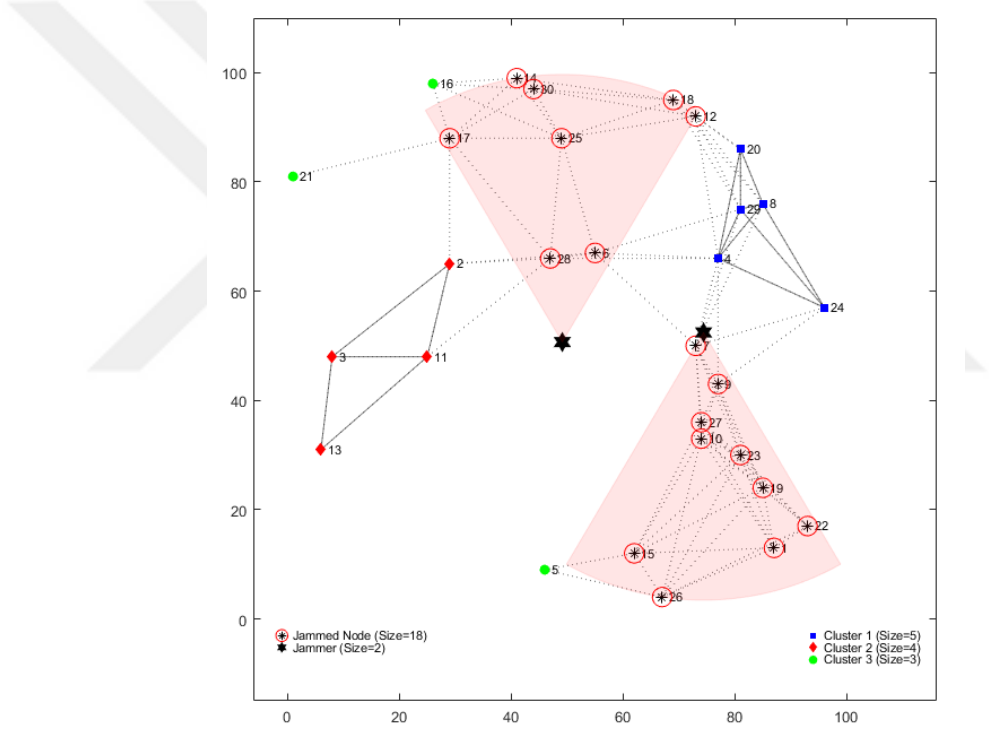


Figure 4.19: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=2$, $\theta=60^\circ$, $d_j=49$

Figure 4.20 is obtained by using two jammers with 45° directional antenna. Nodes 16 and 21 are involved in the communication network for the first time. A completely different set of jammed nodes and cluster structure emerges compared to Figure 4.14 and other previous results. A total of 17 nodes are jammed, and 1 node is disconnected with this combination. The cluster sizes, which are 6, 5, 5 in Figure 4.14, are 5, 4, 4 here. Again, different and more successful results are obtained compared to the jammers with omnidirectional antenna.

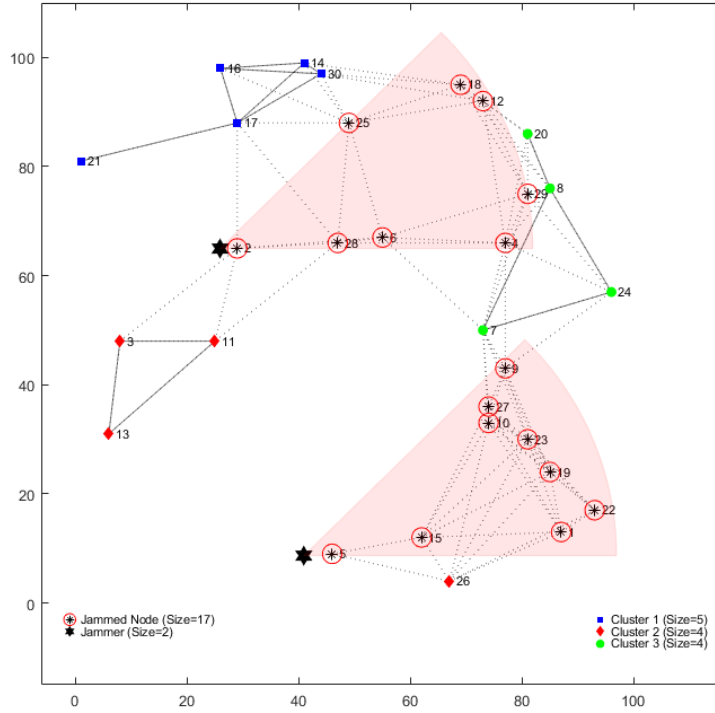


Figure 4.20: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=2$, $\theta=45^\circ$, $d_j=56$

As in Case 1, using the directional antenna can affect the results by changing the cluster structures in this case as well. Table 4.5 provides a summary of this case. In the table, omnidirectional antenna and directional antenna are abbreviated as OA and DA, respectively.

Table 4.5: Summary results of DAAM for two jammers

	2 OA	1 OA & 1 DA			2 DA		
	-	90°	60°	45°	90°	60°	45°
Total # of Nodes	30	30	30	30	30	30	30
# of Jammed Nodes	14	15	16	17	15	18	17
Node Success Rate	47%	50%	53%	57%	50%	60%	57%
Total # of Direct Links	93	93	93	93	93	93	93
# of Cut Direct Links	69	69	76	80	69	79	82
Link Success Rate	74%	74%	82%	86%	74%	85%	88%
Total # of Indirect Links	342	342	342	342	342	342	342
# of Cut Indirect Links	338	338	340	339	338	340	339
Com. Success Rate	99%	99%	99%	99%	99%	99%	99%

Case 3 (Three Jammers):

Illustrative examples are shown for all alternatives in the case of using one and two jammers under the same conditions in the previous two cases. The effects of the omnidirectional and directional antenna at three different angles on the results were examined, and summary tables were presented. However, showing all alternatives is difficult since there are many combinations when using three jammers. For this reason, two illustrative examples will be included in this case. Firstly, the combination of two jammers with omnidirectional antenna and one jammer with 60° directional antenna; secondly, the combination of one jammer with omnidirectional antenna and two jammers with 60° directional antenna will be shown. Both examples are obtained by running the final model, Directional Antenna Addition Model in Section 3.2.6, at the same node coordinates for $n_r = 40$, $n_c = 2$ and $d_o = 30$ in an area of 100 km². As in other cases, the jamming distance (d_j) of the jammer with omnidirectional antenna is determined as 20 km. The jamming distance (d_j) of the jammer with 60° (θ) directional antenna is calculated as 49 km according to Table 4.3.

Figure 4.21 is obtained by using two jammers with omnidirectional antenna and one jammer with 60° directional antenna. The network is divided into two clusters as desired. A total of 26 nodes are jammed, and 1 node is disconnected. Cluster sizes are determined as 7.

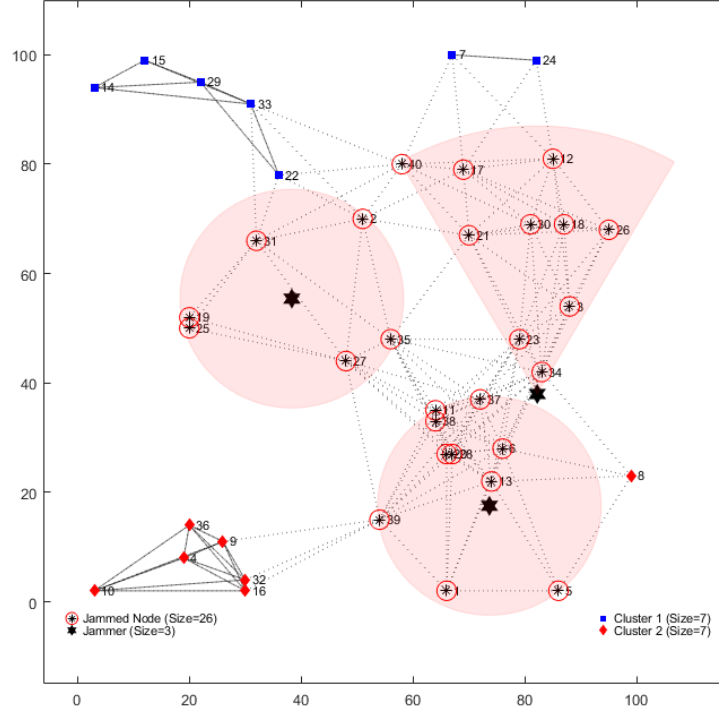


Figure 4.21: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=2$, $d_j=20$, $n_{\bar{j}}=1$, $\theta=60^\circ$, $d_{\bar{j}}=49$

Figure 4.22 is obtained by using one jammer with omnidirectional antenna and two jammers with 60° directional antenna. The placement and cluster structures obtained with this combination differ from those in Figure 4.21. All nodes in cluster 1 in Figure 4.21 are jammed here. On the other hand, some nodes jammed in Figure 4.21 can communicate in this figure. As a result, the whole structure is different except for the cluster represented by the diamond shape on the lower left, and the total number of jammed nodes increases by 1 to 27. Cluster sizes are determined as 7 and 6.

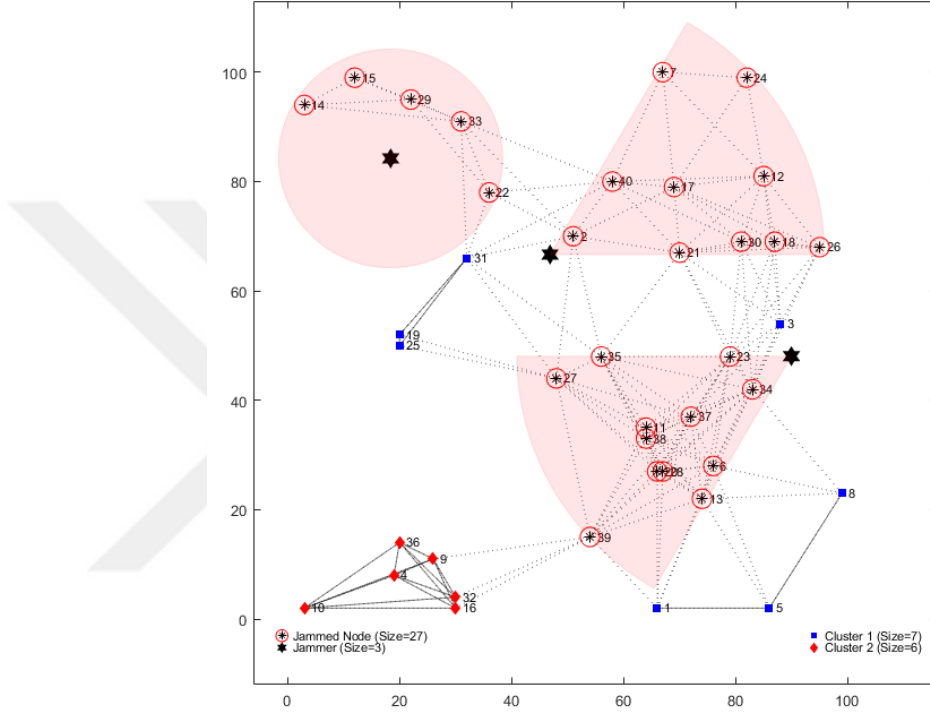


Figure 4.22: Illustrative result of DAAM for $n_r=30$, $n_c=3$, $d_o=30$, $n_j=1$, $d_j=20$, $n_{\bar{j}}=2$, $\theta=60^\circ$, $d_{\bar{j}}=49$

Even if not all alternatives for three jammers have been evaluated, the results vary with the two alternatives. The variety in the results is predicted to increase with the increase of alternatives. A summary is provided in Table 4.6. In the table, omnidirectional antenna and directional antenna are abbreviated as OA and DA, respectively.

Table 4.6: Summary results of DAAM for three jammers

	2 OA	1 OA
	1 DA	2 DA
Total # of Nodes	40	40
# of Jammed Nodes	26	27
Node Success Rate	65%	68%
Total # of Direct Links	159	159
# of Cut Direct Links	135	139
Link Success Rate	85%	88%
Total # of Indirect Links	621	621
# of Cut Indirect Links	619	620
Com. Success Rate	99%	99%

4.2 Experimental Result

In this section, we compare the final model within itself and other models with each other, using different parameter values and performance criteria. We also examine the effects of parameters on the developed models. Comparisons of the models with each other are made in the first subsection, BM, BM+, MM, MME, CLE together and BCM, BCM+,CLE together (Comparative Results of the Developed Models). Due to the directional antenna addition, the final model, DAAM, is compared within itself in the second subsection (Comparative Results of the Final Model). In the last subsection, the effects of the parameters on MM, MME, and CLE are examined (Effects of the Parameters).

In this section, several tables are used for comparisons. Detailed explanations and finding methods of the expressions in these tables, such as direct links, indirect links, cut direct links, cut indirect links, and success rates, are mentioned in Section 3.1. As a reminder, three different performance criteria have been determined for comparison and evaluation. Node Success Rate is the ratio of jammed nodes to the total number of nodes, Link Success Rate is the ratio of the number of cut direct links to the total

number of direct links, and Communication Success Rate is the ratio of the number of cut indirect links to the total number of indirect links. Abbreviations for model names are used many times in this section. These abbreviations are as follows:

BM: Base Model

BM+: Base Model Plus

MM: MinMax Model

MME: Hierarchical Extension of MinMax Model

CLE: Continuous Location Model

BCM: Base Continuous Location Model

BCM+: Base Continuous Location Model Plus

DAAM: Directional Antenna Addition Model

4.2.1 Comparative Results of the Developed Models

In this section, we compare models based on the work of Feng et al. [1] and developed models except the final model. As mentioned in Section 4.1, since the numbers of jammers is taken as an output from the Base Model and the Base Continuous Model may not be the same, two comparisons are presented again. The first comparison includes the Base Model, Base Model Plus, MinMax Model, Hierarchical Extension of MinMax Model to evaluate differences in the discretized plane, and Continuous Location Model to evaluate differences in the transition from discretized plane to the real plane. The second comparison includes Base Continuous Location Model, Base Continuous Location Model Plus, and Continuous Location Model to evaluate the differences in the real plane. We use different parameter values and performance criteria for these comparisons.

The comparison tables are created by keeping the field size, communication distance, and jamming distance constant and using the same number of jammers. However, each table has results for the different numbers of radios (20, 30, 40, 50) and base clusters (3, 4, 5). The number of unjammed clusters is also included in the tables to make a proper comparison since the number of clusters in the Base Models is inconsistent. As a reminder, BM, BM+, BCM, and BCM+ cannot divide the network into the desired number of clusters in some cases due to the drawback of constraint (3.2).

This drawback has been corrected with constraint (3.12) in developed models. Therefore, the number of the unjammed clusters should be considered for comparisons. In the tables, each value is the average of 30 results obtained by running the models after randomly changing the coordinates of the nodes. So, each model has been run a total of 720 times.

Table 4.7 shows the results for BM, BM+, MM, MME, and CLE in the field of 200 km² with the communication distance of 30 km and the jamming distance of 40 km. When Table 4.7 is examined in detail, it is seen that the performance results increase with each developed model. In particular, the difference in results between BM+ and MM is remarkable. For each parameter combination, approximately 10%, 15%, and 20% gain are obtained for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively. This difference is even greater when MME and CLE are compared with BM+. The developed models (MM, MME, and CLE) give better results for each performance criteria than the based models (BM and BM+). When the last model CLE and the first model BM are compared, the following average gains are obtained in Node Success Rate, Link Success Rate, and Communication Success Rate, respectively: For 20 radio, >20%, >34%, >32%. For 30 radio, >23%, >34%, >38%. For 40 radio, >20%, >27%, >33%. For 50 radio, >15%, >23%, >25%.

Table 4.8 shows the results for BM, BM+, MM, MME, and CLE in the field of 100 km² with the communication distance of 30 km and the jamming distance of 20 km. Again, the performance results increase with each developed model. This time, the difference in results between MME and CLE particularly draws attention. In this combination of the parameter, positioning the jammers on the real plane affects the performance considerably. CLE outperforms MME by approximately >10% for Node Success Rate, >8% for Link Success Rate, and >5% for Communication Success Rate in almost every result. As in Table 4.7, the developed models (MM, MME, and CLE) give better results than the base models (BM and BM+) for each performance criteria. When the last model CLE and the first model BM are compared, the following average gains are obtained in Node Success Rate, Link Success Rate, and Communication Success Rate, respectively: For 20 radio, >17%, >21%, >12%. For 30 radio, >18%, >20%, >10%. For 40 radio, >17%, >18%, >9%. For 50 radio, >16%, >18%, >9%.

Table 4.7: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 30 km, and the jamming distance is 40 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	54.5	61.2	63.8	64.0	67.0	35.2	45.0	48.6	48.6	51.8	67.5	70.9	70.9	67.8	68.4
		3	32.7	34.0	59.2	59.3	64.7	4.6	6.9	52.0	51.5	59.4	5.8	5.8	65.6	66.4	69.8
	4	3	47.8	56.0	58.3	59.2	63.2	39.3	50.0	53.3	54.6	58.9	73.8	80.3	87.6	90.9	88.1
		4	35.0	37.3	59.0	58.7	64.2	7.0	9.9	51.7	51.1	58.6	12.6	14.3	70.7	68.8	77.1
	5	4	45.7	52.0	58.3	58.2	65.0	33.8	39.8	54.1	53.6	61.6	58.3	58.4	74.6	73.8	83.4
		5	44.0	50.0	58.2	58.8	64.2	22.5	28.9	47.1	48.8	57.4	45.7	50.6	64.9	64.2	69.9
	Average		43.3	48.4	59.5	59.7	64.7	23.8	30.1	51.1	51.4	58.0	43.9	46.7	72.4	72.0	76.1
# of Radios = 30	3	2	19.0	26.1	43.6	43.3	47.0	11.6	22.6	52.0	52.0	54.5	26.5	38.0	65.1	64.9	68.1
		3	18.8	20.8	40.6	41.2	47.3	2.6	5.5	38.6	41.1	47.2	8.8	10.9	52.9	58.8	64.4
	4	3	23.3	31.9	40.3	41.0	44.8	20.8	29.0	42.1	42.8	48.0	47.7	53.4	70.5	68.4	74.0
		4	22.2	25.9	41.3	41.3	46.2	8.8	13.8	40.6	40.5	46.4	25.1	28.0	58.0	53.2	66.2
	5	4	27.0	35.7	38.2	39.1	43.9	20.3	29.1	35.8	35.8	42.3	54.6	60.2	67.8	68.0	72.0
		5	25.8	30.9	41.6	42.6	47.8	14.2	20.1	41.2	42.2	47.3	31.6	37.5	66.4	68.4	70.4
	Average		22.7	28.5	40.9	41.4	46.2	13.0	20.0	41.7	42.4	47.6	32.4	38.0	63.4	63.6	69.2
# of Radios = 40	3	2	14.9	19.9	34.8	35.1	38.8	7.7	14.4	41.7	41.9	44.3	26.7	33.9	62.8	62.5	65.0
		3	13.9	18.6	33.6	33.8	39.4	6.3	13.5	37.2	37.4	42.9	18.3	26.6	68.2	67.9	73.1
	4	3	18.7	26.6	31.8	32.2	36.1	18.9	26.4	35.1	35.7	40.2	39.2	46.7	61.5	62.7	63.0
		4	16.3	23.4	33.7	34.6	37.9	13.8	21.9	37.7	39.6	43.0	32.8	41.9	68.2	68.9	72.4
	5	4	24.3	30.8	34.5	35.3	39.6	25.5	32.0	37.1	38.4	43.8	52.1	57.0	65.7	66.1	70.1
		5	19.6	26.7	33.3	33.6	36.3	18.3	27.3	37.7	38.1	41.5	46.1	56.7	68.6	69.6	72.0
	Average		17.9	24.3	33.6	34.1	38.0	15.1	22.6	37.7	38.5	42.6	35.9	43.8	65.8	66.3	69.3
# of Radios = 50	3	2	9.9	16.1	28.3	28.6	32.2	8.9	16.3	37.1	37.2	41.3	30.3	38.5	64.4	64.4	67.2
		3	10.0	15.7	26.9	27.3	31.5	8.7	15.5	36.9	37.0	41.9	32.2	39.7	70.4	71.1	75.0
	4	3	15.4	21.3	26.2	26.8	31.1	16.8	22.3	32.8	33.5	38.5	44.1	48.2	63.7	63.7	69.7
		4	16.0	22.3	26.3	26.1	30.5	19.9	25.9	35.8	35.8	40.9	53.0	57.5	72.3	72.6	77.3
	5	4	18.5	24.7	27.0	27.7	32.1	26.1	31.1	34.3	35.5	40.8	66.2	68.4	73.4	73.9	76.6
		5	17.0	24.6	26.2	26.0	30.3	23.4	31.7	35.9	35.9	39.9	64.0	70.7	71.1	72.6	77.5
	Average		14.5	20.8	26.8	27.1	31.3	17.3	23.8	35.5	35.8	40.6	48.3	53.8	69.2	69.7	73.9

Table 4.8: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 30 km, and the jamming distance is 20 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	18.3	23.0	27.7	27.7	37.3	32.8	37.0	49.5	49.5	58.7	68.2	72.3	83.3	83.3	89.4
		3	23.2	27.5	32.8	34.5	39.8	34.0	39.0	50.4	53.3	58.5	67.6	70.2	81.5	82.5	89.3
	4	3	25.7	30.3	33.2	34.2	42.5	45.9	51.2	55.8	57.1	65.5	82.9	85.3	86.9	87.4	92.1
		4	26.3	31.8	32.0	35.2	40.5	38.6	44.2	47.8	51.9	59.2	78.5	80.8	85.6	86.3	89.3
	5	3	31.0	36.2	38.5	39.7	49.2	54.4	58.7	62.6	63.9	72.6	88.9	90.3	91.2	92.1	95.0
		4	32.7	36.5	40.3	41.8	52.3	55.8	59.9	64.1	66.0	74.3	90.4	91.6	92.7	92.6	95.7
	Average		26.2	30.9	34.1	35.5	43.6	43.6	48.3	55.0	57.0	64.8	79.4	81.8	86.9	87.4	91.8
# of Radios = 30	3	2	19.8	24.3	30.3	30.9	39.4	37.6	42.3	51.7	52.0	61.3	71.0	74.1	81.0	81.3	88.1
		3	21.6	26.2	29.3	30.0	37.6	38.9	44.2	49.0	50.2	60.6	77.6	80.8	85.5	85.4	91.2
	4	2	29.0	32.4	36.1	37.3	51.8	51.3	54.6	59.4	61.0	75.0	82.4	84.6	87.9	88.0	94.6
		3	29.3	34.4	38.0	38.9	49.6	53.6	58.5	63.2	64.4	73.9	88.6	91.0	91.8	92.5	96.7
	5	3	34.3	38.4	41.2	41.9	52.9	59.8	64.0	67.9	68.5	78.2	90.2	92.1	92.8	93.5	97.3
		4	37.1	41.1	43.8	45.1	50.4	58.9	62.0	66.5	68.2	75.5	92.8	94.1	95.2	95.3	97.6
	Average		28.5	32.8	36.5	37.4	46.9	50.0	54.3	59.6	60.7	70.8	83.8	86.1	89.0	89.3	94.2
# of Radios = 40	3	2	23.8	29.2	30.8	31.6	41.5	44.2	50.8	54.6	55.8	65.6	77.7	80.7	83.7	83.8	88.7
		3	25.9	31.2	33.9	34.3	42.7	46.4	51.8	57.3	57.9	68.0	78.2	81.0	86.5	86.6	93.5
	4	2	30.6	34.1	36.6	37.4	47.3	54.9	58.4	62.1	63.3	72.3	83.0	85.2	86.8	86.7	91.9
		3	30.7	33.5	37.0	37.3	45.8	51.8	54.6	60.7	62.1	71.1	87.6	88.9	90.6	91.0	95.8
	5	2	44.3	47.1	52.3	52.7	65.3	69.0	71.6	77.8	78.3	86.5	90.4	91.9	93.8	93.6	97.6
		3	38.1	40.6	43.7	43.3	55.7	63.5	65.7	69.5	70.1	79.9	92.4	93.0	93.9	94.1	97.5
	Average		32.2	35.9	39.0	39.4	49.7	55.0	58.8	63.7	64.6	73.9	84.9	86.8	89.2	89.3	94.2
# of Radios = 50	3	2	26.8	31.2	33.8	34.1	43.1	48.0	53.2	58.6	58.9	69.2	77.9	80.3	83.1	83.1	89.7
		3	28.1	32.1	33.1	33.6	42.3	49.0	52.8	55.7	57.0	67.4	79.1	81.2	85.1	84.9	92.5
	4	2	32.3	35.3	40.5	40.9	50.9	55.6	58.6	67.4	67.7	77.1	83.8	85.5	88.1	88.2	92.8
		3	34.7	38.2	39.7	40.3	49.8	57.9	60.6	63.5	64.9	76.3	88.2	89.5	91.8	92.1	95.7
	5	2	43.5	45.4	48.2	49.1	60.3	69.8	71.4	75.2	76.1	84.2	89.1	89.9	91.8	92.0	96.2
		3	41.8	44.7	46.1	46.4	59.7	66.7	69.1	72.1	72.4	84.8	92.3	93.3	95.3	95.5	98.2
	Average		34.5	37.8	40.2	40.7	51.0	57.8	60.9	65.4	66.2	76.5	85.1	86.6	89.2	89.3	94.2

In Tables 4.7 and 4.8, BM, BM+, MM, MME, and CLE were compared with different parameter combinations for three performance criteria. CLE gave the best results in all comparisons. One of the most important reasons for this is that CLE places the jammers on the real plane while BM and BM+ place them only on the node locations. Now, CLE will be compared with BCM and BCM+, the real plane adaptation of BM and BM+, to test performance on the real plane.

