OPTIMUM JAMMER DEPLOYMENT

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ABSTRACT

OPTIMUM JAMMER DEPLOYMENT

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Jamming systems are critical in electronic warfare scenarios aimed at disrupting target communication networks. This thesis develops a comprehensive method for optimizing the placement of jamming systems. A mathematical model is proposed to maximize the Line-of-Sight between systems and target areas while enhancing signal strength at these locations. Additionally, the model aims to minimize the risk of detection by enemy systems. Practical applicability is ensured by incorporating constraints such as geographical accessibility, terrain obstacles, and deployment feasibility into a topological map. The study investigates stationary and mobile jamming systems against both stationary and mobile targets.

Furthermore, the thesis study explores power allocation optimization for jamming systems, integrating this process with topological maps to enhance operational effectiveness. The objective is to minimize the likelihood of detection while maximizing jamming performance.

Another focus is optimizing jammer placement to disrupt self-localization capabilities in target communication networks. While existing studies address this problem in two-dimensional space, this thesis extends it to three-dimensional scenarios, offering a novel approach to jammer deployment.

The findings improve the effectiveness of electronic warfare operations by disrupting enemy communications and providing strategic advantages. The proposed optimization method minimizes jammer usage while ensuring effective coverage and optimizing resource allocation. Comprehensive simulations and constraints provide tools for informed military decision-making and adaptability to dynamic battlefield conditions. This thesis makes significant contributions to academic literature and practical military applications in electronic warfare, combining theoretical innovation with real-world applicability.

Keywords: Jammer Placement, Optimization, Line-of-Sight, Power, Signal Level.

ÖZ

EN UYGUN SİNYAL BOZUCU YERLEŞİMİ

Yiğit, Atakan
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği
Tez Yöneticisi: Prof. Dr. Mehmet Kemal Leblebicioğlu

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Karıştırma sistemleri hedef haberleşme ağlarını için elektronik harp senaryolarında önemli bir yer tutmaktadır. Bu tez, karıştırma sistemlerinin yerleşim optimizasyonu için kapsamlı bir yöntem geliştirmeyi amaçlamaktadır. Çalışmada, karıştırma sistemlerinin elektronik harp alanında etkili bir şekilde konuşlandırılması için matematiksel bir model sunmaktadır. Bu model, sistemlerden hedef bölgelere oluşan görüş alanını ve bölgelerdeki sinyal seviyelerini arttırmayı amaçlamaktadır. Ayrıca, oluşturulan model karıştırma sistemlerinin düşman sistemler tarafından tespit edilme riskini düşürmeyi hedeflemektedir. Modelin pratik uygulanabilirliğinin arttırılması adına topolojik harita üzerinde; coğrafi erişim, arazi engelleri, konuşlanma kolaylığı gibi kısıtlar da incelenmiştir. Çalışma kapsamında sabit ve hareketli karıştırma sistemleri, sabit ve hareketli hedefler karşısında incelenmiştir.

Tez kapsamında, karıştırma sistemlerinin güç tahsisi optimizasyonu üzerine de çalışılmıştır. Bu çalışma da pratik uygulanabilirliği arttırmak adına topolojik harita üzerinde gerçekleştirilmiştir. Ayrıca, güç optimizasyonu ile hedef sistemler tarafından tespit edilme ihtimalinin en aza indirgenmesi amaçlanmıştır.

Haberleşme ağlarındaki elemanlar, haberleşme sürecinde kendi konumlarını ağdaki diğer sistemler ile paylaşmaktadır. Bu tez çalışmasında, hedef haberleşme ağlarının kendi konumlarını bulmalarını engelleyecek şekilde karıştırma sistemlerinin yerleşim optimizasyonu da çalışılmıştır. Bu problem için literatürde bulunan birçok çalışma iki boyutlu senaryolarda sürdürülürken bu tez kapsamında üç boyutlu uzayda yerleşim çalışmaları yapılmıştır.

Tez bulguları, elektronik harp operasyonlarının etkinliğini artırarak düşman iletişimlerini bozmayı ve stratejik avantaj sağlamayı hedeflemektedir. Geliştirilen optimizasyon yöntemi, daha az jammer kullanımıyla etkili kapsama sağlama olanağı sunarak kaynak kullanımını optimize etmektedir. Çalışma, senaryolar ve kısıtlar üzerinde kapsamlı simülasyonlar yaparak, askeri alanlarda daha bilinçli kararlar alma ve savaş alanı koşullarına uyum sağlama konusunda değerli bir araç sunmaktadır.

Anahtar Kelimeler: Karıştırıcı Yerleşimi, Optimizasyon, Görüş Hattı, Güç, Sinyal Seviyesi.