Table 4.9 shows the results for BCM, BCM+, and CLE in the field of 200 km² with the communication distance of 30 km and the jamming distance of 40 km. Table 4.9 shows that CLE gives the best results for all parameter combinations. Especially the difference in Communication Success Rate is remarkable. In almost every result, CLE is approximately >12% better than BCM+. When the last model CLE and the first model BCM are compared, the following average gains are obtained in Node Success Rate, Link Success Rate, and Communication Success Rate, respectively: For 20 radio, >12%, >22%, >21%. For 30 radio, >12%, >17%, >18%. For 40 radio, >12%, >16%, >16%. For 50 radio, >9%, >12%, >14%.

Table 4.10 shows the results for BCM, BCM+, and CLE in the field of 100 km² with the communication distance of 30 km and the jamming distance of 20 km. Again, CLE gives the best results for all parameter combinations. Specifically, CLE is approximately >7% better than BCM+ for almost every result in Link Success Rate. When the last model CLE and the first model BCM are compared, the following average gains are obtained in Node Success Rate, Link Success Rate, and Communication Success Rate, respectively: For 20 radio, >9%, >11%, >6%. For 30 radio, >9%, >11%, >7%. For 40 radio, >11%, >16%, >6%. For 50 radio, >12%, >14%, >6%.

Table 4.9: Comparative results of BCM, BCM+, and CLE when the field size is 200 km², the communication distance is 30 km, and the jamming distance is 40 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	49.3%	54.5%	59.7%	30.4%	36.9%	50.3%	42.8%	51.1%	56.1%
		3	52.3%	60.8%	67.0%	36.6%	49.0%	60.0%	56.8%	65.1%	70.4%
	4	3	51.7%	57.2%	65.7%	36.2%	42.7%	61.6%	53.7%	59.1%	77.5%
		4	48.5%	53.2%	62.7%	32.6%	39.1%	57.2%	46.4%	50.6%	78.7%
	5	4	50.7%	57.0%	60.5%	42.5%	49.4%	57.2%	62.2%	65.1%	82.4%
		5	55.2%	62.2%	69.2%	35.2%	45.4%	61.4%	50.7%	58.3%	74.9%
	Average		51.3%	57.5%	64.1%	35.6%	43.8%	57.9%	52.1%	58.2%	73.3%
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	38.9%	45.8%	50.8%	33.8%	40.8%	50.0%	49.3%	53.7%	64.1%
		3	37.7%	36.6%	45.9%	23.7%	29.6%	45.6%	40.8%	48.2%	64.4%
	4	3	37.7%	44.1%	48.4%	32.9%	39.5%	47.9%	53.0%	59.2%	64.6%
		4	33.1%	39.3%	46.9%	25.9%	32.0%	44.4%	42.3%	47.9%	67.6%
	5	4	33.1%	39.6%	45.7%	30.6%	36.8%	45.0%	50.7%	53.9%	67.6%
		5	34.7%	42.4%	47.8%	29.1%	36.2%	47.1%	49.6%	55.0%	70.0%
	Average		34.7%	41.3%	47.6%	29.3%	35.8%	46.7%	47.6%	53.0%	66.4%
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	25.6%	33.6%	42.4%	23.3%	31.5%	47.6%	51.1%	57.8%	67.7%
		3	23.0%	30.3%	38.6%	21.6%	29.4%	42.5%	40.6%	46.3%	69.3%
	4	3	27.5%	34.6%	39.2%	31.0%	37.1%	42.6%	54.6%	56.9%	70.2%
		4	25.0%	31.4%	38.0%	26.8%	33.1%	42.9%	55.5%	58.9%	70.4%
	5	4	27.8%	33.3%	35.7%	31.8%	36.3%	41.3%	64.8%	66.3%	75.4%
		5	27.8%	33.0%	37.1%	28.5%	34.2%	43.0%	56.3%	60.7%	70.8%
	Average		26.1%	32.7%	38.5%	27.2%	33.6%	43.3%	53.8%	57.8%	70.6%
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	20.1%	24.9%	32.7%	23.5%	27.0%	40.7%	49.4%	52.3%	66.2%
		3	20.2%	26.5%	32.0%	27.0%	31.7%	42.2%	52.7%	54.1%	76.5%
	4	3	21.1%	28.1%	31.6%	28.5%	34.7%	40.2%	60.2%	63.9%	71.8%
		4	21.8%	27.5%	30.5%	29.1%	33.8%	39.3%	59.5%	62.6%	74.4%
	5	4	20.5%	25.8%	29.1%	28.7%	32.7%	38.5%	66.8%	68.7%	74.3%
		5	24.0%	28.5%	30.1%	29.7%	33.5%	38.7%	64.4%	66.4%	75.6%
	Average		21.3%	26.9%	31.0%	27.8%	32.3%	39.9%	58.8%	61.3%	73.1%

Table 4.10: Comparative results of BCM, BCM+, and CLE when the field size is 100 km², the communication distance is 30 km, and the jamming distance is 20 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	30.2%	33.5%	34.7%	46.1%	47.9%	53.9%	73.7%	73.7%	83.3%
		3	27.5%	32.2%	35.5%	44.1%	47.8%	56.2%	73.2%	74.4%	87.9%
	4	3	32.8%	40.0%	41.2%	52.8%	58.4%	63.4%	84.7%	85.2%	89.0%
		4	27.8%	33.5%	36.7%	45.7%	50.1%	58.0%	85.8%	87.9%	92.5%
	5	4	46.0%	53.3%	59.2%	67.4%	72.7%	80.4%	94.3%	95.0%	97.1%
		5	35.5%	43.0%	48.5%	58.0%	64.2%	72.0%	93.1%	94.2%	95.2%
	Average		33.3%	39.3%	42.6%	52.3%	56.9%	64.0%	84.1%	85.1%	90.8%
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	30.3%	34.3%	38.9%	47.1%	50.2%	60.3%	75.7%	78.6%	88.2%
		3	27.0%	33.7%	33.9%	47.5%	52.4%	55.6%	75.8%	76.6%	87.8%
	4	3	38.3%	44.3%	46.6%	59.8%	63.6%	69.5%	89.6%	90.8%	95.5%
		4	31.9%	42.4%	43.8%	56.0%	64.3%	69.2%	89.3%	92.5%	95.0%
	5	4	43.0%	48.6%	50.3%	65.7%	69.3%	75.7%	93.9%	95.1%	97.4%
		5	39.8%	50.7%	51.3%	65.8%	73.6%	77.7%	95.8%	97.0%	98.1%
	Average		35.1%	42.3%	44.1%	57.0%	62.2%	68.0%	86.7%	88.4%	93.7%
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	33.6%	38.7%	44.8%	52.3%	56.3%	68.8%	78.7%	81.2%	90.7%
		3	28.4%	35.3%	38.6%	49.7%	56.2%	63.4%	78.8%	82.7%	89.5%
	4	3	35.3%	39.9%	46.1%	57.4%	61.1%	71.0%	88.2%	89.5%	94.3%
		4	34.7%	42.0%	48.6%	57.9%	65.0%	76.1%	90.4%	92.6%	95.7%
	5	4	43.6%	50.0%	53.3%	68.9%	73.5%	79.0%	95.2%	96.0%	97.3%
		5	42.1%	52.1%	55.2%	66.8%	74.3%	82.7%	96.3%	97.4%	98.3%
	Average		36.3%	43.0%	47.8%	58.8%	64.4%	73.5%	87.9%	89.9%	94.3%
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			BCM	BCM+	CLE	BCM	BCM+	CLE	BCM	BCM+	CLE
	3	2	33.3%	38.6%	42.1%	53.9%	57.5%	67.1%	77.0%	79.3%	89.4%
		3	30.1%	36.9%	43.9%	52.4%	59.4%	71.2%	79.1%	83.2%	91.5%
	4	3	38.1%	45.1%	50.3%	61.8%	66.0%	75.2%	90.3%	92.2%	95.2%
		4	36.5%	43.4%	48.3%	59.1%	64.4%	74.8%	89.9%	91.5%	94.4%
	5	4	45.4%	54.7%	59.9%	70.9%	76.5%	86.2%	94.9%	95.9%	98.4%
		5	45.9%	54.7%	57.5%	72.4%	78.1%	84.6%	95.7%	97.1%	98.8%
	Average		38.2%	45.6%	50.3%	61.8%	67.0%	76.5%	87.8%	89.9%	94.6%

When the Tables 4.7, 4.8, 4.9 and 4.10 are examined together, the differences in success rates between the developed models and the based models are greater at field size is 200 compared to 100. Since the radios are close to each other in a small field, a jammer placed in any way can already jam in a certain number of nodes. However, since the radios are far from each other in a large field, the jamming rate of a jammer decreases. Therefore, a more precise placement is required. That is, the developed models make more precise jammer placement. Another thing that supports this inference is the number of radios. When looking at combinations with fewer radios, the differences in the success rates between the developed models and the based models increase. Because the sparse placement of the radios increases the importance of the position of the jammers, the developed models which make precise jammer placement have a higher success rate.

4.2.2 Comparative Results of the Final Model (DAAM)

In Section 4.2.1, experimental results were obtained and examined for models using homogeneous jammers with omnidirectional antenna. Changes in performance criteria depending on new approaches and improvements for the Base and Base Continuous Location Model were specified. It is shown with illustrative examples in Section 4.1.3 that the directional antennas designed with the Directional Antenna Addition Model in Section 3.2.6 can also change the results. Now, the effects of using jammers with directional antenna on the experimental results are examined by comparing the Directional Antenna Addition Model within itself. In addition, the jamming angles of the directional antenna are also included in the examination. The results are obtained by running the Directional Antenna Addition Model in Section 3.2.6 with different parameters without comparing two or more models.

In the tables used in the comparisons, the field size, the communication distance, and the jamming distance for each angle are kept constant as in the previous tables. However, each table has results for the different numbers of radios (30,40), jammers (1,2), and clusters (2,3). Each value is the average of 30 results obtained by running the Directional Antenna Addition Model after randomly changing the coordinates of the nodes.

Table 4.11 and 4.12 show the results for the Directional Antenna Addition Model in the field of 100 km^2 with the communication distance of 30 km. The jamming distance of the jammer with omnidirectional antenna is determined as 20 km. Consequently, the jamming distances of the jammers with directional antenna are calculated as 40 km, 49 km, and 56 km for the jamming angles of 90° , 60° , and 45° , respectively, according to Table 4.3.

Table 4.11: Comparative results of DAAM according to antenna type and angles when the field size is 100 km^2 , and the communication distance is 30 km

# of Radios = 30	# of Jammers	# of Clusters	Node Success Rate (%)				Link Success Rate (%)				Com. Success Rate (%)			
			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna		
				45°	60°	90°		45°	60°	90°		45°	60°	90°
	1	2	26.2	27.0	27.7	27.4	46.2	47.7	47.2	47.4	75.6	81.5	79.5	77.5
		3	26.1	26.2	27.5	25.5	44.7	48.4	49.7	44.1	82.4	87.0	88.9	84.6
	2	2	53.0	62.1	60.8	58.1	76.9	82.6	81.6	79.7	96.2	97.6	97.5	96.8
		3	50.7	60.0	57.8	54.6	75.1	83.2	81.1	78.7	97.1	98.6	98.4	98.0
	Average		39.0	43.8	43.4	41.4	60.8	65.5	64.9	62.5	87.8	91.2	91.1	89.2
# of Radios = 40	# of Jammers	# of Clusters	Node Success Rate (%)				Link Success Rate (%)				Com. Success Rate (%)			
			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna		
				45°	60°	90°		45°	60°	90°		45°	60°	90°
	1	2	24.8	25.6	25.0	25.6	45.5	46.6	47.3	45.7	63.4	74.3	69.3	67.5
		3	25.0	27.8	28.1	29.7	44.3	52.3	55.4	51.4	74.0	85.7	85.5	74.7
	2	2	47.5	54.0	53.5	52.0	72.5	78.4	77.5	76.3	93.1	95.7	95.1	95.5
		3	47.1	52.2	49.2	51.3	73.5	80.0	75.6	76.7	95.2	97.3	97.0	96.6
	Average		36.1	39.9	39.0	39.7	59.0	64.3	63.9	62.5	81.4	88.2	86.7	83.6

In Table 4.11, using the directional antenna in each combination gives better results than using the omnidirectional antenna. In particular, approximately $>4\%$, $>3\%$, and $>1\%$ better Node Success Rate, Link Success Rate, and Communication Success Rate, respectively, are obtained with directional antenna for two jammers. The results are closer together in scenarios for a single jammer, but the directional antenna is still successful even a little. According to the table, there is no remarkable difference in success rates between the jamming angles of the directional antenna. With minor differences, the most successful results in all performance criteria belong to the 45° directional antenna. When the jammer with 45° directional antenna is compared to the jammer with omnidirectional antenna, the gain of approximately $>3\%$, $>4\%$, and

>3% are obtained for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively.

Table 4.12: Comparative results of DAAM according to alternative uses when the field size is 100 km², and the communication distance is 30 km

Angle of Ant. = 45°	# of Radios	# of Clusters	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			Omnidirectional:Directional			Omnidirectional:Directional			Omnidirectional:Directional		
			2:0	1:1	0:2	2:0	1:1	0:2	2:0	1:1	0:2
	30	2	53.0	59.6	62.1	76.9	81.2	82.6	96.2	97.3	97.6
		3	50.7	56.1	60.0	75.1	81.3	83.2	97.1	98.1	98.6
	40	2	47.5	52.1	54.0	72.5	77.0	78.4	93.1	95.1	95.7
		3	47.1	49.7	52.2	73.5	77.1	80.0	95.2	96.9	97.3
	Average		49.6	54.4	57.1	74.5	79.2	81.1	95.4	96.9	97.3
Angle of Ant. = 60°	# of Radios	# of Clusters	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			Omnidirectional:Directional			Omnidirectional:Directional			Omnidirectional:Directional		
			2:0	1:1	0:2	2:0	1:1	0:2	2:0	1:1	0:2
	30	2	53.0	58.3	60.8	76.9	80.2	81.6	96.2	97.2	97.5
		3	50.7	55.9	57.8	75.1	80.1	81.1	97.1	98.0	98.4
	40	2	47.5	51.2	53.5	72.5	76.5	77.5	93.1	94.6	95.1
		3	47.1	48.3	49.2	73.5	75.3	75.6	95.2	96.2	97.0
	Average		49.6	53.4	55.3	74.5	78.0	78.9	95.4	96.5	97.0
Angle of Ant. = 90°	# of Radios	# of Clusters	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			Omnidirectional:Directional			Omnidirectional:Directional			Omnidirectional:Directional		
			2:0	1:1	0:2	2:0	1:1	0:2	2:0	1:1	0:2
	30	2	53.0	56.0	58.1	76.9	77.9	79.7	96.2	96.4	96.8
		3	50.7	53.9	54.6	75.1	78.2	78.7	97.1	97.9	98.0
	40	2	47.5	50.8	52.0	72.5	75.6	76.3	93.1	94.6	95.5
		3	47.1	50.2	51.3	73.5	75.8	76.7	95.2	96.3	96.6
	Average		49.6	52.7	54.0	74.5	76.9	77.9	95.4	96.3	96.7

Table 4.12 offers all combinations of using two jammers. 2:0 corresponds to the using two jammers with omnidirectional antenna, 1:1 one jammer with omnidirectional antenna and one jammer with directional antenna, 0:2 two jammers with directional antenna. Success rates increase for all performance criteria from 2:0 to 1:1 and from 1:1 to 0:2 in each combination. Specifically, 2:0 gives better rates than 1:1 in every result, approximately >3% for both Node Success Rate and Link Success Rate when

the number of radios is 30 and approximately $>1\%$ for Communication Success Rate when the number of radios is 40. The most obvious difference is between 2:0 and 0:2 for the jamming angle of 45° . 0:2 gives better results on average $>6\%$, $>6\%$, and $>2\%$ for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively. The closest result is between 1:1 and 0:2 for the jamming angle of 90° . The difference between results is, on average, $>1\%$, $>0\%$, and $>0\%$ for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively.

Table 4.13 and 4.14 show the results for the Directional Antenna Addition Model in the field of 200 km^2 with the communication distance of 30 km. The jamming distance of the jammer with omnidirectional antenna is determined as 40 km. Consequently, the jamming distances of the jammers with directional antenna are calculated as 80 km, 98 km, and 113 km for the jamming angles of 90° , 60° , and 45° , respectively, according to Table 4.3.

Table 4.13: Comparative results of DAAM according to antenna type and angles when the field size is 200 km^2 , and the communication distance is 30 km

	# of Jammers	# of Clusters	Node Success Rate (%)				Link Success Rate (%)				Com. Success Rate (%)			
			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna		
				45°	60°	90°		45°	60°	90°		45°	60°	90°
# of Radios = 30	1	2	47.8	50.8	49.0	50.0	47.0	52.4	49.4	51.4	58.0	67.1	64.8	64.6
		3	47.2	51.2	49.5	49.5	47.0	52.5	50.9	51.5	63.2	66.3	67.3	68.5
	2	2	69.8	76.0	72.5	70.8	71.7	79.9	74.4	75.1	83.0	91.2	85.9	85.9
		3	69.7	74.8	72.3	71.8	72.2	78.1	74.8	75.5	82.7	91.5	90.1	88.8
	Average		58.6	63.2	60.8	60.5	59.5	65.7	62.4	63.4	71.7	79.0	77.0	77.0
	# of Jammers	# of Clusters	Node Success Rate (%)				Link Success Rate (%)				Com. Success Rate (%)			
			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna			Omnidir. Antenna	Directional Antenna		
				45°	60°	90°		45°	60°	90°		45°	60°	90°
# of Radios = 40	1	2	40.3	44.6	42.1	41.1	43.1	51.6	47.1	45.0	63.4	67.9	67.9	64.2
		3	39.3	44.4	42.4	41.5	43.3	50.8	47.4	44.0	70.0	70.2	70.8	67.8
	2	2	62.8	69.3	66.3	66.5	70.5	77.6	74.3	73.1	87.5	89.0	89.5	85.6
		3	62.0	69.9	66.3	66.8	70.2	77.9	75.3	74.2	87.8	90.4	89.6	87.7
	Average		51.1	57.0	54.3	54.0	56.8	64.5	61.0	59.1	77.2	79.4	79.5	76.3

In Table 4.13, the lowest success rate in all performance criteria belongs to using the omnidirectional antenna, and the highest success rate is using the 45° directional an-

tenna. The differences between these two uses are average $>4\%$, $>6\%$, and $>2\%$ for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively. Strikingly, this difference is approximately $>6\%$, $>8\%$, and $>8\%$ for the combination of 30 radios, 2 jammers, and 2 clusters. On the other hand, the success rates for using 60° and 90° directional antennas are quite close to each other. The differences are only on average $>0\%$, $>0\%$, and $>2\%$ for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively. Compared to using the omnidirectional antenna, the gains of these two uses are approximately $>2\%$, $>2\%$, and $>3\%$ for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively.

Like Table 4.12, Table 4.14 offers all combinations of using two jammers. The notations 2:0, 1:1, and 0:2 are also used here. Success rates increase for all performance criteria from 2:0 to 1:1 and from 1:1 to 0:2 in each combination as in Table 4.14. In the results, the increase in the success rates from 2:0 to 1:1 is usually more significant than the increase from 1:1 to 0:2. As an example, the differences in results from 2:0 to 1:1 and from 1:1 to 0:2 for the angle of 60° are following: $>2\%$ and $>1\%$ for Node Success Rate, $>3\%$ and $>0\%$ for Link Success Rate, $>2\%$ and $>1\%$ for Communication Success Rate. The closest results are between 1:1 and 0:2, where 90° directional antenna is used. The differences between results are, on average, $>0\%$, $>0\%$, and $>1\%$ for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively.

Table 4.14: Comparative results of DAAM according to alternative uses when the field size is 200 km², and the communication distance is 30 km

Angle of Ant. = 45°	# of Radios	# of Clusters	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			Omnidirectional:Directional			Omnidirectional:Directional			Omnidirectional:Directional		
			2:0	1:1	0:2	2:0	1:1	0:2	2:0	1:1	0:2
	30	2	69.8	73.0	76.0	71.7	76.8	79.9	83.0	87.3	91.2
		3	69.7	71.8	74.8	72.2	75.8	78.1	82.7	85.8	91.5
	40	2	62.8	68.1	69.3	70.5	76.3	77.6	87.5	88.3	89.0
		3	62.0	67.6	69.9	70.2	76.5	77.9	87.8	89.3	90.4
	Average		66.1	70.1	72.5	71.1	76.4	78.4	85.2	87.7	90.5
Angle of Ant. = 60°	# of Radios	# of Clusters	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			Omnidirectional:Directional			Omnidirectional:Directional			Omnidirectional:Directional		
			2:0	1:1	0:2	2:0	1:1	0:2	2:0	1:1	0:2
	30	2	69.8	71.0	72.5	71.7	74.4	74.4	83.0	86.2	85.9
		3	69.7	70.0	72.3	72.2	73.6	74.8	82.7	85.9	90.1
	40	2	62.8	65.8	66.3	70.5	74.5	74.3	87.5	89.0	89.5
		3	62.0	65.8	66.3	70.2	74.2	75.3	87.8	87.9	89.6
	Average		66.1	68.1	69.3	71.1	74.2	74.7	85.2	87.3	88.8
Angle of Ant. = 90°	# of Radios	# of Clusters	Node Success Rate (%)			Link Success Rate (%)			Com. Success Rate (%)		
			Omnidirectional:Directional			Omnidirectional:Directional			Omnidirectional:Directional		
			2:0	1:1	0:2	2:0	1:1	0:2	2:0	1:1	0:2
	30	2	69.8	70.8	70.8	71.7	74.9	75.1	83.0	90.5	85.9
		3	69.7	72.0	71.8	72.2	76.4	75.5	82.7	88.6	88.8
	40	2	62.8	65.5	66.5	70.5	72.2	73.1	87.5	87.3	85.6
		3	62.0	65.5	66.8	70.2	72.8	74.2	87.8	87.3	87.7
	Average		66.1	68.5	69.0	71.1	74.1	74.5	85.2	88.4	87.0

The results in Tables 4.11, 4.12, 4.13, and 4.14 support the illustrative examples in Section 4.1. According to the results, more successful rates are obtained by using the jammers with directional antenna. It was inferred from the previous tables that the hierarchical MinMax approach gives better results than the Base approach and jammers in the real plane than in the discretized plane. With these tables, it is inferred that combinations including directional antennas yield more successful results than combinations using only omnidirectional antennas.

4.2.3 Effects of the Parameters

In Sections 4.2.1 and 4.2.2, comparative results were obtained for all models developed in this study, and evaluations were made. In this section, the effects of four different parameters, number of radios, field size, communication distance, and jamming distance, on performance criteria are examined. As mentioned in Section 3.1, three different performance criteria have been determined for comparison and evaluation. As a reminder, Node Success Rate is the ratio of jammed nodes to the total number of nodes, Link Success Rate is the ratio of the number of cut direct links to the total number of direct links, and Communication Success Rate is the ratio of the number of cut indirect links to the total number of indirect links.

In Figures 4.23, 4.24, 4.25, and 4.26, the effect of a parameter on the success rates for the developed models (MM, MME, and CLE) is examined by keeping all other parameters constant. 30 different results are obtained by changing the node coordinates randomly, and the averages of these results are shown in line charts to examine the change. In the figures, MM, MME, and CLE are represented by a diamond, a square, and a triangle respectively.

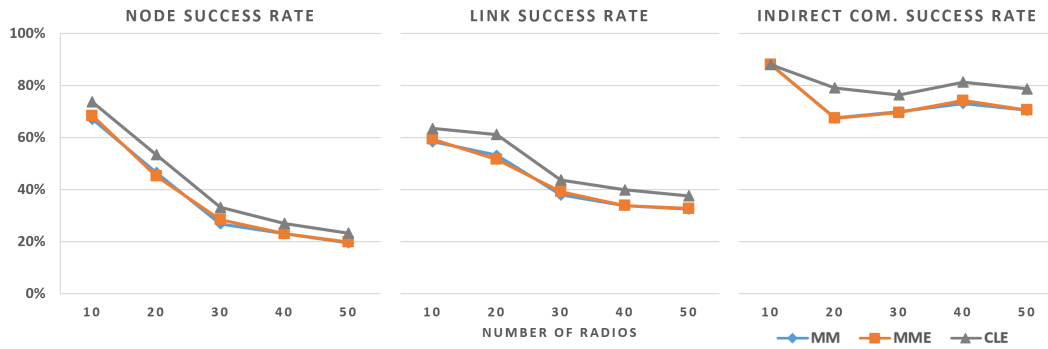


Figure 4.23: The effect of the number of radios on the developed models regarding performance criteria

Figure 4.23 shows the effect of the number of radios on the models' performances. All other parameters are kept constant, and the average results obtained by changing the number of radios to 10, 20, 30, 40, and 50 are given. As the number of radios increases, dividing the network into clusters with the same number of jammers be-

comes more challenging. Because the constraints that must be met while positioning the jammers become more complex. Node Success Rate is reduced in all models as more complex constraints negatively affect the objective function. In the same way, the ratio of cut direct links to total direct links decreases because fewer nodes are jammed compared to the total number of radios. Therefore, as the number of radios increases, Link Success Rate decreases in all models. However, since the increase in the number of indirect links is higher than the number of radios, the same effect is not seen in the Communication Success Rate. For example, when the number of radios doubles, the number of indirect links more than doubles. For this reason, more indirect links are cut for each jammed node, although proportionally fewer nodes are jammed. Since these two changes balance each other, a significant change is not observed in the Communication Success Rate.

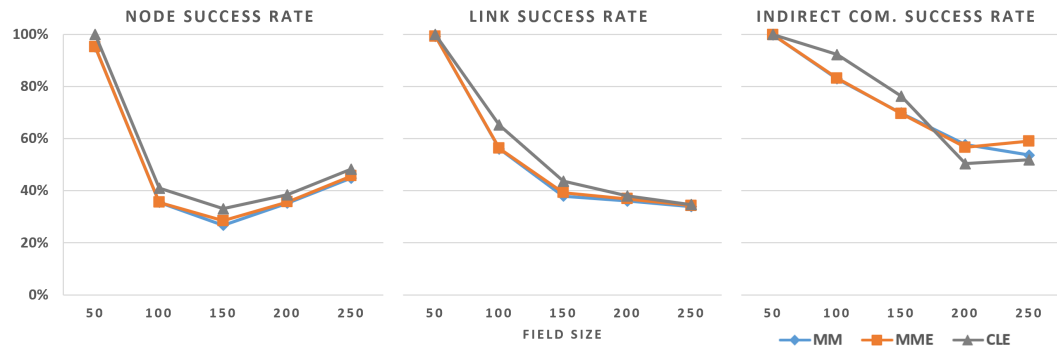


Figure 4.24: The effect of the field size on the developed models regarding performance criteria

Figure 4.24 shows the effect of the field size on the models' performances. All other parameters are kept constant, and the average results obtained by changing the field size to 50, 100, 150, 200, and 250 are given. Since the nodes are very close to each other when the field size is 50, the number of jammers is sufficient to jam all nodes in all models. However, as the nodes move away from each other with the increase in field size, the ratio of the jamming domain to the total field decrease. Because of this, the number of nodes in the jamming domain decreases, and the Node Success Rate reaches its lowest value when the field size equals 150. Since the communication distance is constant, the links between the nodes also begin to decrease with the further increase in field size. Thus, dividing the network into the same number of clusters

becomes easier, and the Node Success Rate has an increasing trend after the value of 150 as the jammer(s) can be positioned more flexibly. Although the complexity of the constraints on the positioning of the jammers has decreased, the Link Success Rate and the Communication Success Rate tend to fall due to the decreasing number of jammed nodes, direct links, and indirect links. When field size is 200 and 250, jamming a large number of nodes does not cause cut a large number of links either, as nodes have few or no links now. As can be seen in the figure, although more nodes are jammed with CLE, it falls behind MM and MME in Communication Success Rate as these nodes do not have many links.

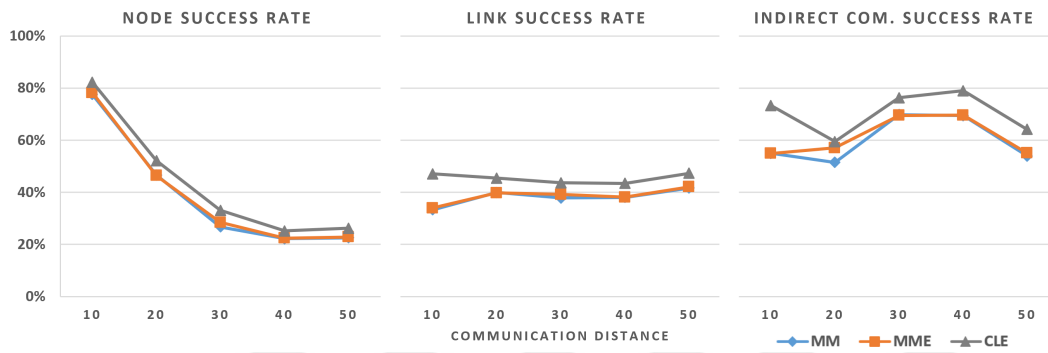


Figure 4.25: The effect of the communication distance on the developed models regarding performance criteria

Figure 4.25 shows the effect of the communication distance on the models' performances. All other parameters are kept constant, and the average results obtained by changing the communication distance to 10, 20, 30, 40, and 50 are given. When the communication distance is small, dividing the network into the desired number of clusters is easy because there are no complex link structures between the nodes. However, when the communication distance increases, the number of links increases, and it becomes difficult to divide the network into the same number of clusters in the complex structure. The jammers can be positioned more flexibly for the communication distance is 10, but the flexibility on the positioning of the jammers decreases for the communication distance is 50. In other words, models place jammer(s) by jamming fewer nodes but reaching the desired number of clusters. This is the reason for the decreasing trend in Node Success Rate. Although the number of jammed nodes decreases by increasing the communication distance, the same decrease is not

seen in Link Success Rate and Communication Success Rate, as the number of direct and indirect links increases for each node. Because these two opposite variables balance each other, Link Success Rate and Communication Success Rate do not show an increasing or decreasing trend.

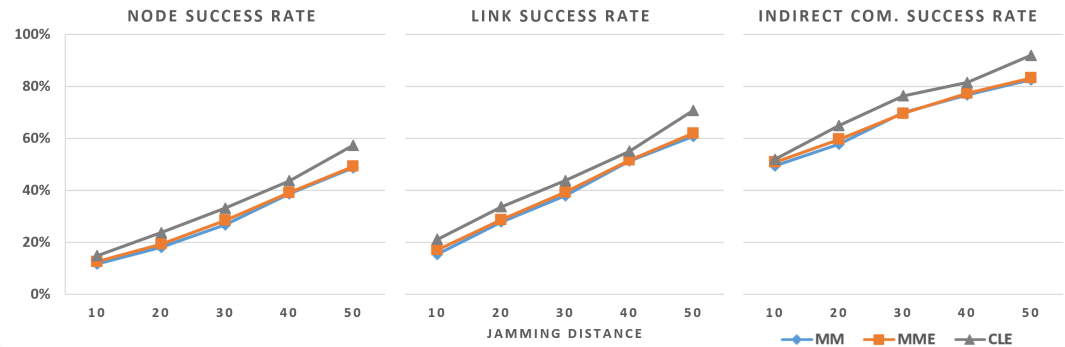


Figure 4.26: The effect of the jamming distance on the developed models regarding performance criteria

Figure 4.26 shows the effect of the jamming distance on the models' performances. All other parameters are kept constant, and the average results obtained by changing the jamming distance to 10, 20, 30, 40, and 50 are given. As expected, the increase in jamming distance results in an increase in the performance of all models. This parameter is directly proportional to Node Success Rate, Link Success Rate, and Communication Success Rate.



CHAPTER 5

CONCLUSION

In this thesis, the optimal jammer placement problem in a wireless communication network by clustering is discussed. Within the scope of the problem, it is aimed to divide the communication network into clusters that cannot communicate by jamming the signals of the homogenous radios on a two-dimensional plane. Many studies that have worked on this problem are examined, and one is taken as a base. The model taken as the base, called the Base Model, finds the minimum number of jammers so that the network can be divided into the desired number of clusters by placing the jammers at the radio locations. Drawbacks, possible performance improvements, and new approaches that can be created are identified by examining the model in detail. The first developed model, MinMax Model, aims to minimize the number of radios in the cluster with the most radios by bringing a new approach to the problem. In addition, the drawbacks in the Base Model have been eliminated with this model. Next, an extension is added to the MinMax Model. This extension, called hierarchical extension, minimizes the number of radios not only for the cluster with the highest number of radios but also for the following clusters hierarchically. As well, the hierarchical extension of the MinMax Model is also studied on the real plane. The approach remains the same, but jammers can be placed at any point on the real plane, not just on radio locations, with the new model called Continuous Location Model. Thus, the problem-solving approach becomes applicable in real life. With the next model, Base Continuous Location Model, the Base Model is adapted to the real plane to compare the base and minmax approaches on the real plane. Finally, Directional Antenna Addition Model is introduced, in which jammers are not assumed to be homogenous. In this model, jammers can have omnidirectional antenna causing circular jamming or directional antenna causing directional jamming.

The models are run with the same or different parameter values, and the results are visualized to show their differences. The visual examples include radios, links, jammer(s), clusters, jammed radios, and cut links for each model. Node Success Rate, Link Success Rate, and Communication Success Rate are determined as performance criteria, and performance comparisons are made by obtaining a large number of results in different parameter combinations from the models. In addition, the effects of # of radios, field size, communication distance, and jamming distance on the developed models are analyzed with line graphs.

As a first result, the developed models give better results than the base models for each performance criteria. Moreover, Continuous Location Model gives the best results among all models. It has $\sim 15\%$, $\sim 20\%$, and $\sim 20\%$ better results for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively, compared to the Base Model in each parameter combination. Compared to the Base Continuous Location Model, the values are $\sim 10\%$, $\sim 12\%$, and $\sim 10\%$ this time.

As a second result, jammers with directional antenna give better results than jammers with omnidirectional antenna for each performance criteria. Compared to the omnidirectional antenna, the results with the directional antenna are better on average as follows: $\sim 3\%$, $\sim 4\%$, and $\sim 4\%$ for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively. In addition, in the combination of using two jammers, using two jammers with directional antennas gives $\sim 2\%$, $\sim 2\%$, $\sim 1\%$ better result to compared to using one jammer with directional antenna and one jammer with omnidirectional antenna, and $\sim 5\%$, $\sim 5\%$, $\sim 3\%$ compared to using two jammers with omnidirectional antenna for Node Success Rate, Link Success Rate, and Communication Success Rate, respectively.

As a third result, the increase in the number of radios causes a decrease in the Node Success Rate and Link Success Rate but does not have much effect on the Communication Success Rate. As field size increases, Node Success Rate first decreases then increases, while Link Success Rate and Communication Success Rate only decrease. The increase in communication distance reduces the Node Success Rate but does not significantly affect the Link Success Rate and the Communication Success Rate. Finally, an increase is observed in all succes rates with the rise of the jamming distance.

Three suggestions are made for future work. The locations of enemy radios are assumed to be known precisely in this study. However, it is not possible to know exactly the coordinates of enemy locations in real life. As a first suggestion, the locations of radios can be determined as stochastic instead of deterministic. In this study, it is assumed that all radios within the jamming domain are jammed at the same rate regardless of the proximity of the jammer. However, the effect of jamming signals decreases as the distance increases in real life. Even, the jamming effect is negligible for specific frequencies at long distances. As a second suggestion, minimizing the distance of the radios from the jammer within certain parameters and constraints can be included in the objective function. This study is carried out on a two-dimensional plane. However, the geographical structure of the field, such as the altitudes of the jammers and radios, changes the effect of jamming signals in real life. As a final suggestion, this study can be expanded to three dimensions by adding the altitude variable.



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Appendix A

RUN TIMES OF THE MODELS

Table A.1: Average run times of the models when the field size is 100 km², and the number of radios is 30

Model	Average Run Time (sec)
Base Model	1.67
MinMax Model	1.75
Hierarchical Extension of MinMax Model	1.86
Continuous Location Model	2.92
Base Continuous Location Model	4.62
Directional Antenna Addition Model	80.56

Table A.2: Average run times of the models when the field size is 100 km², and the number of radios is 40

Model	Average Run Time (sec)
Base Model	1.95
MinMax Model	1.79
Hierarchical Extension of MinMax Model	1.91
Continuous Location Model	5.47
Base Continuous Location Model	15.12
Directional Antenna Addition Model	306.05

Table A.3: Average run times of the models when the field size is 200 km², and the number of radios is 30

Model	Average Run Time (sec)
Base Model	2.15
MinMax Model	1.76
Hierarchical Extension of MinMax Model	1.86
Continuous Location Model	3.98
Base Continuous Location Model	3.85
Directional Antenna Addition Model	52.96

Table A.4: Average run times of the models when the field size is 200 km², and the number of radios is 40

Model	Average Run Time (sec)
Base Model	1.63
MinMax Model	1.82
Hierarchical Extension of MinMax Model	1.91
Continuous Location Model	6.70
Base Continuous Location Model	3.92
Directional Antenna Addition Model	412.11



Appendix B

ADDITIONAL COMPARATIVE RESULTS OF THE MODELS



Table B.1: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 20 km, and the jamming distance is 20 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	24.5	29.7	41.3	42.0	49.7	28.4	34.2	52.6	51.9	59.6	53.7	58.1	77.5	76.7	79.2
		3	19.7	24.0	45.7	45.2	51.5	8.7	14.0	51.5	51.1	57.6	17.8	23.5	69.1	67.8	77.1
	4	3	26.5	33.0	40.7	43.2	50.8	26.1	34.5	47.7	51.3	59.0	53.3	62.9	78.6	81.9	88.9
		4	29.2	32.8	42.2	46.0	49.5	20.6	25.1	43.2	47.3	55.1	44.8	47.7	61.5	64.8	73.2
	5	4	32.7	41.2	43.7	46.2	50.5	33.2	41.3	48.0	50.7	57.3	63.8	69.0	72.4	75.0	78.6
		5	29.8	37.0	41.7	45.2	50.3	25.8	34.4	46.7	51.0	58.4	59.7	66.9	77.2	77.9	84.7
	Average		27.1	32.9	42.5	44.6	50.4	23.8	30.6	48.3	50.6	57.8	48.8	54.7	72.7	74.0	80.3
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	9.9	14.1	28.4	29.2	35.1	11.0	16.3	40.5	41.4	47.5	31.2	35.5	68.2	65.5	70.0
		3	14.4	19.2	28.6	28.7	34.3	14.7	20.5	40.8	41.2	47.2	46.0	51.6	74.7	75.7	82.6
	4	3	20.9	26.4	28.4	28.6	34.0	30.2	36.0	40.0	40.1	45.4	62.9	67.7	73.6	74.7	81.1
		4	14.4	22.9	25.0	27.8	32.1	21.5	31.8	35.9	40.7	45.2	57.3	66.0	73.1	75.5	77.8
	5	4	21.2	27.4	30.3	30.8	35.7	33.9	39.2	43.6	44.4	49.6	68.5	71.9	78.6	78.5	81.7
		5	21.1	29.7	32.4	33.4	40.1	27.8	36.8	44.7	46.8	52.8	69.9	76.8	81.4	83.0	87.3
	Average		17.0	23.3	28.9	29.7	35.2	23.2	30.1	40.9	42.4	47.9	56.0	61.6	74.9	75.5	80.1
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	11.8	19.4	25.7	25.6	31.7	20.8	28.8	40.3	40.0	46.4	55.3	63.0	76.3	76.3	79.9
		3	12.4	18.9	23.2	23.2	26.7	17.5	25.9	33.2	33.0	38.4	60.9	68.1	75.9	76.2	81.6
	4	3	19.8	26.4	28.3	28.4	34.7	31.3	37.7	42.8	43.2	49.9	75.5	79.5	82.7	82.6	86.2
		4	16.3	22.4	24.9	24.2	28.3	28.3	34.3	37.1	36.8	43.2	74.6	77.8	80.8	80.6	85.6
	5	4	27.3	34.4	35.3	37.1	44.8	43.4	49.2	52.4	54.2	63.0	85.6	88.2	89.5	90.2	92.9
		5	24.9	31.9	32.7	33.2	38.4	40.9	46.6	48.3	48.8	55.4	82.5	85.5	87.0	88.3	90.3
	Average		18.8	25.6	28.3	28.6	34.1	30.4	37.1	42.4	42.7	49.4	72.4	77.0	82.0	82.3	86.1
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	12.5	18.5	23.2	23.4	28.1	22.8	29.2	37.4	37.9	44.5	68.9	73.9	79.5	79.7	83.8
		3	15.0	21.7	24.4	24.7	28.0	24.5	33.2	38.1	39.2	43.1	66.9	72.2	76.9	77.0	80.9
	4	3	21.4	27.7	30.0	30.7	36.3	37.1	42.9	47.1	48.2	54.1	78.5	81.9	85.0	85.4	88.6
		4	19.6	24.9	27.5	27.6	32.9	33.5	38.9	43.8	43.9	52.0	81.0	83.6	86.8	86.8	90.5
	5	3	27.9	34.3	36.1	37.7	44.9	47.0	52.3	55.7	57.4	65.0	86.8	88.2	89.5	90.2	93.8
		4	25.9	32.6	34.3	35.1	43.4	44.0	49.4	53.5	54.8	63.8	87.9	89.7	92.3	92.5	94.8
	Average		20.4	26.6	29.2	29.9	35.6	34.8	41.0	45.9	46.9	53.8	78.3	81.6	85.0	85.3	88.7