Ad Augusta Per Angusta

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
EW	Electronic Warfare
ES	Electronic Support
EP	Electronic Protection
EA	Electronic Attack
SNR	Signal-to-Noise Ratio
UAV	Unmanned Aerial Vehicles
ABC	Ant Bee Colony
GA	Genetic Algorithm
DTED	Digital Terrain Elevation Data
OSM	Open Street Map
LOS	Line-of-Sight
GIS	Geographic Information System
RF	Radio Frequency
dB	Decibel
ITU	International Telecommunication Union
NLOS	Non-Line-of-Sight
m	Meter
dBm	Decibel Miliwatts
PSO	Particle Swarm Optimization

MPSO	Modified Particle Swarm Optimization
W	Watt
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
TOA	Time-of-Arrival
RSS	Received Signal Strength
CRLB	Cramer-Rao Lower Bound
FIM	Fisher Information Matrix
2D	Two-Dimensional
3D	Three-Dimensional

CHAPTER 1

INTRODUCTION

In the contemporary battlefield, Electronic Warfare (EW) Systems are starting to gain importance with the contribution of developing technologies, and the ability to disrupt enemy communications is a critical element of these systems.

In a military application, Electronic Warfare uses electromagnetic energy to detect and prevent hostile use of the electromagnetic spectrum [1]. Electronic jamming is a technique in electronic warfare in which jammers emit signals that interfere with an enemy's radars and block the receivers with highly concentrated energy signals. Jammers are primarily used to block radio signals.

As military operations increasingly require complex communications networks, the ability to jam or interfere with these networks can provide significant tactical advantages [2]. Jammers, devices designed to emit signals that block or degrade enemy communication channels, are central to this effort. However, the success of jamming operations is not only a function of the deployment of jammers but also depends on the strategic optimization of their placement and the number of units used. Effective deployment ensures that enemy communications are sufficiently disrupted while minimizing resource expenditure and operational risk.

1.1 Structure of Electronic Warfare and Jamming Event

Electronic Warfare is separated into three parts. These are Electronic Support (ES), Electronic Protection (EP), and Electronic Attack (EA) events [3]. ES is an action that involves detection, recognition, and response to friendly and enemy units by performing a search, identification, and blocking of the enemy’s electromagnetic radiation [3]. EP is an action that protects electronic vehicles, communication, infrastructure, and military equipment from any effects of the electromagnetic spectrum [3]. EA is an action that uses electromagnetic energy, especially radio waves and radar frequencies, directed energy, or anti-radiation weapons to attack the enemy’s facilities and equipment, thereby reducing its intelligence-sharing capabilities and preventing its electronic communication [3]. This offensive approach involves targeting multiple enemy radars and communication systems. EA employs varied tactics, and jamming is one of them. It involves transmitting undesired signals to enemy receivers to degrade the enemy's access to critical information.

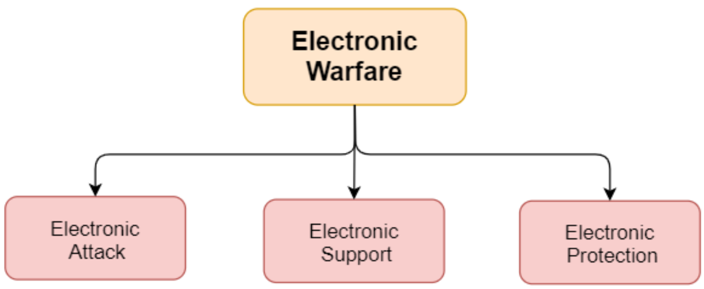

Figure 1.1. The Concept of Electronic Warfare

Jammer systems can be adapted to perform different types of jamming strategies for various needs in electronic warfare systems [4]. Barrage jamming and spot jamming are the main noise jamming strategies. Barrage jamming involves transmitting a wideband noise signal across a range of frequencies [5]. Spot jamming focuses on a narrow frequency band, targeting specific enemy communication channels [6]. It is also possible in spot jamming that the jamming signal is rapidly swept across a range of frequencies, which is called sweep jamming [7]. Furthermore, jammer transmission can be continuous or periodic in spot jamming. In continuous jamming, usually, there is one target and a single frequency band, and the jamming process continues until stopped by the operator. If multiple frequency bands are defined, jamming is performed by switching between frequencies. Periodic jamming is a cyclical jamming type performed with receive and transmit phases [8]. Frequency detection is made for a certain period of time; after the detection, the receiver transmits its detections to the jamming unit, and the frequency is jammed. Other than noise jamming, deceptive jamming involves mimicking or altering the enemy's signals to confuse or mislead their communication or radar systems [9]. These jamming strategies are usually used proactively. Reactive jamming has similar logic to proactive periodic jamming, but it is also expected to react at high speed, so it can provide extra flexibility by offering a way for jamming systems to move between different frequency bands [10].