Table B.2: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 20 km, and the jamming distance is 30 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	28.3	42.5	54.8	55.0	63.5	32.2	45.8	63.2	63.5	69.6	56.6	64.7	83.4	83.3	90.0
		3	23.0	30.7	58.2	58.0	67.0	10.7	20.6	63.9	63.4	73.0	16.5	26.1	80.9	80.5	87.7
	4	3	29.8	44.3	56.2	56.7	64.8	29.7	43.7	63.1	64.0	72.2	48.3	65.4	82.7	83.6	90.1
		4	33.5	43.8	57.8	59.0	67.8	30.5	38.8	62.7	64.3	74.7	48.8	57.3	85.6	86.3	93.9
	5	4	38.0	52.0	57.7	58.3	67.0	41.7	52.5	64.3	65.5	75.8	73.3	77.9	88.7	88.6	94.5
		5	33.2	46.7	57.2	59.3	66.0	27.7	44.1	60.9	64.7	73.5	56.9	71.2	87.8	88.2	90.7
	Average		31.0	43.3	57.0	57.7	66.0	28.7	40.9	63.0	64.2	73.1	50.1	60.4	84.9	85.1	91.2
# of Radios = 30	3	2	12.7	21.3	43.7	44.0	51.8	11.9	20.4	51.2	52.5	60.7	34.6	44.0	82.1	83.0	85.4
		3	18.4	31.9	47.0	47.8	53.1	20.9	35.9	59.3	60.7	64.8	49.9	64.6	84.9	84.2	88.7
	4	3	20.7	35.3	45.4	45.4	52.3	29.2	44.2	58.1	57.9	65.7	57.6	66.8	86.5	85.9	90.8
		4	21.8	37.2	42.7	42.4	48.4	29.5	45.5	54.1	55.0	61.3	64.3	74.8	80.2	82.5	88.5
	5	4	26.1	39.8	44.0	44.4	50.7	36.8	49.6	55.6	56.8	63.2	70.5	77.3	81.6	82.7	88.5
		5	23.6	40.1	44.4	44.1	51.2	32.8	50.5	56.2	56.5	65.3	74.3	81.6	88.2	88.9	93.6
	Average		20.5	34.3	44.5	44.7	51.3	26.8	41.0	55.8	56.6	63.5	58.5	68.2	83.9	84.5	89.3
# of Radios = 40	3	2	14.5	32.5	42.1	42.0	47.8	22.5	41.2	57.1	57.0	62.7	64.3	75.9	87.1	86.8	89.8
		3	17.6	35.2	40.7	40.9	47.8	26.5	43.9	56.2	56.0	63.2	67.6	81.1	90.5	90.8	94.2
	4	3	21.3	36.8	41.3	41.5	44.7	34.6	48.5	55.5	55.7	61.6	77.3	83.0	88.1	88.3	91.5
		4	22.0	37.3	39.9	40.0	45.5	32.9	48.9	56.4	57.0	61.9	77.6	85.7	91.0	91.1	94.1
	5	4	27.3	39.8	42.0	42.3	46.9	42.6	54.2	58.8	59.9	65.0	85.1	88.7	90.5	90.6	93.8
		5	29.0	40.9	41.9	41.6	47.0	46.0	56.2	58.0	57.6	64.5	87.2	90.1	91.4	91.6	94.2
	Average		21.9	37.1	41.3	41.4	46.6	34.2	48.8	57.0	57.2	63.2	76.5	84.1	89.8	89.9	92.9
# of Radios = 50	3	2	15.2	31.8	38.5	38.7	44.1	26.1	43.8	55.0	55.3	60.4	71.8	82.0	88.2	88.5	91.2
		3	17.9	34.0	36.2	36.5	40.5	29.5	46.2	51.7	51.9	58.2	72.7	81.2	87.1	87.3	92.0
	4	3	25.5	37.9	39.3	39.3	44.5	44.5	54.1	56.8	56.9	63.3	85.8	89.2	90.3	90.4	94.1
		4	24.9	38.3	37.5	36.9	40.7	41.1	53.1	54.7	53.8	58.9	82.6	87.4	89.1	89.3	93.3
	5	3	31.4	43.9	47.1	47.2	54.3	50.8	58.9	64.1	64.6	70.8	89.2	91.2	92.7	92.9	95.0
		4	32.2	43.4	44.7	45.3	51.1	51.5	61.3	64.0	64.2	70.1	90.0	92.0	93.5	93.6	96.1
	Average		24.5	38.2	40.5	40.7	45.9	40.6	52.9	57.7	57.8	63.6	82.0	87.2	90.2	90.3	93.6

Table B.3: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 20 km, and the jamming distance is 40 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	38.7	62.2	78.3	79.0	85.8	41.6	61.5	84.4	84.2	90.7	63.8	74.9	96.6	96.5	98.9
		3	26.3	39.2	74.8	74.3	81.5	14.3	29.9	78.9	78.5	85.4	21.2	36.2	92.5	92.1	97.5
	4	3	35.5	58.7	76.0	76.3	84.2	35.9	60.5	82.3	82.5	89.3	54.8	75.5	96.6	96.6	98.6
		4	29.7	43.7	72.3	73.7	82.0	22.4	35.7	75.8	76.4	86.6	41.9	53.1	90.4	90.8	98.8
	5	3	42.2	65.7	76.5	75.8	85.5	46.3	68.8	82.2	81.5	89.0	83.0	91.2	97.8	97.3	98.9
		4	41.8	62.0	71.2	73.3	83.2	44.8	62.5	76.6	78.2	88.0	69.5	81.5	94.4	95.1	99.4
	Average		35.7	55.2	74.9	75.4	83.7	34.2	53.2	80.0	80.2	88.2	55.7	68.7	94.7	94.8	98.7
# of Radios = 30	3	2	16.6	31.8	63.0	63.4	72.6	16.4	30.6	72.4	73.2	82.6	41.3	54.0	90.6	91.7	95.8
		3	20.6	41.6	64.7	65.9	73.8	20.8	42.5	75.3	76.0	84.0	51.2	64.8	95.2	95.2	98.0
	4	3	25.2	47.2	64.1	64.1	72.2	31.5	52.3	74.0	74.4	82.9	58.1	69.8	92.6	92.5	97.0
		4	26.3	51.0	64.7	64.2	72.8	37.7	59.0	76.1	76.0	85.1	70.7	83.8	96.3	96.6	98.6
	5	4	27.7	58.8	64.6	65.2	73.8	40.6	68.1	75.6	76.2	84.6	80.0	90.1	94.2	95.4	97.7
		5	32.7	55.0	63.9	64.4	73.2	45.1	63.9	74.7	75.2	85.5	78.5	88.1	95.2	95.5	98.4
	Average		24.8	47.6	64.1	64.6	73.1	32.0	52.7	74.7	75.2	84.1	63.3	75.1	94.0	94.5	97.6
# of Radios = 40	3	2	17.7	41.8	59.8	59.8	67.6	24.4	47.3	72.8	72.6	80.5	60.7	75.0	94.7	94.7	97.6
		3	19.4	50.9	63.8	63.7	71.2	28.3	59.2	77.4	77.5	84.3	68.9	87.4	96.3	96.3	98.4
	4	3	24.4	51.8	59.9	60.0	67.3	37.7	61.8	74.7	74.6	81.9	78.1	89.1	94.9	95.0	98.2
		4	27.8	56.1	61.3	61.6	67.9	40.2	64.5	74.5	74.5	81.6	80.0	87.8	97.0	97.1	98.6
	5	4	32.3	56.0	59.9	60.1	67.0	48.9	66.6	72.9	73.1	81.8	88.0	92.9	95.4	95.4	98.5
		5	29.0	55.3	59.8	60.2	66.4	44.8	67.9	74.7	75.0	81.6	84.9	93.7	96.3	96.4	98.4
	Average		25.1	52.0	60.7	60.9	67.9	37.4	61.2	74.5	74.6	82.0	76.8	87.7	95.8	95.8	98.3
# of Radios = 50	3	2	17.5	48.6	58.9	58.9	65.5	28.6	59.1	75.9	76.0	81.3	75.4	89.0	96.4	96.5	97.9
		3	18.3	53.0	58.6	58.8	64.9	30.3	65.1	75.4	76.1	81.9	78.1	92.3	96.9	96.9	98.3
	4	3	26.9	54.9	58.3	58.3	63.7	45.6	68.3	76.1	76.0	81.2	85.8	92.7	97.0	97.0	98.3
		4	31.3	58.1	61.2	61.5	65.2	52.2	74.8	79.8	80.1	84.0	90.3	95.8	97.8	97.8	98.8
	5	3	35.5	55.4	59.1	59.3	64.9	54.8	69.8	76.4	76.5	81.3	91.8	95.0	97.1	97.1	98.4
		4	30.6	55.9	55.6	56.1	62.2	52.2	72.0	72.9	73.4	80.8	91.0	95.4	96.0	96.0	98.3
	Average		26.7	54.3	58.6	58.8	64.4	43.9	68.2	76.1	76.4	81.8	85.4	93.4	96.8	96.9	98.3

Table B.4: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 30 km, and the jamming distance is 20 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	18.3	23.0	27.7	27.7	37.3	32.8	37.0	49.5	49.5	58.7	68.2	72.3	83.3	83.3	89.4
		3	23.2	27.5	32.8	34.5	39.8	34.0	39.0	50.4	53.3	58.5	67.6	70.2	81.5	82.5	89.3
	4	3	25.7	30.3	33.2	34.2	42.5	45.9	51.2	55.8	57.1	65.5	82.9	85.3	86.9	87.4	92.1
		4	26.3	31.8	32.0	35.2	40.5	38.6	44.2	47.8	51.9	59.2	78.5	80.8	85.6	86.3	89.3
	5	3	31.0	36.2	38.5	39.7	49.2	54.4	58.7	62.6	63.9	72.6	88.9	90.3	91.2	92.1	95.0
		4	32.7	36.5	40.3	41.8	52.3	55.8	59.9	64.1	66.0	74.3	90.4	91.6	92.7	92.6	95.7
	Average		26.2	30.9	34.1	35.5	43.6	43.6	48.3	55.0	57.0	64.8	79.4	81.8	86.9	87.4	91.8
# of Radios = 30	3	2	19.8	24.3	30.3	30.9	39.4	37.6	42.3	51.7	52.0	61.3	71.0	74.1	81.0	81.3	88.1
		3	21.6	26.2	29.3	30.0	37.6	38.9	44.2	49.0	50.2	60.6	77.6	80.8	85.5	85.4	91.2
	4	2	29.0	32.4	36.1	37.3	51.8	51.3	54.6	59.4	61.0	75.0	82.4	84.6	87.9	88.0	94.6
		3	29.3	34.4	38.0	38.9	49.6	53.6	58.5	63.2	64.4	73.9	88.6	91.0	91.8	92.5	96.7
	5	3	34.3	38.4	41.2	41.9	52.9	59.8	64.0	67.9	68.5	78.2	90.2	92.1	92.8	93.5	97.3
		4	37.1	41.1	43.8	45.1	50.4	58.9	62.0	66.5	68.2	75.5	92.8	94.1	95.2	95.3	97.6
	Average		28.5	32.8	36.5	37.4	46.9	50.0	54.3	59.6	60.7	70.8	83.8	86.1	89.0	89.3	94.2
# of Radios = 40	3	2	23.8	29.2	30.8	31.6	41.5	44.2	50.8	54.6	55.8	65.6	77.7	80.7	83.7	83.8	88.7
		3	25.9	31.2	33.9	34.3	42.7	46.4	51.8	57.3	57.9	68.0	78.2	81.0	86.5	86.6	93.5
	4	2	30.6	34.1	36.6	37.4	47.3	54.9	58.4	62.1	63.3	72.3	83.0	85.2	86.8	86.7	91.9
		3	30.7	33.5	37.0	37.3	45.8	51.8	54.6	60.7	62.1	71.1	87.6	88.9	90.6	91.0	95.8
	5	2	44.3	47.1	52.3	52.7	65.3	69.0	71.6	77.8	78.3	86.5	90.4	91.9	93.8	93.6	97.6
		3	38.1	40.6	43.7	43.3	55.7	63.5	65.7	69.5	70.1	79.9	92.4	93.0	93.9	94.1	97.5
	Average		32.2	35.9	39.0	39.4	49.7	55.0	58.8	63.7	64.6	73.9	84.9	86.8	89.2	89.3	94.2
# of Radios = 50	3	2	26.8	31.2	33.8	34.1	43.1	48.0	53.2	58.6	58.9	69.2	77.9	80.3	83.1	83.1	89.7
		3	28.1	32.1	33.1	33.6	42.3	49.0	52.8	55.7	57.0	67.4	79.1	81.2	85.1	84.9	92.5
	4	2	32.3	35.3	40.5	40.9	50.9	55.6	58.6	67.4	67.7	77.1	83.8	85.5	88.1	88.2	92.8
		3	34.7	38.2	39.7	40.3	49.8	57.9	60.6	63.5	64.9	76.3	88.2	89.5	91.8	92.1	95.7
	5	2	43.5	45.4	48.2	49.1	60.3	69.8	71.4	75.2	76.1	84.2	89.1	89.9	91.8	92.0	96.2
		3	41.8	44.7	46.1	46.4	59.7	66.7	69.1	72.1	72.4	84.8	92.3	93.3	95.3	95.5	98.2
	Average		34.5	37.8	40.2	40.7	51.0	57.8	60.9	65.4	66.2	76.5	85.1	86.6	89.2	89.3	94.2

Table B.5: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 30 km, and the jamming distance is 30 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	24.2	36.2	43.5	44.2	55.2	36.9	50.1	61.7	61.9	74.6	73.4	81.4	90.5	90.3	95.0
		3	23.2	35.8	43.3	45.5	54.3	32.3	45.4	63.2	65.4	75.1	68.9	77.8	91.3	91.8	97.0
	4	2	28.2	37.5	40.0	40.7	54.0	49.3	57.2	61.8	61.7	75.7	84.7	87.3	89.7	89.9	95.0
		3	27.2	42.2	43.8	45.5	52.8	45.7	60.3	62.5	65.6	72.9	78.6	88.7	90.6	90.8	96.8
	5	3	36.0	47.7	51.2	51.2	61.5	56.9	66.5	71.2	72.1	81.3	90.5	93.0	94.2	93.9	96.8
		4	38.5	48.0	47.8	48.0	58.5	60.6	67.7	67.9	69.0	79.6	93.2	95.0	96.1	96.0	98.3
	Average		29.5	41.2	44.9	45.8	56.1	47.0	57.8	64.7	66.0	76.5	81.6	87.2	92.1	92.1	96.5
# of Radios = 30	3	2	22.4	34.1	39.6	39.7	48.6	42.3	54.4	61.3	62.1	70.3	71.3	79.5	85.6	86.0	92.2
		3	25.4	36.7	37.7	37.2	42.9	43.2	55.1	56.7	56.7	65.4	80.4	85.5	89.0	88.8	93.8
	4	2	32.9	40.3	44.7	45.0	53.1	53.6	59.9	66.3	66.4	74.5	86.1	88.9	90.4	90.6	93.6
		3	32.1	45.6	46.8	46.7	54.8	55.0	66.0	68.3	68.9	76.9	88.4	92.1	93.0	93.3	96.1
	5	2	46.3	54.6	61.3	61.7	71.9	68.5	73.8	81.5	81.7	88.3	92.2	94.0	96.2	96.4	98.2
		3	37.3	49.1	54.2	53.9	62.6	62.7	71.0	76.1	76.2	83.5	92.6	95.1	96.2	96.2	98.1
	Average		32.8	43.4	47.4	47.4	55.6	54.2	63.4	68.4	68.7	76.5	85.2	89.2	91.7	91.9	95.3
# of Radios = 40	3	2	28.1	40.3	44.4	44.7	51.7	51.1	63.4	69.1	69.2	76.2	78.6	84.7	88.3	88.4	93.1
		3	28.4	38.6	41.3	40.5	47.4	49.3	57.7	62.9	63.0	70.9	81.7	86.7	88.5	88.5	94.2
	4	2	37.5	45.9	51.4	51.6	61.1	59.2	66.4	73.3	73.7	80.5	87.1	90.6	93.4	93.3	95.9
		3	38.0	48.2	49.8	49.8	55.4	64.2	71.7	74.9	74.9	79.5	89.3	92.6	93.6	93.7	96.5
	5	2	47.7	54.3	63.3	63.7	71.9	71.3	75.5	85.2	85.4	89.5	92.9	94.2	96.8	97.0	98.6
		3	44.5	52.9	58.7	59.1	68.4	70.4	75.1	81.7	81.7	87.7	94.3	96.0	97.6	97.7	99.1
	Average		37.4	46.7	51.5	51.6	59.3	60.9	68.3	74.5	74.6	80.7	87.3	90.8	93.0	93.1	96.2
# of Radios = 50	3	2	30.1	44.7	49.0	49.8	56.8	53.1	66.9	73.2	73.7	79.2	78.9	85.5	88.9	89.1	93.1
		3	32.5	45.8	49.5	49.7	56.1	49.8	62.9	71.0	71.6	78.2	85.3	90.0	93.0	93.1	95.4
	4	2	40.1	50.0	58.7	59.1	67.3	64.1	71.7	79.2	79.7	85.7	87.4	91.4	95.3	95.4	97.4
		3	43.1	53.5	57.5	57.8	65.0	67.3	74.0	80.5	80.8	85.7	92.0	94.5	95.8	95.8	97.7
	5	2	48.1	53.9	61.8	62.4	71.2	71.2	74.3	82.4	83.0	88.8	91.9	93.9	96.5	96.5	98.6
		3	50.1	57.7	63.2	64.4	71.5	75.2	79.6	86.0	86.6	91.1	94.9	96.6	98.2	98.2	99.3
	Average		40.7	50.9	56.6	57.2	64.6	63.4	71.6	78.7	79.2	84.8	88.4	92.0	94.6	94.7	96.9

Table B.6: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 30 km, and the jamming distance is 40 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	31.2	48.8	66.0	64.8	77.2	41.6	60.8	81.0	80.1	89.2	71.3	84.3	95.4	95.2	99.0
		3	31.7	57.2	68.7	69.2	77.8	43.3	67.4	83.3	83.5	90.8	79.2	92.2	98.0	98.1	99.7
	4	2	33.5	51.3	61.5	60.5	75.2	52.2	66.6	78.7	78.6	88.7	87.5	92.4	96.2	95.9	98.9
		3	37.5	60.7	65.3	65.7	77.8	54.8	73.6	79.7	80.7	90.3	84.6	93.7	96.5	96.3	99.4
	5	3	43.0	63.2	66.8	66.5	79.5	64.1	76.6	81.7	81.7	91.9	93.3	96.4	97.7	97.7	99.8
		4	40.7	61.0	64.2	65.5	75.7	61.1	75.3	79.5	81.1	88.9	89.8	93.4	96.7	96.7	99.4
	Average		36.3	57.0	65.4	65.4	77.2	52.9	70.1	80.7	81.0	90.0	84.3	92.1	96.7	96.7	99.4
# of Radios = 30	3	2	24.4	48.7	56.3	56.6	66.7	40.4	63.6	75.8	76.0	85.8	75.8	86.9	95.1	95.2	98.1
		3	32.0	55.4	59.8	60.1	67.7	53.0	74.0	80.6	81.2	88.0	85.1	94.5	97.4	97.5	99.0
	4	2	33.9	54.8	55.3	55.4	66.0	55.4	72.9	76.8	76.9	85.1	86.2	92.3	95.1	95.1	98.2
		3	39.7	59.0	61.2	61.6	69.8	62.6	76.7	81.2	81.2	89.7	91.8	95.4	96.6	96.6	99.2
	5	2	43.2	56.8	57.8	57.8	67.9	66.0	74.3	76.4	76.4	85.3	91.6	93.9	94.4	94.4	98.1
		3	38.1	56.1	59.3	59.6	67.2	64.1	75.6	79.4	79.8	88.2	92.4	95.1	96.3	96.4	99.0
	Average		35.2	55.1	58.3	58.5	67.5	56.9	72.8	78.4	78.6	87.0	87.2	93.0	95.8	95.9	98.6
# of Radios = 40	3	2	31.4	55.6	56.3	56.4	63.4	54.7	75.1	79.2	79.3	84.8	82.8	92.1	94.5	94.6	98.0
		3	31.2	55.6	57.2	57.2	63.2	53.3	73.9	77.6	77.6	85.2	85.3	93.2	95.1	95.1	98.5
	4	2	42.2	57.8	59.5	59.5	67.9	67.6	77.3	80.8	80.8	86.9	89.6	93.2	95.0	95.0	97.6
		3	44.8	60.6	60.2	60.3	67.3	71.4	81.0	83.5	83.5	88.8	93.6	96.2	98.0	98.0	99.0
	5	3	50.0	63.3	64.4	64.8	71.3	75.7	83.4	85.1	85.2	90.4	96.1	97.8	97.9	97.9	98.9
		4	46.6	59.5	59.3	59.3	64.5	73.2	81.7	82.1	82.2	87.8	96.3	97.9	98.2	98.2	98.9
	Average		41.0	58.7	59.5	59.6	66.3	66.0	78.7	81.4	81.4	87.3	90.6	95.0	96.4	96.5	98.5
# of Radios = 50	3	2	34.1	52.7	55.7	55.7	61.3	57.7	72.8	80.0	80.0	85.5	78.6	88.4	93.5	93.5	97.0
		3	32.6	52.6	55.2	55.2	58.9	52.1	71.6	77.2	77.2	83.2	84.5	92.2	94.5	94.5	97.4
	4	2	42.9	59.1	62.9	63.0	68.8	67.6	79.5	84.3	84.3	88.5	89.1	93.5	95.5	95.5	98.0
		3	43.8	57.5	57.1	57.1	62.5	70.2	80.2	80.5	80.5	85.8	90.9	94.3	95.2	95.2	97.4
	5	2	53.3	66.9	71.1	71.3	77.0	79.1	85.3	88.8	88.9	92.0	94.6	96.6	97.4	97.4	98.6
		3	52.3	62.5	62.1	62.4	66.7	78.5	83.6	84.2	84.1	88.3	94.7	96.0	96.6	96.7	98.2
	Average		43.2	58.6	60.7	60.8	65.9	67.5	78.8	82.5	82.5	87.2	88.7	93.5	95.4	95.5	97.8

Table B.7: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 40 km, and the jamming distance is 20 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	1	41.5	45.3	48.5	48.5	62.5	69.2	72.0	75.5	75.5	86.0	67.9	72.3	76.8	76.8	93.2
		2	26.2	30.3	37.7	38.5	50.8	49.8	54.2	66.9	67.6	77.6	78.3	80.2	84.3	84.7	92.5
	4	2	30.7	34.3	40.2	40.8	56.8	58.3	61.5	69.3	69.7	82.5	87.0	88.4	89.4	89.8	96.9
		3	38.2	41.3	39.5	42.2	52.8	66.7	69.0	68.5	71.2	81.2	91.5	92.6	93.4	94.0	97.6
	5	2	44.2	45.8	47.2	48.5	65.8	75.3	76.4	77.4	78.5	89.0	91.1	91.6	93.4	93.9	98.4
		3	43.5	46.5	48.0	49.8	66.2	72.8	75.2	76.4	78.9	89.1	94.4	95.1	95.4	95.6	99.2
	Average		37.4	40.6	43.5	44.7	59.2	65.4	68.0	72.3	73.6	84.2	85.0	86.7	88.8	89.1	96.3
# of Radios = 30	3	1	44.8	46.0	47.7	47.7	57.3	71.3	72.5	73.4	73.4	81.9	69.5	72.3	73.9	73.9	87.3
		2	32.1	34.0	36.3	37.2	48.6	57.2	59.1	64.5	65.6	76.3	82.7	83.3	86.6	86.6	94.1
	4	2	39.2	41.4	43.4	44.6	60.1	67.6	69.3	72.5	73.6	85.2	89.1	90.2	91.5	91.7	97.4
		3	36.9	37.9	40.4	40.7	52.1	64.2	64.8	68.1	68.8	78.0	93.0	93.3	93.3	93.4	97.3
	5	2	43.1	44.7	46.6	47.9	62.7	71.9	73.0	76.0	76.9	87.3	91.3	91.9	92.3	92.6	97.7
		3	41.1	42.6	42.4	44.7	61.6	69.2	70.2	70.8	72.9	85.2	95.3	95.5	95.8	95.8	98.2
	Average		39.5	41.1	42.8	43.8	57.1	66.9	68.2	70.9	71.9	82.3	86.8	87.7	88.9	89.0	95.3
# of Radios = 40	3	1	45.5	46.6	49.8	49.8	58.3	73.0	74.2	77.2	77.2	84.3	69.4	70.6	74.2	74.2	85.3
		2	34.9	36.4	38.3	38.9	49.8	60.7	62.0	66.5	66.7	78.2	80.8	81.5	85.9	86.5	93.4
	4	2	41.3	42.8	46.2	46.7	59.0	69.3	70.7	75.0	75.2	85.7	89.0	90.3	91.7	92.2	96.3
		3	45.8	47.0	48.1	48.6	57.9	71.5	72.6	74.8	75.2	84.6	91.4	92.1	93.7	93.8	97.9
	5	2	50.6	51.3	54.0	54.3	68.3	78.8	79.4	81.6	81.6	91.8	92.9	93.1	94.2	94.4	98.0
		3	49.7	50.6	51.6	51.8	64.3	77.9	78.6	80.3	80.7	89.5	95.8	96.1	96.9	96.9	98.7
	Average		44.6	45.8	48.0	48.3	59.6	71.9	72.9	75.9	76.1	85.7	86.6	87.3	89.4	89.7	94.9
# of Radios = 50	3	1	46.9	48.9	52.9	52.9	61.3	73.7	75.5	80.1	80.3	86.8	71.3	73.4	77.2	76.7	85.7
		2	35.7	37.9	40.8	40.9	49.9	59.7	61.9	67.7	67.8	77.3	81.6	82.5	88.0	88.0	93.1
	4	2	42.1	43.3	46.0	46.6	59.5	69.7	71.0	74.9	75.3	86.0	89.4	89.8	91.8	92.0	96.3
		3	44.7	45.5	45.5	46.1	54.9	70.4	70.8	73.0	73.4	83.4	93.1	93.2	94.6	94.6	98.0
	5	2	48.3	48.8	50.5	51.3	64.7	76.8	77.3	78.9	79.6	89.3	92.5	92.6	93.3	93.5	97.1
		3	49.2	50.3	51.8	51.6	63.6	76.2	77.0	79.8	79.9	89.6	95.7	95.9	96.8	97.1	99.1
	Average		44.5	45.8	47.9	48.2	59.0	71.1	72.3	75.7	76.1	85.4	87.3	87.9	90.3	90.3	94.9

Table B.8: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 40 km, and the jamming distance is 30 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	1	39.5	45.7	46.8	46.8	54.3	66.7	69.7	69.8	69.8	77.8	70.0	73.9	75.9	75.9	83.8
		2	30.5	39.7	44.0	44.2	51.8	56.2	64.1	68.9	69.1	77.4	81.1	85.2	88.8	88.8	94.8
	4	2	36.3	45.2	50.8	51.7	61.7	64.5	72.4	76.6	76.9	83.0	87.4	91.0	93.4	93.6	96.4
		3	37.5	45.3	47.7	49.7	61.3	62.7	68.5	74.7	75.6	83.5	92.1	93.8	95.3	95.4	98.6
	5	2	49.7	55.5	61.3	62.2	72.8	75.5	79.2	84.8	85.0	89.8	93.8	95.2	96.5	96.7	97.9
		3	46.5	55.0	56.7	57.7	68.7	75.1	79.9	82.5	83.1	89.0	96.2	97.1	97.1	97.1	99.1
	Average		40.0	47.7	51.2	52.0	61.8	66.8	72.3	76.2	76.6	83.4	86.8	89.4	91.2	91.3	95.1
# of Radios = 30	3	1	44.1	49.0	50.9	50.9	58.2	72.1	74.4	75.8	75.8	80.8	72.5	75.7	77.6	77.6	85.1
		2	32.2	42.1	44.9	45.8	54.7	58.6	66.2	71.2	71.6	80.3	82.0	85.3	87.7	87.8	92.4
	4	2	45.8	54.9	59.8	60.7	72.3	74.2	79.6	84.6	84.8	91.8	90.5	93.1	95.9	96.1	98.0
		3	46.7	53.1	55.3	55.9	66.1	74.8	78.5	81.7	81.9	88.3	94.5	95.6	96.6	96.6	98.7
	5	2	52.7	58.6	62.0	63.7	75.4	79.4	82.8	86.5	87.3	93.5	93.7	95.5	97.1	97.2	99.0
		3	51.1	59.2	59.9	60.1	72.9	76.8	81.7	85.0	85.2	91.9	95.5	96.8	97.9	97.9	99.3
	Average		45.4	52.8	55.5	56.2	66.6	72.6	77.2	80.8	81.1	87.7	88.1	90.3	92.1	92.2	95.4
# of Radios = 40	3	1	46.3	51.9	59.7	59.6	67.8	72.1	75.4	83.8	83.7	88.2	74.3	79.7	87.9	87.9	92.6
		2	38.0	47.8	53.5	53.8	62.2	64.4	71.8	79.3	79.3	85.9	82.7	86.8	91.6	91.7	95.1
	4	2	48.3	57.8	61.9	62.4	72.4	75.5	81.6	86.6	86.8	91.7	91.4	95.0	97.1	97.3	99.3
		3	47.7	57.8	61.8	61.9	71.0	74.4	81.4	85.9	86.1	92.4	94.6	96.8	98.3	98.4	99.4
	5	2	53.3	57.5	62.2	62.9	73.4	78.9	81.4	86.7	86.9	92.0	94.8	95.9	97.2	97.5	99.4
		3	52.9	59.2	60.8	61.3	70.2	80.0	83.1	85.5	85.6	91.8	96.7	97.6	98.1	98.5	99.6
	Average		47.7	55.3	60.0	60.3	69.5	74.2	79.1	84.6	84.7	90.3	89.1	92.0	95.0	95.2	97.6
# of Radios = 50	3	1	49.6	55.4	63.9	63.9	70.9	74.4	78.6	86.2	85.6	89.8	76.3	84.3	92.3	92.4	95.5
		2	42.9	50.5	57.1	57.5	66.1	68.0	74.1	82.4	82.7	88.1	82.8	87.1	92.0	92.1	95.2
	4	2	52.6	57.8	61.4	62.3	70.8	77.9	81.5	85.5	86.3	90.8	92.3	93.9	97.0	97.1	99.0
		3	48.5	56.1	60.8	61.6	70.3	74.9	79.3	85.3	85.7	91.6	94.1	96.0	98.4	98.6	99.4
	5	2	54.6	58.5	61.6	62.5	71.4	80.3	82.7	85.8	86.3	91.4	94.4	95.3	96.7	96.8	98.9
		3	55.1	59.8	61.3	61.3	68.7	80.9	83.1	84.9	85.1	90.9	96.8	97.3	98.3	98.3	99.4
	Average		50.5	56.3	61.0	61.5	69.7	76.1	79.9	85.0	85.3	90.4	89.4	92.3	95.8	95.9	97.9

Table B.9: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 100 km², the communication distance is 40 km, and the jamming distance is 40 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	1	40.3	56.0	63.5	63.5	76.8	66.1	76.1	83.1	83.1	91.4	76.3	86.8	92.7	92.7	97.8
		2	35.2	55.8	60.7	61.2	73.0	57.1	72.5	81.7	81.9	90.8	82.8	91.0	95.9	96.0	99.2
	4	2	45.2	60.3	62.5	63.0	76.2	70.7	80.6	83.0	83.1	92.3	90.0	94.2	96.3	96.5	99.2
		3	42.0	61.8	61.7	63.0	73.3	69.8	82.0	84.2	84.5	91.9	93.1	96.4	96.8	96.8	99.7
	5	2	54.0	62.5	64.2	65.5	77.0	80.2	84.8	85.7	86.2	93.5	95.5	97.0	97.2	97.3	99.2
		3	55.2	69.8	69.3	69.5	79.8	81.1	87.4	87.7	87.7	93.7	96.3	97.8	98.2	98.2	99.6
	Average		45.3	61.1	63.6	64.3	76.0	70.8	80.6	84.2	84.4	92.2	89.0	93.9	96.2	96.2	99.1
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	1	42.7	51.4	56.3	56.3	65.9	66.2	70.9	76.7	76.7	85.5	76.4	81.3	86.5	86.5	92.8
		2	35.0	52.0	57.7	57.7	65.3	60.1	72.3	83.2	83.2	89.5	81.5	88.5	93.6	93.6	98.1
	4	2	44.9	56.9	58.2	58.3	67.0	72.2	80.0	82.7	82.7	89.0	90.8	93.3	94.6	94.6	98.0
		3	49.7	61.9	61.7	62.0	68.7	78.1	86.1	86.5	86.8	91.6	94.6	96.3	96.7	96.7	98.9
	5	2	55.9	65.3	68.2	68.2	75.4	82.5	86.8	88.9	88.9	92.3	95.7	96.7	97.3	97.3	98.6
		3	52.6	62.0	62.3	62.3	71.0	82.4	87.2	88.0	87.9	92.0	96.2	96.9	97.1	97.2	98.8
	Average		46.8	58.3	60.7	60.8	68.9	73.6	80.5	84.3	84.4	90.0	89.2	92.2	94.3	94.3	97.6
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	1	45.1	55.6	60.0	60.0	67.3	73.2	78.9	83.8	83.8	89.4	74.4	83.6	86.9	86.9	92.8
		2	40.6	53.5	54.8	54.8	58.8	67.0	75.9	79.4	79.4	86.1	80.9	86.3	89.4	89.4	95.0
	4	2	49.2	62.3	66.3	66.3	73.6	78.1	85.9	89.3	89.3	92.7	91.0	94.1	95.0	95.0	98.0
		3	47.9	59.2	59.4	59.8	67.1	76.3	82.9	83.6	83.7	90.3	93.7	95.3	95.6	95.6	98.2
	5	2	57.6	69.2	73.0	73.0	80.7	84.7	90.3	92.7	92.7	95.5	95.3	96.9	97.7	97.7	98.8
		3	57.7	70.1	72.5	73.3	79.3	86.2	91.0	92.6	92.8	95.4	97.5	98.4	98.6	98.6	99.1
	Average		49.7	61.6	64.3	64.5	71.1	77.6	84.2	86.9	86.9	91.6	88.8	92.4	93.9	93.9	97.0
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	1	47.1	54.0	57.5	57.5	64.0	73.4	77.1	81.6	81.6	86.7	75.8	80.7	83.5	83.5	89.1
		2	41.4	52.9	55.6	55.7	60.2	68.4	76.6	81.0	80.9	86.6	80.0	84.5	86.9	86.9	93.2
	4	1	61.1	69.7	73.8	73.8	79.2	85.4	88.6	91.8	91.8	94.7	90.1	92.0	93.5	93.5	95.5
		2	56.2	65.7	70.1	70.1	75.0	82.9	88.0	91.2	91.1	94.1	90.9	93.2	94.8	94.9	97.3
	5	2	62.9	74.3	79.5	79.6	85.1	87.3	92.1	95.3	95.3	97.3	95.6	97.7	98.5	98.6	99.2
		3	60.6	69.0	71.9	72.2	77.2	86.3	89.7	91.5	91.7	94.1	97.4	98.2	98.5	98.5	99.3
	Average		54.9	64.3	68.1	68.2	73.4	80.6	85.3	88.7	88.7	92.2	88.3	91.1	92.6	92.6	95.6

Table B.10: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 20 km, and the jamming distance is 20 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	61.2	67.0	68.2	68.3	70.0	30.8	42.2	44.8	44.9	44.3	77.4	79.7	80.0	79.8	66.1
		3	41.2	41.8	57.2	57.7	62.7	7.9	9.0	41.3	42.6	48.1	5.3	8.6	62.6	62.5	51.3
	4	3	56.7	62.0	63.8	64.3	65.5	33.7	41.4	45.0	45.7	45.4	53.4	58.8	68.9	74.7	64.8
		4	42.5	44.5	57.7	57.8	61.5	11.7	14.0	42.9	44.8	47.7	15.6	17.3	64.9	49.9	54.9
	5	4	54.2	55.2	60.5	60.5	62.8	30.5	32.3	45.0	44.7	46.3	47.4	48.0	68.4	65.1	66.9
		5	44.8	48.0	57.3	58.3	60.5	16.6	20.8	42.4	45.0	47.5	23.6	24.4	64.3	65.9	56.3
	Average		50.1	53.1	60.8	61.2	63.8	21.9	26.6	43.6	44.6	46.5	37.1	39.5	68.2	66.3	60.1
# of Radios = 30	3	2	21.8	23.8	45.8	45.8	48.8	2.9	8.4	53.3	53.5	55.4	17.4	23.2	75.1	76.7	77.3
		3	25.9	26.7	40.0	40.3	43.8	3.4	4.2	32.7	33.6	35.9	5.6	5.9	45.0	47.3	48.2
	4	4	27.3	28.7	39.6	40.2	43.3	7.6	9.2	32.8	34.0	35.7	12.8	15.0	49.8	49.8	51.8
		4	32.9	37.4	38.9	40.9	44.3	23.0	27.6	34.4	37.3	41.8	48.3	52.8	63.5	68.3	71.9
	5	4	27.2	29.8	38.1	39.8	43.7	7.5	11.5	29.1	33.1	36.5	16.3	20.0	55.2	50.4	57.7
		5	27.2	29.8	38.1	39.8	43.7	7.5	11.5	29.1	33.1	36.5	16.3	20.0	55.2	50.4	57.7
	Average		27.0	29.3	40.5	41.4	44.8	8.9	12.2	36.5	38.3	41.1	20.1	23.4	57.7	58.5	61.4
# of Radios = 40	3	2	15.6	17.5	31.8	31.8	34.3	4.5	9.2	36.4	37.0	38.7	16.1	20.9	46.6	48.5	49.8
		3	17.5	18.3	32.6	32.2	34.6	3.2	4.0	32.2	32.5	34.5	8.4	9.0	44.0	43.0	51.2
	4	3	23.5	27.6	30.2	30.9	34.8	19.3	23.1	30.3	31.2	35.6	43.5	47.3	62.9	61.3	63.0
		4	18.9	20.3	30.8	31.9	35.2	4.7	6.8	28.3	31.3	32.3	10.9	15.1	49.5	48.4	54.5
	5	4	25.8	29.3	30.5	31.8	34.6	19.8	23.2	28.2	30.8	33.8	48.1	50.7	59.4	62.9	63.8
		5	23.2	27.1	30.5	31.7	33.2	16.4	20.7	28.2	30.9	32.0	34.9	39.4	50.5	54.1	55.2
	Average		20.7	23.4	31.1	31.7	34.4	11.3	14.5	30.6	32.3	34.5	27.0	30.4	52.2	53.0	56.3
# of Radios = 50	3	2	12.0	13.3	27.0	27.0	29.1	2.2	4.9	33.0	33.4	35.2	10.0	14.8	51.3	49.9	59.7
		3	10.5	13.6	23.3	23.6	26.5	3.2	8.2	29.1	29.5	31.7	20.5	27.1	54.3	55.4	60.0
	4	3	14.9	18.5	23.2	23.2	25.9	13.0	18.2	28.9	28.8	31.4	38.0	43.7	59.4	59.9	62.5
		4	15.0	18.1	23.4	24.1	26.8	12.4	15.9	28.8	29.7	32.0	35.0	39.4	60.8	61.3	65.5
	5	4	17.2	20.9	23.1	23.9	26.4	18.6	22.3	27.2	27.6	30.6	50.4	53.8	58.0	61.1	63.8
		5	16.8	20.9	23.2	23.8	26.1	17.1	21.8	28.0	28.8	30.4	46.5	51.8	60.4	61.1	63.2
	Average		14.4	17.5	23.9	24.3	26.8	11.1	15.2	29.2	29.7	31.9	33.4	38.4	57.4	58.1	62.4

Table B.11: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 20 km, and the jamming distance is 30 km

# of Radios = 20	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	64.0	70.2	69.8	69.0	74.2	39.0	49.5	44.6	43.9	55.0	79.2	81.6	64.8	66.5	75.1
		3	42.5	43.7	63.3	63.0	69.0	10.3	12.8	51.3	51.2	58.1	5.8	5.8	57.4	56.4	57.7
	4	3	59.7	67.2	67.3	67.0	71.7	43.0	53.7	52.0	51.9	58.4	66.2	74.6	75.7	71.9	81.2
		4	42.8	45.2	64.2	63.5	69.0	9.8	12.7	52.0	51.3	58.5	13.5	13.5	53.5	60.1	62.6
	5	4	52.5	59.3	63.7	64.5	66.5	36.4	44.3	55.9	56.7	56.5	59.6	62.7	71.3	69.9	65.8
		5	51.8	54.8	64.5	65.0	69.2	23.7	27.0	50.7	51.2	58.4	26.6	26.6	56.3	64.1	69.2
	Average		52.2	56.7	65.5	65.3	69.9	27.0	33.3	51.1	51.0	57.5	41.8	44.1	63.2	64.8	68.6
# of Radios = 30	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	3	25.2	28.1	46.6	46.6	52.3	4.0	7.7	39.4	38.6	47.5	10.0	12.3	56.9	50.5	57.6
	4	4	28.0	31.3	46.1	46.6	52.9	9.3	12.8	38.7	39.9	46.4	17.5	21.4	55.8	54.1	62.6
	5	4	35.2	45.2	49.8	49.9	54.1	28.9	39.8	47.6	48.6	52.7	56.3	64.9	71.5	72.1	77.9
		5	29.0	31.8	47.3	47.6	53.9	6.4	10.0	39.5	38.8	47.0	14.2	16.4	58.0	54.1	57.2
	Average		29.4	34.1	47.4	47.6	53.3	12.1	17.6	41.3	41.5	48.4	24.5	28.7	60.6	57.7	63.8
# of Radios = 40	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	16.9	23.0	39.8	40.4	45.0	7.0	17.7	43.1	43.6	49.8	25.0	33.8	61.1	61.5	63.8
		3	18.0	20.2	39.1	39.1	43.8	3.8	5.9	38.5	39.7	43.8	8.7	10.9	58.3	58.4	62.9
	4	3	23.1	31.3	37.4	38.1	42.1	19.5	27.7	39.3	40.1	43.1	45.3	48.9	65.5	66.0	71.3
		4	18.9	22.0	39.1	39.0	43.8	6.1	11.5	39.0	39.7	42.7	19.9	22.7	57.5	58.6	65.6
5	4	27.0	34.6	39.1	39.9	43.0	22.4	30.0	38.5	39.2	41.6	43.4	47.3	58.7	58.2	69.0	
	5	24.8	32.3	36.6	38.1	43.3	18.9	26.0	35.4	38.4	43.5	39.8	47.3	60.0	62.2	69.1	
	Average		21.5	27.2	38.5	39.1	43.5	13.0	19.8	39.0	40.1	44.1	30.3	35.2	60.2	60.8	66.9
# of Radios = 50	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	11.7	17.0	33.1	32.9	36.4	4.9	11.6	38.6	38.5	42.2	18.7	26.6	63.1	64.0	64.4
		3	13.9	19.9	34.2	34.7	37.9	7.3	14.5	39.7	39.6	43.2	28.0	36.4	66.9	67.1	69.1
	4	3	19.1	27.8	30.9	31.6	35.7	18.5	26.6	33.2	34.1	39.0	48.6	54.6	63.9	64.5	67.5
		4	18.3	24.5	32.9	33.1	36.7	16.0	22.6	37.6	38.2	42.0	42.3	50.8	67.3	68.1	71.7
5	4	18.1	24.4	29.7	30.7	34.1	18.0	24.5	34.0	36.0	39.7	50.7	55.5	63.6	65.1	67.1	
	5	19.3	26.7	30.6	31.5	35.8	21.8	29.5	36.0	37.5	41.1	57.2	62.8	67.5	68.6	71.9	
	Average		16.7	23.4	31.9	32.4	36.1	14.4	21.6	36.5	37.3	41.2	40.9	47.8	65.4	66.2	68.6

Table B.12: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 20 km, and the jamming distance is 40 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	62.7	70.2	72.5	71.0	77.0	39.1	53.3	55.1	50.8	61.8	66.1	72.2	67.6	56.3	64.1
		3	40.7	44.0	68.8	69.7	73.5	7.6	12.3	59.2	60.9	65.1	9.2	13.3	62.9	62.9	71.9
	4	3	60.0	68.7	73.2	73.3	76.5	36.8	52.1	58.2	58.3	62.6	56.5	65.6	66.4	68.1	69.2
		4	43.3	47.2	67.5	67.8	72.8	11.4	15.2	56.5	57.0	64.3	16.0	16.7	59.8	57.6	74.1
	5	4	57.3	64.7	69.0	69.3	73.8	39.6	50.9	57.3	59.0	64.9	63.8	68.4	68.6	72.0	75.4
		5	53.0	58.7	71.5	71.7	76.3	27.3	34.6	60.4	59.8	67.1	35.7	37.9	65.5	66.6	77.6
	Average		52.8	58.9	70.4	70.5	75.0	26.9	36.4	57.8	57.6	64.3	41.2	45.7	65.2	63.9	72.0
# of Radios = 30	3	2	24.9	35.4	55.3	55.8	61.7	12.4	23.1	54.6	55.5	61.9	36.7	42.7	68.2	71.5	71.7
		3	26.9	29.0	55.3	55.4	61.6	4.2	7.6	50.2	49.6	56.4	7.4	12.0	54.2	53.7	64.8
	4	3	32.7	51.2	58.7	59.6	62.8	24.0	46.8	55.6	55.9	60.1	54.5	68.1	77.9	77.6	78.1
		4	29.1	36.6	53.6	54.8	60.3	11.2	19.7	48.1	49.5	55.4	23.3	33.8	56.9	59.1	66.9
	5	4	36.6	51.2	55.2	55.4	58.7	31.9	48.8	54.8	55.0	58.2	60.1	72.0	79.5	79.5	81.9
		5	32.2	37.1	57.2	57.1	61.6	9.6	16.7	50.7	50.2	57.3	14.2	23.7	53.7	54.0	66.1
	Average		30.4	40.1	55.9	56.4	61.1	15.6	27.1	52.3	52.6	58.2	32.7	42.0	65.1	65.9	71.6
# of Radios = 40	3	2	17.1	26.2	47.7	47.1	52.3	8.2	20.6	51.5	51.2	57.2	24.2	37.8	70.9	69.2	69.2
		3	19.3	24.9	50.1	50.3	54.9	5.3	10.2	50.6	51.4	55.9	10.7	17.4	65.0	66.0	74.7
	4	3	22.8	39.8	47.6	48.4	52.3	19.8	36.9	49.7	50.8	55.8	49.6	58.9	72.7	73.3	78.4
		4	20.8	27.0	47.1	48.0	53.1	9.1	16.0	48.4	49.4	53.7	20.2	25.5	68.7	70.0	77.2
	5	4	25.5	41.7	48.5	48.9	52.4	22.7	40.0	50.7	51.5	56.1	51.6	62.2	76.1	77.6	81.5
		5	26.8	37.9	47.1	48.0	53.1	21.3	31.9	49.7	50.2	54.9	40.2	50.3	71.2	71.6	79.8
	Average		22.0	32.9	48.0	48.4	53.0	14.4	25.9	50.1	50.8	55.6	32.7	42.0	70.8	71.3	76.8
# of Radios = 50	3	2	14.7	25.5	41.7	41.9	45.1	10.4	21.0	46.1	46.4	51.1	29.8	37.7	66.0	66.0	66.2
		3	15.5	25.7	43.3	43.3	47.5	8.6	21.1	48.0	48.2	54.0	26.5	39.8	72.2	69.6	74.3
	4	3	22.1	34.8	41.5	41.6	45.3	23.1	34.8	45.0	45.1	49.0	51.0	57.1	71.3	70.4	74.5
		4	17.5	27.5	41.3	42.1	45.8	14.4	23.9	46.7	47.6	52.1	37.1	43.6	72.6	72.3	77.1
	5	4	18.5	34.1	40.1	40.6	43.6	22.9	39.9	45.9	46.7	49.9	55.9	69.5	76.0	76.4	80.1
		5	22.8	37.5	42.1	41.9	46.5	26.6	42.3	48.6	49.4	54.2	61.4	69.1	77.2	77.4	83.2
	Average		18.5	30.8	41.6	41.9	45.6	17.7	30.5	46.7	47.2	51.7	43.6	52.8	72.5	72.0	75.9

Table B.13: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 30 km, and the jamming distance is 20 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	21.3	26.3	31.0	31.7	36.8	23.8	28.4	36.5	38.3	44.1	55.6	59.6	66.5	67.0	69.7
		3	23.5	25.2	34.5	36.2	43.7	10.2	12.7	38.4	40.8	50.3	26.7	30.5	57.4	59.3	68.3
	4	3	22.0	24.5	26.8	28.7	37.0	19.8	22.6	32.5	35.3	44.2	40.2	43.5	65.7	68.1	73.2
		4	29.7	31.7	36.0	37.7	43.7	21.1	23.6	36.4	39.8	46.4	37.5	39.2	65.1	66.4	71.7
	5	4	27.0	28.3	31.3	33.5	41.7	28.7	30.4	36.8	41.3	48.6	65.4	67.0	73.7	76.0	80.3
		5	30.5	32.3	32.8	36.3	42.5	28.0	29.7	35.2	39.6	48.5	61.8	62.6	66.3	69.2	75.4
	Average		25.7	28.1	32.1	34.0	40.9	21.9	24.6	36.0	39.2	47.0	47.9	50.4	65.8	67.7	73.1
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	9.2	11.1	19.1	19.8	23.3	7.9	10.7	28.9	29.0	33.5	24.4	28.9	46.4	45.2	55.5
		3	11.7	13.6	18.8	20.8	24.8	10.5	13.8	26.1	29.5	34.6	42.3	43.5	58.9	59.5	66.4
	4	3	15.3	18.2	20.3	21.0	27.6	24.2	28.0	33.8	34.9	42.4	58.2	62.4	69.1	69.7	74.9
		4	14.8	17.3	19.3	20.2	26.1	17.6	20.2	29.1	32.0	37.4	47.9	52.5	66.2	68.7	73.5
	5	4	20.4	23.0	24.7	26.0	34.1	30.3	33.1	37.9	39.7	48.3	65.6	67.9	74.6	75.1	80.1
		5	15.7	18.7	20.6	21.4	25.8	23.7	26.9	32.3	34.1	38.9	59.9	61.5	69.7	71.6	74.8
	Average		14.5	17.0	20.5	21.5	26.9	19.0	22.1	31.3	33.2	39.2	49.7	52.8	64.2	65.0	70.9
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	9.5	12.3	14.2	14.5	19.6	17.3	21.0	24.1	24.1	31.9	59.3	61.7	65.3	65.7	74.3
		3	10.1	13.0	16.5	16.9	21.3	14.6	18.3	25.2	25.9	33.2	55.8	59.9	71.3	71.4	76.1
	4	3	16.2	18.5	19.9	20.7	26.2	28.2	30.8	34.2	35.0	41.1	74.0	75.6	77.8	78.2	82.2
		4	13.4	15.8	16.8	17.3	21.8	20.4	22.6	26.8	26.2	34.8	67.8	69.2	72.8	73.7	79.6
	5	4	21.3	25.2	25.9	26.4	34.3	36.2	39.8	44.1	44.3	54.5	80.2	82.0	85.2	85.7	90.2
		5	21.0	23.3	24.7	25.1	31.0	35.4	37.9	41.5	41.5	49.6	82.1	83.5	84.4	85.0	88.9
	Average		15.2	18.0	19.7	20.1	25.7	25.3	28.4	32.7	32.8	40.9	69.9	72.0	76.1	76.6	81.9
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	10.0	12.8	16.1	16.3	21.3	18.7	22.5	29.7	29.6	37.5	65.7	68.5	70.7	70.8	74.7
		3	10.9	13.1	16.9	17.1	21.7	18.3	21.0	29.7	30.0	37.4	63.9	66.3	71.5	71.6	79.4
	4	3	17.5	20.2	22.3	23.0	27.9	33.3	36.2	42.2	43.2	48.2	78.0	79.6	82.5	82.7	87.4
		4	17.9	19.9	22.5	23.0	27.9	29.3	31.4	38.8	39.5	46.6	77.7	79.0	81.6	82.7	88.9
	5	3	24.0	25.7	29.7	30.1	37.9	43.0	44.7	51.0	51.6	59.6	83.7	84.9	87.5	87.8	91.4
		4	20.1	21.8	22.5	23.8	31.7	34.7	36.5	38.4	42.6	52.6	85.9	86.3	87.9	88.6	92.2
	Average		16.7	18.9	21.7	22.2	28.1	29.5	32.1	38.3	39.4	47.0	75.8	77.4	80.3	80.7	85.7

Table B.14: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 30 km, and the jamming distance is 30 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	23.5	30.7	41.3	40.8	47.3	27.0	34.5	50.7	50.9	55.3	60.2	66.1	76.7	80.3	83.1
		3	21.5	25.8	44.5	45.5	53.5	11.2	16.2	50.8	52.6	61.0	23.9	29.7	65.4	67.5	78.2
	4	3	27.0	34.3	44.0	45.5	54.0	26.8	34.5	53.3	53.7	63.0	51.6	58.1	80.2	81.2	88.7
		4	25.5	33.8	43.7	45.5	50.7	17.8	27.0	44.3	47.0	54.9	38.4	45.1	66.3	68.3	77.7
	5	4	27.3	37.2	37.7	41.0	46.8	29.9	39.3	41.9	46.4	55.1	65.1	69.0	76.6	75.6	83.5
		5	36.3	41.8	46.0	48.3	54.3	34.3	39.2	51.1	54.2	60.9	64.3	67.6	73.5	75.4	81.8
	Average		26.9	33.9	42.9	44.4	51.1	24.5	31.8	48.7	50.8	58.4	50.6	55.9	73.1	74.7	82.2
# of Radios = 30	3	2	10.8	14.4	31.7	31.3	34.4	10.6	15.2	44.9	44.1	47.8	32.8	36.5	65.9	63.2	68.0
		3	15.2	20.6	28.1	29.1	34.1	18.3	24.0	39.2	41.2	45.3	44.9	52.5	70.8	71.2	77.1
	4	3	18.2	24.7	29.1	29.4	32.4	23.4	32.7	40.5	41.5	44.5	52.5	61.2	70.0	70.9	76.9
		4	14.1	20.4	26.2	28.3	33.4	16.9	24.6	36.4	39.2	44.9	50.2	57.3	72.4	74.9	78.1
	5	4	20.3	30.2	34.2	34.8	40.8	31.5	42.9	49.2	50.7	55.8	64.5	72.6	76.7	78.3	82.9
		5	21.2	27.1	30.0	30.8	36.1	26.8	32.8	38.8	40.7	46.7	67.9	71.6	77.4	77.8	81.9
	Average		16.6	22.9	29.9	30.6	35.2	21.3	28.7	41.5	42.9	47.5	52.1	58.6	72.2	72.7	77.5
# of Radios = 40	3	2	12.1	18.1	24.9	25.5	31.1	19.3	26.2	38.4	39.3	44.5	61.2	66.6	76.3	76.0	79.7
		3	12.3	18.2	23.6	23.7	27.3	17.7	25.1	34.6	35.3	40.7	57.6	62.9	74.9	75.2	82.0
	4	3	18.4	25.3	28.5	29.5	35.3	29.7	35.4	43.8	45.1	49.9	74.3	77.5	82.0	82.7	87.1
		4	18.3	24.0	26.3	26.0	31.2	27.2	32.8	38.5	38.4	45.6	71.8	76.1	80.8	81.3	85.7
	5	4	23.8	30.8	35.3	35.3	42.9	38.2	45.3	52.5	52.9	60.3	82.6	85.7	88.8	89.4	92.0
		5	24.3	31.5	33.1	33.7	40.8	38.8	45.4	51.1	51.7	59.0	81.5	86.0	88.9	89.1	91.8
	Average		18.2	24.6	28.6	28.9	34.7	28.5	35.0	43.2	43.8	50.0	71.5	75.8	81.9	82.3	86.4
# of Radios = 50	3	2	12.1	20.9	26.0	26.1	31.8	22.7	32.2	41.9	42.0	48.7	67.6	74.9	80.0	80.1	84.7
		3	12.9	20.4	22.5	22.3	26.1	23.1	32.5	36.8	36.7	41.6	64.3	72.1	77.4	77.5	81.4
	4	3	21.0	25.2	27.3	27.5	33.1	37.0	40.1	44.3	44.2	50.9	80.1	81.6	84.6	85.0	88.4
		4	21.8	27.7	30.6	31.1	37.3	36.1	41.9	48.0	48.7	55.6	81.0	84.3	86.5	87.7	90.9
	5	3	26.9	32.9	36.5	37.2	45.8	45.0	50.7	56.4	57.1	66.1	85.8	88.2	90.2	90.8	94.0
		4	26.8	34.6	35.7	35.7	42.3	45.8	51.5	56.6	56.4	63.7	88.1	90.4	92.5	92.7	94.9
	Average		20.3	27.0	29.8	30.0	36.1	35.0	41.5	47.3	47.5	54.4	77.8	81.9	85.2	85.6	89.0

Table B.15: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 30 km, and the jamming distance is 40 km

# of Radios = 20	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	26.2	39.7	51.8	52.7	61.0	28.4	41.4	60.7	61.3	69.1	54.7	62.9	81.3	82.6	85.2
		3	21.5	30.0	53.8	53.8	62.2	9.3	19.5	60.2	60.3	68.4	21.9	30.3	77.5	77.4	83.5
	4	3	32.2	46.5	56.0	56.3	62.0	35.1	49.1	64.3	64.8	70.6	56.0	68.7	83.1	84.2	87.1
		4	29.7	36.3	51.2	52.5	59.5	23.5	29.9	53.2	54.4	64.3	43.6	49.2	77.0	78.7	87.9
	5	4	35.7	49.8	52.8	54.0	59.8	38.7	51.1	56.1	57.3	65.5	70.2	74.3	82.0	82.1	90.5
		5	29.8	43.7	48.2	52.0	59.7	27.8	41.4	55.0	58.7	67.8	60.5	68.3	83.3	84.2	89.6
Average			29.2	41.0	52.3	53.6	60.7	27.1	38.7	58.2	59.5	67.6	51.1	58.9	80.7	81.5	87.3
# of Radios = 30	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	14.4	20.4	40.2	40.0	45.9	13.2	20.0	50.1	49.2	55.3	37.2	45.7	72.1	72.4	76.2
		3	16.0	26.6	40.1	41.0	46.1	19.4	31.4	54.6	55.8	59.7	47.4	59.9	81.5	82.1	86.6
	4	3	20.3	31.2	37.6	37.8	45.0	27.6	37.3	49.2	49.3	57.5	57.6	63.8	78.1	78.1	84.9
		4	19.4	30.8	37.0	39.0	43.6	27.2	38.1	48.8	51.2	56.6	56.8	64.2	80.4	82.2	84.4
	5	4	23.2	33.9	39.4	39.7	45.0	33.5	44.7	53.0	53.2	58.0	69.9	75.4	81.6	82.1	87.8
		5	24.0	34.3	38.9	39.3	43.2	33.1	43.3	50.2	51.3	57.3	64.8	71.9	78.3	79.9	85.8
Average			19.6	29.5	38.9	39.5	44.8	25.7	35.8	51.0	51.7	57.4	55.6	63.5	78.7	79.5	84.3
# of Radios = 40	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	11.9	25.0	33.9	34.3	40.3	18.4	32.2	46.6	47.0	53.8	62.1	73.6	80.7	81.6	85.5
		3	15.2	29.1	35.3	35.6	40.1	21.5	37.6	48.7	49.2	57.4	59.8	72.3	86.6	86.8	90.1
	4	3	22.6	32.0	33.8	34.4	40.0	35.3	44.5	48.6	49.5	56.4	77.2	82.0	85.9	86.0	89.8
		4	21.2	32.3	34.0	33.8	37.9	32.2	43.4	46.3	46.5	54.5	75.6	80.7	85.4	85.9	89.9
	5	4	29.4	37.8	40.1	40.1	44.5	44.3	51.3	55.3	55.0	61.9	84.5	87.3	89.7	89.9	92.0
		5	24.8	36.0	38.7	38.6	43.4	38.1	48.2	53.7	53.5	60.6	83.4	87.9	89.1	89.1	92.7
Average			20.8	32.0	35.9	36.1	41.0	31.7	42.9	49.9	50.1	57.4	73.8	80.6	86.2	86.5	90.0
# of Radios = 50	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	13.5	26.3	31.3	31.5	36.2	22.9	37.0	44.6	45.0	49.9	70.4	78.4	83.3	83.3	86.4
		3	18.5	30.0	33.5	33.1	37.7	32.1	44.1	51.5	51.2	57.3	72.1	78.9	85.3	85.8	90.2
	4	3	22.5	32.5	34.9	34.7	38.6	39.4	48.3	51.3	51.3	56.2	83.3	86.4	88.4	88.6	91.4
		4	24.9	34.1	35.5	35.7	40.9	39.0	48.0	51.2	51.5	58.1	82.8	86.3	89.0	89.1	92.0
	5	3	32.9	41.7	45.1	45.8	52.3	50.7	58.3	63.2	63.7	69.3	88.9	91.4	92.9	93.0	95.0
		4	29.1	39.2	42.1	42.1	46.8	46.9	55.8	60.9	61.5	67.2	89.0	91.4	92.8	93.2	94.9
Average			23.5	34.0	37.1	37.1	42.1	38.5	48.6	53.8	54.1	59.7	81.1	85.5	88.6	88.9	91.7

Table B.16: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 40 km, and the jamming distance is 20 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	16.3	19.7	20.2	21.3	27.7	26.8	30.7	32.0	34.1	43.6	52.9	58.3	66.2	68.6	75.4
		3	16.0	17.8	22.5	24.5	28.2	19.6	22.1	37.7	40.1	45.1	50.8	52.5	74.4	73.5	81.7
	4	3	18.5	20.5	21.0	22.3	28.2	31.2	33.8	37.5	39.3	47.0	66.3	68.9	73.3	73.8	80.5
		4	20.0	20.5	22.7	23.8	31.3	28.2	28.8	34.0	36.7	45.6	73.2	73.8	78.0	79.0	85.1
	5	3	28.3	29.5	29.8	30.5	41.5	50.2	50.7	52.3	53.1	64.9	80.4	80.4	81.2	80.9	88.9
		4	22.3	23.7	25.5	26.3	35.8	37.8	39.3	42.4	45.2	55.6	81.6	82.8	85.2	86.0	89.9
	Average		20.3	21.9	23.6	24.8	32.1	32.3	34.2	39.3	41.4	50.3	67.5	69.5	76.4	77.0	83.6
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	12.1	15.0	17.0	17.3	24.9	23.4	27.4	31.5	31.7	43.2	66.1	69.1	72.2	73.1	79.4
		3	14.0	15.7	19.3	19.7	26.2	26.0	28.3	36.5	36.9	46.7	65.5	66.5	71.8	72.3	83.4
	4	3	22.0	23.8	25.3	26.1	37.0	39.8	41.9	46.9	47.6	61.2	78.7	79.9	82.7	84.1	90.9
		4	22.0	23.2	24.7	26.2	33.8	38.7	39.9	45.2	46.0	59.2	82.4	83.3	85.8	86.5	92.7
	5	3	26.8	28.0	30.8	31.9	45.6	50.3	51.6	56.3	57.4	71.6	86.1	86.6	88.1	89.6	94.8
		4	27.4	28.7	28.4	30.1	41.1	49.1	50.1	52.4	54.5	67.6	88.6	89.1	90.0	90.6	96.0
	Average		20.7	22.4	24.3	25.2	34.8	37.9	39.9	44.8	45.7	58.2	77.9	79.1	81.8	82.7	89.5
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	17.0	18.6	21.6	22.2	31.8	34.5	36.4	39.8	40.5	53.5	71.4	73.0	77.3	77.6	84.1
		3	18.8	20.7	21.1	21.5	27.7	34.8	37.5	39.8	40.4	49.4	73.1	74.9	77.9	78.0	85.6
	4	2	26.3	27.3	29.3	29.9	42.6	47.7	48.9	51.5	52.1	67.2	80.3	81.3	83.4	83.6	90.2
		3	22.3	23.0	27.8	28.3	37.8	42.0	42.7	51.3	51.7	63.6	83.8	84.1	86.6	87.0	93.0
	5	3	33.3	34.3	34.3	35.8	49.1	59.5	60.6	60.8	62.3	76.9	90.3	90.6	91.2	91.5	96.3
		4	31.4	33.0	33.1	34.2	42.8	54.8	56.5	57.7	59.2	69.8	90.8	91.1	92.4	92.9	96.6
	Average		24.8	26.1	27.8	28.6	38.6	45.5	47.1	50.1	51.0	63.4	81.6	82.5	84.8	85.1	91.0
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	19.7	21.0	22.8	23.6	33.3	38.0	39.4	42.4	43.4	57.7	74.2	75.2	77.1	77.5	84.9
		3	23.5	24.3	25.3	25.7	32.1	41.0	42.0	44.2	44.8	55.2	75.8	76.2	79.7	79.8	88.0
	4	2	29.1	30.3	32.7	33.6	44.1	53.0	54.4	57.1	58.3	71.4	80.7	81.9	82.7	83.6	90.3
		3	26.4	27.3	28.8	29.2	38.1	46.5	47.4	51.1	51.9	65.3	83.7	84.1	85.6	86.1	92.8
	5	3	33.7	34.5	36.5	37.4	50.9	58.6	59.4	63.8	64.1	77.7	90.0	90.4	91.9	92.7	96.4
		4	33.6	34.3	33.7	34.9	44.0	58.5	59.0	59.7	61.1	71.7	91.7	91.9	92.4	92.7	96.8
	Average		27.7	28.6	30.0	30.7	40.4	49.3	50.3	53.0	53.9	66.5	82.7	83.3	84.9	85.4	91.5

Table B.17: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 40 km, and the jamming distance is 30 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	17.2	20.5	29.5	30.3	36.0	26.4	29.7	45.6	46.8	53.1	50.9	54.1	75.5	76.3	81.0
		3	19.2	26.0	31.7	33.2	41.3	25.4	32.6	47.0	48.9	58.6	60.4	66.2	84.4	85.1	89.4
	4	3	22.0	28.7	30.3	33.0	40.3	37.0	42.4	47.9	51.3	59.4	66.8	74.2	79.8	81.5	87.8
		4	22.0	28.2	30.8	32.0	38.7	30.4	37.5	45.9	47.7	57.6	67.2	72.8	86.1	86.5	89.4
	5	3	34.0	40.5	41.3	42.3	56.7	54.4	60.3	64.1	64.9	76.3	85.9	88.7	91.4	91.3	95.1
		4	30.8	37.2	37.8	39.5	48.2	47.8	53.5	57.1	58.8	67.9	83.2	86.2	89.0	90.2	93.4
	Average		24.2	30.2	33.6	35.1	43.5	36.9	42.7	51.3	53.1	62.1	69.1	73.7	84.4	85.1	89.4
# of Radios = 30	3	2	16.4	22.3	27.1	27.3	34.7	31.2	37.9	48.3	48.8	55.5	62.9	68.4	77.9	78.0	83.5
		3	17.1	21.1	25.4	26.8	30.6	29.6	35.1	41.0	42.6	48.8	71.9	75.3	79.9	80.9	86.4
	4	3	25.2	30.1	34.2	34.9	44.7	45.9	50.3	56.6	57.0	66.3	82.9	85.6	89.0	89.4	92.9
		4	27.3	33.8	35.8	36.4	45.1	45.2	50.9	56.9	58.0	67.8	86.7	89.4	91.1	91.6	95.6
	5	3	32.6	37.0	40.6	40.9	53.3	53.4	57.4	63.2	63.7	74.0	88.5	90.4	92.6	93.0	96.7
		4	32.1	37.2	39.6	39.6	48.4	54.5	59.8	61.7	63.6	72.1	88.4	90.3	92.8	92.8	96.3
	Average		25.1	30.3	33.8	34.3	42.8	43.3	48.6	54.6	55.6	64.1	80.2	83.2	87.2	87.6	91.9
# of Radios = 40	3	2	19.9	25.3	29.3	29.4	37.6	37.4	43.8	50.1	51.2	58.8	73.4	78.9	82.2	82.5	88.3
		3	22.0	28.0	29.7	29.9	36.2	37.9	43.6	47.9	47.7	57.9	76.0	79.7	83.5	83.6	87.9
	4	2	29.7	34.0	37.8	38.2	48.3	50.6	54.2	60.3	61.4	72.0	83.0	85.3	87.0	87.6	93.2
		3	27.1	32.1	33.3	33.8	42.9	48.6	52.8	56.9	57.2	65.3	86.1	88.2	89.6	89.9	93.5
	5	3	36.7	40.5	43.5	44.5	55.9	60.0	63.5	69.8	70.4	80.0	91.8	92.6	95.0	95.1	97.3
		4	32.1	36.1	36.5	38.0	49.8	54.0	57.3	59.7	61.8	73.9	92.6	93.5	94.1	94.3	97.0
	Average		27.9	32.7	35.0	35.6	45.1	48.1	52.5	57.5	58.3	68.0	83.8	86.4	88.6	88.8	92.8
# of Radios = 50	3	2	24.3	31.0	33.9	34.1	43.7	42.9	49.4	55.8	55.9	67.5	76.5	80.7	85.0	85.2	90.9
		3	24.5	28.9	31.9	32.5	40.1	42.2	46.8	54.0	54.7	65.3	78.3	80.9	85.9	86.2	91.3
	4	2	32.5	35.0	38.7	39.5	48.9	54.8	57.2	61.7	63.1	72.5	83.4	84.9	87.3	87.6	92.4
		3	30.9	34.7	37.9	37.7	46.9	51.8	55.5	61.0	60.8	71.6	86.4	88.3	89.6	89.8	94.4
	5	3	38.3	42.7	45.3	46.1	59.1	62.7	66.4	70.1	71.0	83.3	90.8	92.0	94.0	94.3	97.4
		4	37.6	41.5	42.1	43.3	52.1	61.5	64.0	67.2	68.2	77.6	93.2	93.9	94.9	95.3	97.3
	Average		31.3	35.6	38.3	38.9	48.5	52.6	56.6	61.6	62.3	72.9	84.8	86.8	89.4	89.7	94.0

Table B.18: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 150 km², the communication distance is 40 km, and the jamming distance is 40 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	20.0	30.0	43.2	43.3	52.8	25.9	36.3	56.3	56.5	68.8	52.6	60.3	86.1	86.2	91.6
		3	20.2	32.5	41.8	43.7	52.2	24.8	38.8	58.0	59.5	69.0	58.8	68.6	85.6	86.7	92.9
	4	3	26.2	36.5	40.2	42.2	51.0	39.5	50.3	57.3	59.4	69.9	71.5	79.2	88.2	88.9	93.3
		4	28.7	40.8	43.3	44.8	50.7	39.2	51.3	57.6	58.3	69.9	76.4	83.4	86.0	87.6	94.0
	5	3	33.3	42.3	46.8	47.5	59.8	49.1	56.0	63.2	63.9	75.1	82.1	85.1	88.8	89.4	94.3
		4	34.2	44.0	46.3	48.3	57.0	48.4	58.2	62.1	63.8	74.6	85.8	89.4	91.0	92.0	95.3
	Average		27.1	37.7	43.6	45.0	53.9	37.8	48.5	59.1	60.2	71.2	71.2	77.7	87.6	88.5	93.6
# of Radios = 30	3	2	18.0	28.3	32.8	33.1	39.6	34.8	47.0	53.8	54.0	59.8	68.8	75.8	82.8	83.0	88.2
		3	20.3	31.4	35.4	36.4	40.9	33.9	46.2	51.4	54.4	60.8	73.5	80.6	84.2	85.3	91.6
	4	2	30.0	37.2	42.1	42.7	52.1	47.6	54.1	61.5	61.9	69.9	84.3	87.1	88.8	89.0	93.3
		3	27.2	36.4	39.1	39.1	46.2	46.9	54.5	58.1	58.8	66.0	83.7	88.4	90.2	90.2	93.4
	5	3	36.9	46.4	49.1	49.8	62.2	59.2	65.6	69.9	70.7	80.4	88.9	92.0	94.9	94.8	96.9
		4	33.6	43.7	48.0	49.3	57.7	54.6	63.6	68.6	69.5	76.8	90.7	93.0	94.7	94.8	96.6
	Average		27.7	37.3	41.1	41.7	49.8	46.2	55.2	60.6	61.6	68.9	81.6	86.1	89.3	89.5	93.3
# of Radios = 40	3	2	23.1	33.5	36.1	36.1	43.2	42.6	53.8	57.1	58.1	65.8	75.8	82.5	85.8	85.8	90.9
		3	23.8	32.8	37.6	37.8	42.7	39.9	47.2	55.5	55.8	63.1	78.4	82.3	87.2	87.3	91.8
	4	2	32.5	42.4	47.6	48.0	56.2	53.4	61.6	68.6	69.0	73.9	84.7	89.0	91.3	91.5	94.2
		3	30.8	36.9	40.5	40.9	47.8	52.2	56.8	61.1	61.4	69.1	87.0	89.5	91.7	91.8	94.5
	5	3	43.3	49.3	51.9	53.0	62.3	66.8	71.2	75.2	75.9	83.4	92.8	94.2	95.7	95.9	97.9
		4	38.3	46.0	47.8	48.2	55.6	61.2	66.9	70.3	70.8	78.2	93.3	94.7	95.7	95.6	97.6
	Average		32.0	40.1	43.6	44.0	51.3	52.7	59.6	64.6	65.2	72.2	85.3	88.7	91.2	91.3	94.5
# of Radios = 50	3	2	24.8	37.1	43.3	43.7	50.3	45.5	57.1	65.6	66.2	71.9	76.9	83.2	87.8	87.8	91.1
		3	27.3	38.1	42.3	42.2	48.5	44.2	54.9	62.9	62.8	70.0	78.5	83.8	88.6	88.8	93.1
	4	2	35.9	44.8	53.1	53.7	62.1	57.0	63.8	74.2	75.0	79.9	86.0	90.2	94.0	94.1	96.4
		3	35.7	45.7	48.8	49.6	57.0	59.1	66.4	72.3	73.0	79.8	88.5	91.5	94.2	94.3	96.4
	5	3	41.1	50.5	50.9	51.9	61.1	65.7	72.1	72.9	73.9	82.9	92.5	94.5	95.8	96.0	98.0
		4	41.9	50.2	52.1	52.5	58.5	65.1	71.0	74.1	74.7	80.8	93.5	95.4	96.2	96.4	97.8
	Average		34.4	44.4	48.4	49.0	56.2	56.1	64.2	70.3	70.9	77.5	86.0	89.7	92.8	92.9	95.5

Table B.19: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 20 km, and the jamming distance is 20 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	73.3	77.5	80.3	79.8	79.3	35.2	43.3	62.7	61.6	51.1	73.1	75.3	79.2	77.5	69.2
		3	64.2	65.3	72.5	72.3	73.2	18.6	21.1	45.3	44.9	42.3	22.2	23.3	48.3	46.7	35.0
	4	3	74.5	77.7	81.5	81.8	80.0	26.4	33.3	56.8	57.4	45.2	41.7	45.0	55.0	55.0	35.0
		4	63.0	66.0	72.7	73.3	74.0	21.5	28.6	44.0	47.9	42.1	23.1	24.2	41.7	41.7	31.7
	5	4	72.3	73.3	75.8	76.7	75.3	34.4	36.4	41.5	46.8	38.4	41.7	41.7	51.7	51.7	30.0
		5	63.8	66.2	70.5	71.5	73.3	26.3	31.4	42.5	45.2	44.0	20.2	23.6	36.7	36.7	25.0
	Average		68.5	71.0	75.6	75.9	75.9	27.1	32.3	48.8	50.6	43.8	37.0	38.8	52.1	51.5	37.6
# of Radios = 30	3	3	45.1	46.6	55.8	55.7	57.9	9.0	11.6	34.9	33.0	34.8	12.9	14.3	51.6	56.5	47.6
		4	45.2	46.1	55.2	56.0	57.8	4.9	6.4	32.4	35.4	34.5	9.2	10.9	56.0	55.3	48.5
	5	5	46.2	48.0	55.9	56.1	58.0	11.7	15.0	34.0	35.2	34.7	15.2	16.6	57.3	58.4	49.3
		Average	45.5	46.9	55.6	55.9	57.9	8.5	11.0	33.8	34.6	34.7	12.4	13.9	55.0	56.7	48.4
# of Radios = 40	3	3	36.5	36.8	49.3	49.1	50.9	1.3	1.9	31.5	31.0	31.6	4.7	5.5	41.2	42.3	48.9
		4	38.3	39.7	49.3	49.0	50.1	5.5	7.4	31.8	31.3	29.5	15.0	15.7	44.6	41.8	45.2
	5	5	41.4	45.3	48.9	49.0	49.7	14.4	20.0	30.8	31.1	30.3	25.6	30.9	42.8	46.4	45.0
		Average	38.8	40.6	49.2	49.0	50.2	7.1	9.8	31.4	31.1	30.5	15.1	17.4	42.9	43.5	46.4
# of Radios = 50	3	3	25.0	25.7	36.8	36.7	38.1	1.7	3.2	27.5	27.0	27.7	5.2	8.5	51.5	52.8	50.3
		4	28.7	31.3	36.7	36.8	37.9	10.0	13.5	27.3	27.5	28.1	20.0	24.1	48.6	50.1	50.5
	5	5	29.9	33.3	36.5	36.5	38.1	15.0	18.6	27.1	26.6	27.8	36.2	39.6	50.6	49.6	51.8
		Average	27.9	30.1	36.7	36.7	38.0	8.9	11.8	27.3	27.0	27.8	20.5	24.0	50.2	50.8	50.9

Table B.20: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 20 km, and the jamming distance is 30 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	76.3	80.3	80.8	81.2	80.8	40.3	47.4	52.2	58.6	51.3	71.4	73.1	60.3	64.2	56.9
		3	63.7	66.7	76.0	76.5	78.8	20.4	28.2	49.7	51.9	55.5	23.9	26.7	38.3	43.3	35.0
	4	3	73.3	75.2	78.0	77.7	80.0	28.3	31.7	42.9	43.1	44.8	39.4	40.0	38.3	41.7	25.0
		4	62.8	65.5	76.2	76.3	76.5	19.6	25.7	50.2	50.7	51.0	13.9	15.8	36.7	38.3	35.0
	5	4	73.7	75.0	78.5	77.7	79.2	36.1	38.7	49.0	45.9	49.0	44.4	46.7	45.0	45.0	38.3
		5	67.2	69.7	74.7	75.7	75.8	29.7	34.9	47.4	49.2	49.0	22.5	22.5	28.3	28.3	28.3
	Average		69.5	72.1	77.4	77.5	78.5	29.1	34.4	48.6	49.9	50.1	35.9	37.5	41.2	43.5	36.4
# of Radios = 30	3	3	43.9	45.2	58.6	58.3	61.2	3.2	5.4	34.5	34.2	39.8	6.7	7.7	46.3	45.8	53.9
		4	45.8	46.6	58.4	58.9	61.2	6.6	8.0	33.7	35.2	39.2	12.2	12.2	52.0	50.1	55.8
	5	5	46.7	48.7	58.6	58.6	59.9	9.9	14.2	35.1	33.7	36.6	17.1	20.6	45.3	50.5	51.5
		Average	45.4	46.8	58.5	58.6	60.8	6.6	9.2	34.4	34.3	38.5	12.0	13.5	47.9	48.8	53.7
	4	4	38.3	40.0	52.5	52.5	54.8	4.9	7.2	33.8	34.5	37.8	8.0	8.3	50.2	52.0	55.6
		5	43.2	46.4	52.3	52.7	54.1	16.9	20.8	32.6	33.7	36.7	32.5	33.7	46.9	50.7	48.8
	Average		39.4	41.1	52.3	52.5	54.6	7.8	10.0	33.2	34.0	37.4	15.1	15.7	47.9	51.6	51.7
# of Radios = 40	3	3	25.3	27.1	40.9	40.5	43.3	2.1	5.2	32.7	31.2	33.8	7.0	10.4	56.9	53.0	52.7
		4	31.3	36.0	41.0	40.8	43.1	15.5	21.4	32.2	31.2	34.3	31.6	38.7	57.8	53.7	54.7
	5	5	31.6	36.5	40.1	40.9	43.3	17.5	23.1	30.5	31.6	35.2	37.2	41.7	56.6	56.3	54.9
		Average	29.4	33.2	40.7	40.7	43.2	11.7	16.6	31.8	31.3	34.4	25.3	30.3	57.1	54.3	54.1
	4	4	31.3	36.0	41.0	40.8	43.1	15.5	21.4	32.2	31.2	34.3	31.6	38.7	57.8	53.7	54.7
		5	31.6	36.5	40.1	40.9	43.3	17.5	23.1	30.5	31.6	35.2	37.2	41.7	56.6	56.3	54.9
	Average		29.4	33.2	40.7	40.7	43.2	11.7	16.6	31.8	31.3	34.4	25.3	30.3	57.1	54.3	54.1
# of Radios = 50	3	3	25.3	27.1	40.9	40.5	43.3	2.1	5.2	32.7	31.2	33.8	7.0	10.4	56.9	53.0	52.7
		4	31.3	36.0	41.0	40.8	43.1	15.5	21.4	32.2	31.2	34.3	31.6	38.7	57.8	53.7	54.7
	5	5	31.6	36.5	40.1	40.9	43.3	17.5	23.1	30.5	31.6	35.2	37.2	41.7	56.6	56.3	54.9
		Average	29.4	33.2	40.7	40.7	43.2	11.7	16.6	31.8	31.3	34.4	25.3	30.3	57.1	54.3	54.1
	4	4	31.3	36.0	41.0	40.8	43.1	15.5	21.4	32.2	31.2	34.3	31.6	38.7	57.8	53.7	54.7
		5	31.6	36.5	40.1	40.9	43.3	17.5	23.1	30.5	31.6	35.2	37.2	41.7	56.6	56.3	54.9
	Average		29.4	33.2	40.7	40.7	43.2	11.7	16.6	31.8	31.3	34.4	25.3	30.3	57.1	54.3	54.1

Table B.21: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 20 km, and the jamming distance is 40 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	74.8	80.2	81.0	81.0	84.3	39.2	53.0	54.9	54.5	66.4	63.6	65.8	57.5	57.5	57.5
		3	61.8	65.0	76.3	75.7	79.8	15.8	24.0	49.1	47.4	58.0	18.9	20.0	35.0	31.7	33.3
	4	3	73.2	76.3	79.0	78.2	82.8	30.5	37.9	47.4	45.7	58.8	46.1	49.4	38.3	38.3	31.7
		4	64.3	66.8	76.5	76.5	79.3	19.2	24.7	45.2	45.4	54.6	19.7	20.8	35.0	33.3	31.7
	5	4	73.0	76.0	78.8	80.2	82.2	34.5	40.6	43.9	48.1	54.1	45.7	46.3	38.0	41.3	38.8
		5	66.8	69.3	74.7	76.0	80.0	25.5	30.3	41.0	45.6	55.0	17.5	17.5	26.7	26.7	26.7
	Average		69.0	72.3	77.7	77.9	81.4	27.5	35.1	46.9	47.8	57.8	35.3	36.7	38.4	38.1	36.6
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	3	45.7	47.1	62.2	62.3	66.3	8.0	10.1	40.7	40.8	46.3	15.0	17.3	54.7	51.2	49.7
	4	4	46.3	47.7	62.2	61.1	66.6	8.6	10.7	40.3	38.7	47.5	15.8	16.1	53.9	55.5	53.5
	5	4	59.4	65.2	69.0	69.6	71.0	29.8	39.9	47.2	48.0	50.4	53.4	58.0	65.3	62.0	71.3
		5	46.6	49.2	62.1	62.9	66.8	11.1	14.9	39.2	42.2	47.2	13.0	13.4	48.1	56.8	47.4
	Average		49.5	52.3	63.9	64.0	67.7	14.4	18.9	41.8	42.4	47.8	24.3	26.2	55.5	56.4	55.5
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	3	36.9	38.1	56.4	56.0	59.3	2.4	3.9	39.6	38.5	43.0	1.7	3.7	54.8	55.8	52.7
	4	4	38.0	40.5	56.7	56.8	59.0	5.4	8.2	39.9	40.0	41.5	8.3	11.2	57.6	52.5	49.8
	5	5	43.8	49.5	56.8	56.9	59.8	16.6	24.2	40.3	40.5	44.1	21.9	28.8	57.7	55.1	53.3
	Average		39.6	42.7	56.6	56.6	59.4	8.1	12.1	39.9	39.7	42.9	10.6	14.6	56.7	54.4	52.0
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	3	25.1	27.0	47.0	46.7	49.7	1.5	4.9	38.8	38.2	41.5	5.8	9.7	59.6	60.0	62.0
	4	4	31.5	40.9	46.5	46.7	49.1	15.5	27.4	37.7	38.5	40.4	29.3	39.9	58.0	60.0	60.4
	5	5	33.1	40.9	46.5	46.5	49.1	19.2	29.1	39.0	39.2	41.0	42.7	49.1	62.2	62.7	61.0
	Average		29.9	36.3	46.7	46.7	49.3	12.1	20.5	38.5	38.6	41.0	26.0	32.9	59.9	60.9	61.1

Table B.22: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 30 km, and the jamming distance is 20 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	50.2	50.5	52.8	53.2	58.7	28.6	29.1	34.1	32.0	40.6	65.7	65.7	60.8	54.7	60.8
		3	38.8	39.3	49.2	47.8	53.5	12.4	13.6	40.3	37.3	47.2	25.8	26.3	52.4	51.0	65.0
	4	3	39.5	40.3	45.7	45.8	50.5	20.8	22.5	34.3	35.4	41.6	44.8	47.7	57.5	56.9	61.0
		4	41.2	42.0	47.7	47.7	53.0	18.9	20.3	38.5	37.8	46.4	39.0	40.4	55.0	51.6	61.0
	5	4	36.7	38.3	41.3	42.2	47.8	23.5	25.0	32.9	34.0	40.8	49.4	50.5	59.6	58.6	67.5
		5	44.2	45.3	49.7	50.3	55.2	24.9	26.8	38.9	39.6	46.6	47.1	47.6	62.5	60.6	57.9
	Average		41.8	42.6	47.7	47.8	53.1	21.5	22.9	36.5	36.0	43.9	45.3	46.4	58.0	55.6	62.2
# of Radios = 30	3	2	16.8	18.0	27.8	28.3	32.8	5.1	7.5	35.5	35.0	39.1	15.7	17.9	48.8	44.9	50.1
		3	23.2	23.6	30.3	30.9	35.1	9.1	9.5	29.4	28.6	34.0	19.8	20.2	44.9	40.9	49.9
	4	3	20.2	22.1	26.4	27.3	31.0	15.8	18.3	28.4	30.5	34.0	34.1	36.3	51.2	51.8	56.4
		4	23.6	25.1	29.2	30.1	34.0	11.8	14.3	28.7	29.1	34.0	26.2	29.2	42.5	43.3	45.9
	5	4	21.6	22.3	26.2	27.8	31.0	12.2	12.9	24.6	27.7	33.0	32.8	33.9	48.9	51.5	59.8
		5	25.3	27.8	30.7	31.9	35.1	16.6	19.4	27.1	29.4	32.9	34.1	36.5	49.1	47.0	55.3
	Average		21.8	23.1	28.4	29.4	33.2	11.8	13.7	29.0	30.1	34.5	27.1	29.0	47.6	46.6	52.9
# of Radios = 40	3	2	13.5	14.1	23.9	24.0	26.7	4.3	5.3	30.8	30.2	33.1	18.2	20.7	44.3	41.9	44.4
		3	14.0	14.7	20.5	21.3	25.0	5.8	7.0	23.5	24.2	29.6	21.5	22.7	42.7	44.9	54.0
	4	3	13.3	14.6	18.8	19.2	22.3	10.5	12.1	21.0	21.5	26.8	36.1	38.7	54.9	53.7	56.8
		4	15.3	16.8	20.9	21.6	24.8	9.1	10.7	24.6	25.9	29.9	29.4	30.4	52.6	54.8	59.9
	5	4	16.3	17.5	19.6	19.6	23.9	16.0	17.6	23.2	23.6	29.1	48.1	51.3	60.8	61.3	67.0
		5	16.5	18.5	19.8	21.4	24.5	15.1	18.5	21.6	24.6	29.4	39.6	43.9	50.8	55.1	61.1
	Average		14.8	16.0	20.6	21.2	24.5	10.1	11.8	24.1	25.0	29.7	32.1	34.6	51.0	51.9	57.2
# of Radios = 50	3	2	8.0	9.0	14.8	15.1	17.7	4.9	6.3	21.4	21.5	25.8	20.3	22.8	39.5	40.7	43.6
		3	9.6	10.9	16.0	16.2	18.9	7.3	9.1	21.3	21.3	26.5	36.7	38.2	50.6	50.6	57.4
	4	3	11.9	12.8	14.9	15.4	18.5	14.1	15.0	20.8	22.4	26.0	45.9	47.4	53.5	54.3	58.4
		4	11.5	13.3	14.9	15.3	18.1	13.5	15.9	20.9	21.6	25.9	44.4	46.0	56.9	58.7	62.3
	5	4	12.9	14.3	15.6	16.3	20.3	17.9	19.5	22.5	24.0	29.9	57.6	59.4	64.6	64.8	69.5
		5	13.0	15.2	16.4	16.8	22.0	17.7	20.3	23.4	24.1	32.2	54.1	56.5	61.6	64.1	69.2
	Average		11.2	12.6	15.4	15.9	19.2	12.6	14.4	21.7	22.5	27.7	43.2	45.0	54.5	55.5	60.1

Table B.23: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 30 km, and the jamming distance is 30 km

# of Radios = 20	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	58.3	64.2	66.2	66.2	70.8	34.5	43.8	46.8	46.1	52.6	68.2	71.8	73.5	70.2	64.3
		3	37.0	40.5	54.3	54.3	59.5	16.0	21.2	47.1	48.2	52.4	26.1	27.6	59.3	62.0	59.8
	4	3	47.7	54.7	56.5	56.0	59.3	36.6	44.8	48.5	47.6	49.5	71.5	76.2	82.3	80.2	74.2
		4	36.5	39.2	54.5	54.5	57.7	10.8	14.9	47.6	47.6	50.8	22.0	25.8	63.9	61.6	66.3
	5	4	43.8	48.8	51.7	52.5	54.7	32.6	38.9	43.5	45.0	46.6	58.8	63.6	72.2	71.1	70.2
		5	45.5	50.7	55.8	56.0	59.8	26.3	33.2	47.4	47.7	52.5	45.9	50.1	67.6	68.2	66.7
Average			44.8	49.7	56.5	56.6	60.3	26.1	32.8	46.8	47.0	50.7	48.8	52.5	69.8	68.9	66.9
# of Radios = 30	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	14.9	16.3	37.6	38.1	40.3	3.5	6.9	45.5	46.9	48.4	11.2	13.8	61.4	59.0	60.9
		3	19.9	22.6	35.1	35.4	39.0	4.7	7.5	34.0	34.6	36.8	12.7	13.9	51.5	55.3	53.4
	4	3	21.4	26.2	33.3	33.3	38.2	19.5	24.4	38.6	38.7	43.5	48.0	52.3	67.3	68.7	68.5
		4	21.1	23.0	33.8	36.4	38.9	7.6	9.4	33.6	37.3	39.6	22.1	24.0	52.6	55.1	54.0
	5	4	24.4	29.1	32.2	32.4	38.6	20.5	26.3	34.1	34.8	43.0	49.7	54.5	66.3	68.2	74.0
		5	24.8	28.3	34.9	36.6	38.0	16.1	19.7	32.8	35.6	37.0	32.4	36.2	60.6	60.1	64.3
Average			21.1	24.3	34.5	35.4	38.8	12.0	15.7	36.4	38.0	41.4	29.4	32.5	59.9	61.1	62.5
# of Radios = 40	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	13.9	16.9	30.7	31.0	33.7	6.3	11.2	37.0	37.1	40.1	21.7	28.6	56.6	55.7	54.7
		3	12.3	14.8	26.3	27.9	30.7	4.4	7.9	30.3	31.4	34.8	16.0	19.1	58.8	57.5	64.2
	4	4	15.0	19.7	28.1	29.0	31.8	9.9	15.9	31.5	33.0	36.0	24.2	31.9	62.0	62.6	65.4
		4	19.0	23.0	24.8	26.3	30.9	19.7	24.9	28.3	30.9	36.3	50.4	54.0	61.5	62.2	67.0
	5	4	19.4	23.4	28.5	28.9	30.8	18.9	23.2	32.9	33.5	34.6	49.1	54.3	63.4	63.9	67.3
		5	15.9	19.6	27.7	28.6	31.6	11.8	16.6	32.0	33.2	36.4	32.3	37.6	60.5	60.4	63.7
Average			15.9	19.6	27.7	28.6	31.6	11.8	16.6	32.0	33.2	36.4	32.3	37.6	60.5	60.4	63.7
# of Radios = 50	# of Base	# of Unj.	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
	Cluster	Cluster	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
	3	2	9.4	12.1	23.1	23.5	26.5	5.0	9.5	29.1	30.0	34.1	19.9	25.2	50.9	52.8	60.6
		3	8.8	13.2	19.6	19.9	23.1	7.5	13.8	29.0	29.4	32.7	32.7	40.6	61.9	61.8	67.3
	4	3	13.7	16.9	19.1	19.5	23.5	16.7	19.4	25.0	25.5	28.3	53.5	56.9	63.8	63.3	67.5
		4	12.3	16.2	19.7	19.9	23.8	14.2	18.5	28.3	28.0	32.6	47.1	51.9	66.2	66.5	69.0
	5	4	15.0	19.3	20.2	20.4	24.4	21.4	26.2	28.3	28.4	31.5	63.4	66.6	69.8	71.4	73.6
		5	16.7	20.7	22.0	22.1	25.7	24.9	29.0	31.1	31.8	35.7	63.2	67.5	70.5	70.4	73.9
Average			12.6	16.4	20.6	20.9	24.5	15.0	19.4	28.4	28.8	32.5	46.6	51.5	63.9	64.4	68.7

Table B.24: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 30 km, and the jamming distance is 40 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	54.5	61.2	63.8	64.0	67.0	35.2	45.0	48.6	48.6	51.8	67.5	70.9	70.9	67.8	68.4
		3	32.7	34.0	59.2	59.3	64.7	4.6	6.9	52.0	51.5	59.4	5.8	5.8	65.6	66.4	69.8
	4	3	47.8	56.0	58.3	59.2	63.2	39.3	50.0	53.3	54.6	58.9	73.8	80.3	87.6	90.9	88.1
		4	35.0	37.3	59.0	58.7	64.2	7.0	9.9	51.7	51.1	58.6	12.6	14.3	70.7	68.8	77.1
	5	4	45.7	52.0	58.3	58.2	65.0	33.8	39.8	54.1	53.6	61.6	58.3	58.4	74.6	73.8	83.4
		5	44.0	50.0	58.2	58.8	64.2	22.5	28.9	47.1	48.8	57.4	45.7	50.6	64.9	64.2	69.9
	Average		43.3	48.4	59.5	59.7	64.7	23.8	30.1	51.1	51.4	58.0	43.9	46.7	72.4	72.0	76.1
# of Radios = 30	3	2	19.0	26.1	43.6	43.3	47.0	11.6	22.6	52.0	52.0	54.5	26.5	38.0	65.1	64.9	68.1
		3	18.8	20.8	40.6	41.2	47.3	2.6	5.5	38.6	41.1	47.2	8.8	10.9	52.9	58.8	64.4
	4	3	23.3	31.9	40.3	41.0	44.8	20.8	29.0	42.1	42.8	48.0	47.7	53.4	70.5	68.4	74.0
		4	22.2	25.9	41.3	41.3	46.2	8.8	13.8	40.6	40.5	46.4	25.1	28.0	58.0	53.2	66.2
	5	4	27.0	35.7	38.2	39.1	43.9	20.3	29.1	35.8	35.8	42.3	54.6	60.2	67.8	68.0	72.0
		5	25.8	30.9	41.6	42.6	47.8	14.2	20.1	41.2	42.2	47.3	31.6	37.5	66.4	68.4	70.4
	Average		22.7	28.5	40.9	41.4	46.2	13.0	20.0	41.7	42.4	47.6	32.4	38.0	63.4	63.6	69.2
# of Radios = 40	3	2	14.9	19.9	34.8	35.1	38.8	7.7	14.4	41.7	41.9	44.3	26.7	33.9	62.8	62.5	65.0
		3	13.9	18.6	33.6	33.8	39.4	6.3	13.5	37.2	37.4	42.9	18.3	26.6	68.2	67.9	73.1
	4	3	18.7	26.6	31.8	32.2	36.1	18.9	26.4	35.1	35.7	40.2	39.2	46.7	61.5	62.7	63.0
		4	16.3	23.4	33.7	34.6	37.9	13.8	21.9	37.7	39.6	43.0	32.8	41.9	68.2	68.9	72.4
	5	4	24.3	30.8	34.5	35.3	39.6	25.5	32.0	37.1	38.4	43.8	52.1	57.0	65.7	66.1	70.1
		5	19.6	26.7	33.3	33.6	36.3	18.3	27.3	37.7	38.1	41.5	46.1	56.7	68.6	69.6	72.0
	Average		17.9	24.3	33.6	34.1	38.0	15.1	22.6	37.7	38.5	42.6	35.9	43.8	65.8	66.3	69.3
# of Radios = 50	3	2	9.9	16.1	28.3	28.6	32.2	8.9	16.3	37.1	37.2	41.3	30.3	38.5	64.4	64.4	67.2
		3	10.0	15.7	26.9	27.3	31.5	8.7	15.5	36.9	37.0	41.9	32.2	39.7	70.4	71.1	75.0
	4	3	15.4	21.3	26.2	26.8	31.1	16.8	22.3	32.8	33.5	38.5	44.1	48.2	63.7	63.7	69.7
		4	16.0	22.3	26.3	26.1	30.5	19.9	25.9	35.8	35.8	40.9	53.0	57.5	72.3	72.6	77.3
	5	4	18.5	24.7	27.0	27.7	32.1	26.1	31.1	34.3	35.5	40.8	66.2	68.4	73.4	73.9	76.6
		5	17.0	24.6	26.2	26.0	30.3	23.4	31.7	35.9	35.9	39.9	64.0	70.7	71.1	72.6	77.5
	Average		14.5	20.8	26.8	27.1	31.3	17.3	23.8	35.5	35.8	40.6	48.3	53.8	69.2	69.7	73.9

Table B.25: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 40 km, and the jamming distance is 20 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	18.2	20.0	24.2	24.2	29.3	19.1	21.9	31.0	30.0	38.2	48.8	53.1	59.6	60.3	64.1
		3	23.5	23.8	29.7	30.2	37.7	13.1	13.9	34.0	33.4	44.4	28.2	28.7	60.0	60.5	64.8
	4	3	22.5	23.7	27.5	28.5	35.0	19.9	21.0	34.8	37.3	44.0	45.1	47.1	63.5	64.2	72.1
		4	25.2	26.5	28.8	29.8	35.7	16.7	18.2	27.5	28.9	35.7	41.4	42.9	64.5	65.5	68.9
	5	4	23.2	24.3	26.3	27.2	34.2	25.6	27.1	33.6	35.3	43.1	59.3	59.7	66.2	67.7	74.4
		5	25.0	26.0	27.8	29.3	37.0	18.9	19.8	27.5	30.2	39.9	56.7	58.1	61.3	64.0	70.8
	Average		22.9	24.1	27.4	28.2	34.8	18.9	20.3	31.4	32.5	40.9	46.6	48.3	62.5	63.7	69.2
# of Radios = 30	3	2	7.6	8.4	14.9	15.1	19.1	6.9	7.5	23.9	24.1	30.6	25.5	26.1	43.4	39.5	50.5
		3	11.8	12.6	15.3	16.2	19.9	11.5	12.6	22.0	23.5	28.9	38.1	39.5	52.2	52.4	58.4
	4	3	14.0	14.8	16.2	16.9	22.7	19.4	20.8	24.3	24.9	33.9	55.7	56.6	61.1	61.1	69.5
		4	12.2	13.4	14.6	14.9	21.3	17.2	18.8	24.3	25.3	33.3	53.3	54.3	62.2	63.7	71.3
	5	4	16.3	17.2	17.9	17.9	27.8	25.0	26.0	28.9	30.0	40.4	63.8	64.3	68.8	70.2	77.8
		5	15.8	17.8	18.1	19.1	25.1	25.2	28.0	31.3	33.3	40.7	60.9	63.3	68.4	69.4	75.2
	Average		12.9	14.0	16.2	16.7	22.6	17.5	19.0	25.8	26.8	34.6	49.6	50.7	59.4	59.4	67.1
# of Radios = 40	3	2	9.7	10.4	11.4	11.7	16.4	18.6	19.9	22.2	22.4	30.3	60.8	61.8	64.9	65.2	71.4
		3	8.3	9.8	11.9	12.4	15.2	10.4	11.9	18.7	19.2	22.6	49.5	50.9	61.9	62.5	70.2
	4	3	15.8	17.0	16.6	17.6	24.3	28.8	30.2	30.3	31.8	40.5	71.3	72.2	74.0	74.2	81.7
		4	12.8	13.8	13.8	14.2	20.2	20.6	21.4	22.8	23.4	33.0	66.6	67.2	69.7	71.5	79.4
	5	4	17.8	18.5	20.2	20.5	29.6	31.1	32.1	36.2	36.4	47.6	78.8	79.3	81.3	82.2	88.4
		5	17.6	18.3	19.1	20.2	29.3	30.5	31.5	33.7	36.9	49.8	79.9	80.5	80.6	82.5	87.6
	Average		13.7	14.6	15.5	16.1	22.5	23.3	24.5	27.3	28.3	37.3	67.8	68.7	72.1	73.0	79.8
# of Radios = 50	3	2	9.7	10.5	11.7	12.2	18.5	19.7	20.7	22.4	24.5	35.1	65.1	65.9	67.8	68.1	75.3
		3	9.2	10.2	10.7	11.3	15.4	15.6	17.0	19.0	20.2	28.4	60.2	61.5	61.8	63.7	72.7
	4	3	15.4	15.9	18.7	19.0	25.5	30.9	31.4	36.5	37.2	47.2	78.6	78.8	80.3	81.0	86.8
		4	16.1	17.1	18.2	18.4	23.7	27.2	28.1	32.5	32.8	43.5	74.7	75.2	78.5	79.2	86.0
	5	4	20.2	20.9	22.9	24.7	36.5	38.9	39.6	42.4	44.9	61.2	82.6	83.2	84.5	85.1	91.3
		5	17.9	18.7	19.8	20.0	28.5	33.7	34.4	37.5	37.3	48.9	84.3	84.9	86.5	86.7	91.1
	Average		14.8	15.5	17.0	17.6	24.7	27.7	28.6	31.7	32.8	44.0	74.2	74.9	76.6	77.3	83.9

Table B.26: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 40 km, and the jamming distance is 30 km

	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)				
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE
# of Radios = 20	3	2	23.0	26.3	33.8	34.3	39.8	25.6	28.8	42.2	42.6	50.4	51.0	55.5	68.4	68.6	73.9
		3	24.0	25.7	37.0	39.3	44.8	11.8	14.4	42.1	44.9	70.0	28.5	32.3	62.4	62.1	67.8
	4	3	23.0	28.0	32.7	35.7	41.7	20.1	24.4	37.9	43.4	52.0	32.0	35.7	62.5	62.8	71.8
		4	28.0	31.3	37.7	38.3	42.8	19.0	23.4	36.9	38.5	44.9	55.8	60.5	69.6	69.6	78.4
	5	4	28.2	31.7	33.2	35.7	41.7	31.0	34.7	39.9	43.6	50.3	66.0	68.8	76.0	78.0	82.1
		5	30.3	34.2	36.3	38.2	43.8	26.7	31.5	35.5	38.9	48.3	60.7	67.1	69.7	72.4	78.1
	Average		26.1	29.5	35.1	36.9	42.4	22.4	26.2	39.1	42.0	49.3	49.0	53.3	68.1	68.9	75.3
# of Radios = 30	3	2	11.0	14.8	22.6	23.1	26.9	11.5	16.5	33.6	33.8	39.2	32.3	39.7	56.5	52.6	62.7
		3	11.7	15.6	21.6	22.8	27.6	12.5	16.9	31.8	34.0	39.9	44.2	47.7	63.2	64.5	70.4
	4	3	17.7	20.3	22.6	22.4	29.0	27.1	30.3	35.5	35.1	42.3	59.6	62.8	69.2	66.6	75.0
		4	13.8	16.8	20.2	21.7	25.9	17.9	21.1	30.1	32.9	36.8	51.4	55.2	67.0	69.1	72.6
	5	4	21.1	24.0	25.4	27.4	33.6	28.6	32.6	37.3	39.8	46.6	65.4	68.8	73.2	75.0	78.6
		5	18.2	21.3	23.7	25.0	29.0	28.4	32.3	37.3	39.9	43.7	65.6	69.3	73.6	74.2	77.7
	Average		15.6	18.8	22.7	23.7	28.6	21.0	24.9	34.3	35.9	41.4	53.1	57.3	67.1	67.0	72.8
# of Radios = 40	3	2	10.0	13.1	16.4	16.9	21.5	16.2	19.7	27.9	28.2	34.0	56.0	57.9	71.0	72.4	75.4
		3	12.3	16.3	17.8	18.2	23.1	18.3	23.4	26.8	27.5	34.4	59.3	63.8	70.3	72.0	77.1
	4	3	16.1	18.9	21.8	21.8	27.5	26.8	30.2	34.9	35.5	41.4	68.0	70.0	75.2	76.9	80.2
		4	14.8	18.9	21.4	21.8	26.3	24.3	29.5	34.0	34.0	41.4	72.6	76.2	79.1	80.1	84.6
	5	4	22.5	25.9	28.2	29.3	37.1	36.6	40.2	44.5	46.7	55.5	82.7	84.1	86.1	87.0	91.0
		5	20.5	25.4	26.2	26.6	34.4	35.5	40.9	43.3	44.9	53.3	80.5	82.7	84.9	85.8	89.5
	Average		16.0	19.8	22.0	22.4	28.3	26.3	30.6	35.2	36.1	43.3	69.8	72.4	77.8	79.0	82.9
# of Radios = 50	3	2	10.9	15.4	17.6	17.7	22.9	20.8	25.5	30.6	30.6	37.7	65.6	70.3	72.5	72.5	78.1
		3	10.3	15.2	18.1	18.3	22.7	18.8	25.4	31.8	32.2	38.3	61.4	68.6	72.2	72.5	78.1
	4	3	17.9	21.3	23.2	23.4	27.8	33.1	37.4	41.8	41.6	46.9	76.6	79.1	81.2	81.6	85.2
		4	18.4	21.1	22.3	22.8	28.3	31.1	34.6	39.4	40.5	48.6	78.2	79.9	82.0	83.3	89.4
	5	3	25.7	28.5	30.5	31.4	39.4	43.2	46.3	50.5	52.1	61.6	87.1	88.4	89.0	89.3	93.1
		4	23.1	26.4	26.1	27.0	33.1	40.8	43.5	44.6	46.1	53.8	85.5	86.7	88.0	88.7	92.8
	Average		17.7	21.3	23.0	23.4	29.0	31.3	35.4	39.8	40.5	47.8	75.7	78.8	80.8	81.3	86.1

Table B.27: Comparative results of BM, BM+, MM, MME, and CLE when the field size is 200 km², the communication distance is 40 km, and the jamming distance is 40 km

# of Radios = 20	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)					
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	
	3	2	23.5	31.2	40.5	40.7	47.8	29.7	36.3	51.6	51.0	56.2	51.1	56.6	73.7	73.3	81.0	
		3	21.0	25.8	46.5	46.7	52.2	9.3	15.1	51.7	51.7	57.2	17.2	23.6	67.2	68.8	77.3	
	4	3	27.2	35.0	43.8	45.2	53.0	27.6	38.5	52.7	54.7	61.7	52.2	64.0	82.5	84.5	89.8	
		4	28.5	33.2	42.7	44.2	49.5	18.1	23.7	42.2	43.9	52.6	47.0	49.9	66.6	68.3	75.9	
	5	4	33.0	40.0	44.7	46.0	52.8	34.4	40.9	49.9	50.8	57.8	64.5	69.9	79.2	79.7	83.1	
		5	31.2	38.7	39.8	45.3	48.8	28.8	35.8	43.7	49.6	56.4	60.7	66.4	74.5	75.3	81.6	
	Average			27.4	34.0	43.0	44.7	50.7	24.6	31.7	48.6	50.3	57.0	48.8	55.1	73.9	75.0	81.4
# of Radios = 30	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)					
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	
	3	2	11.1	17.2	30.7	30.3	35.0	11.5	20.2	43.6	43.8	48.5	39.2	46.7	69.6	68.5	70.7	
		3	13.1	18.4	28.2	29.2	35.3	14.7	20.8	40.3	41.7	48.2	40.2	45.8	71.7	73.4	77.8	
	4	3	20.6	25.1	27.8	30.0	33.4	27.6	31.7	37.0	40.3	44.5	58.5	62.5	70.8	72.1	76.8	
		4	17.6	23.4	25.1	28.1	32.1	26.1	31.5	36.1	41.3	44.0	56.7	62.5	71.1	74.2	77.9	
	5	4	20.6	26.7	28.2	30.7	34.9	32.5	39.5	41.9	44.6	49.9	67.0	71.6	74.4	76.1	78.9	
		5	22.2	31.2	33.4	34.6	40.4	31.8	41.5	45.9	48.2	54.6	69.4	74.8	78.4	80.0	84.4	
	Average			17.5	23.7	28.9	30.5	35.2	24.1	30.9	40.8	43.3	48.3	55.2	60.7	72.7	74.1	77.7
# of Radios = 40	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)					
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	
	3	2	12.5	19.5	24.8	25.1	31.1	21.1	28.4	38.7	39.1	46.3	61.6	67.7	75.4	75.3	79.2	
		3	13.4	20.0	23.1	23.3	27.1	19.9	27.3	33.0	33.6	39.5	61.8	67.3	74.9	76.4	82.6	
	4	3	17.6	23.3	27.7	27.8	33.3	29.3	36.2	44.0	44.0	49.0	70.8	75.4	81.1	80.9	86.3	
		4	18.0	23.3	25.3	25.3	29.5	26.3	31.1	35.4	35.9	42.7	71.7	75.6	79.1	80.2	84.9	
	5	4	23.5	28.7	33.5	33.7	41.3	36.7	41.3	50.1	50.8	57.9	80.9	83.1	87.2	87.3	90.7	
		5	25.8	36.2	37.8	38.5	44.5	41.2	50.8	55.0	56.1	63.2	83.8	88.9	92.0	92.6	95.2	
	Average			18.5	25.1	28.7	28.9	34.5	29.1	35.9	42.7	43.2	49.8	71.8	76.3	81.6	82.1	86.5
# of Radios = 50	# of Base Cluster	# of Unj. Cluster	Node Success Rate (%)					Link Success Rate (%)					Indirect Com. Success Rate (%)					
			BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	BM	BM+	MM	MME	CLE	
	3	2	12.5	20.7	23.6	23.5	28.5	23.4	34.0	38.2	38.3	45.0	66.7	73.1	77.8	78.1	83.3	
		3	13.6	20.5	24.1	24.5	28.1	22.1	30.7	38.9	39.6	44.2	65.6	72.0	77.6	78.0	81.0	
	4	3	21.7	27.6	31.4	31.8	38.6	36.8	42.9	49.7	50.0	57.4	79.9	82.8	86.7	87.1	89.7	
		4	19.5	25.9	27.0	27.5	32.8	33.5	39.1	43.5	44.2	50.2	80.2	82.7	84.7	84.9	88.9	
	5	3	26.3	32.4	36.1	36.9	44.2	43.6	49.0	55.0	55.0	63.7	86.9	89.3	91.2	91.7	94.2	
		4	26.6	34.2	37.1	38.2	44.4	44.3	51.5	58.1	59.3	66.0	88.5	90.9	92.9	93.2	95.3	
	Average			20.0	26.9	29.9	30.4	36.1	33.9	41.2	47.2	47.7	54.4	78.0	81.8	85.2	85.5	88.7