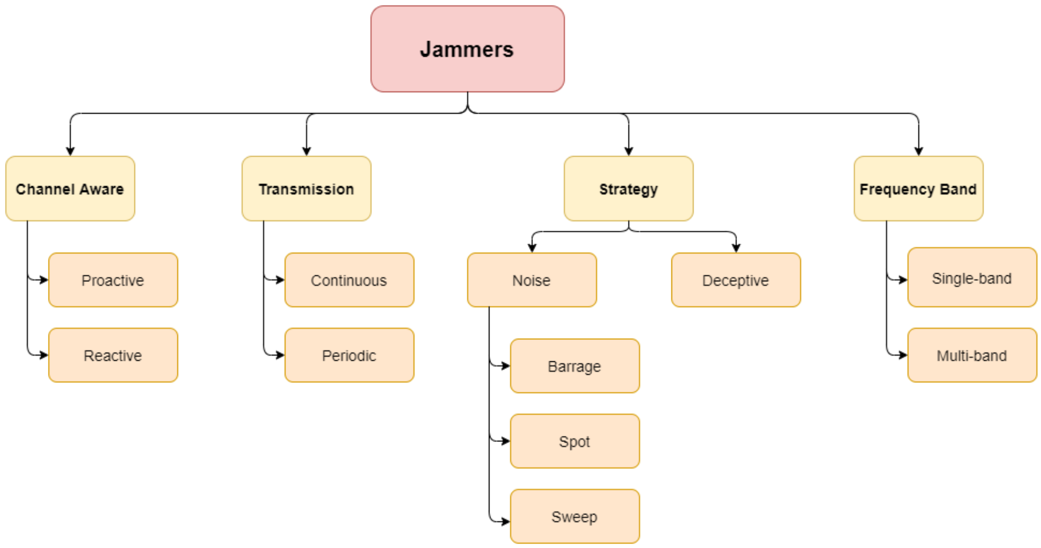

Figure 1.2. Types of Jamming Events

The effectiveness of a jamming operation is not solely determined by the presence of a jammer but by how accurately and successfully it can disrupt the enemy's communication or radar systems. Several factors contribute to the accuracy and success of a jamming event, each influencing the overall outcome of the operation. Understanding these factors is crucial for optimizing jammer deployment and ensuring that the intended targets are effectively neutralized. Jamming coverage, a geographical area within which the jammer can effectively disrupt enemy signals, is influenced by the jammer's power, antenna design, and environmental factors such as terrain and atmospheric conditions. Successful jamming requires ensuring that all critical enemy targets are in the operational area within the jammer's coverage. Also, the success of a jamming event is often measured by the reduction in the enemy’s Signal-to-Noise Ratio (SNR) [11]. A jamming signal is successful when it increases the noise level at the enemy receiver to the point where the desired communication signal is no longer intelligible. The jamming signal must be strong enough to dominate the enemy's signal within the target area. One requirement of the jamming process is that the jammer’s transmission frequency matches the enemy’s communication or radar frequency. Mismatches can lead to ineffective jamming, as the enemy might be able to shift to another frequency or continue operating unaffected. For mobile jammers, the timing of the jamming event relative to the enemy's communication cycles is crucial. Accurate timing ensures that the jammer disrupts the enemy at the most critical moments, such as during data transmission or radar scanning.

1.2 Literature Overview

In history, jamming in the electronic warfare concept started with the Russo-Japanese War of 1904. The Japanese army used jamming techniques to prevent Russia’s intelligence information. For the first time in history, electronic warfare and electronic jamming were used in this war to jam radio signals [12].

During World War I, the German army began to develop encryption techniques to protect the content of its communications against jamming and intelligence activities after it was forced to use radio and telegraph. Besides, the French army and the British army were simulating the electromagnetic signals used by German bombardment and navigation zeppelins [13].

In World War II, the world's first known radar warning receiver, Metox FuMB1, was used on the German ship Bismarck, which was tasked with intercepting British ships [14]. Furthermore, In World War II, the German naval operation called Channel

Dash jammed the radars set up by the British to control the English Channel in 1941 [15].

During the Cold War, NATO and the Warsaw Pacts turned to Electronic Jamming methods, the most important weapon of this war. The Russians put more than a thousand jamming stations into service to neutralize the American-centered broadcasts made in the Eastern Bloc countries. As a precaution, the West started Electronic Intelligence activities and established signal intelligence centers [16].

After these paramount wars, the effect of electronic warfare and electronic jamming on the course of the war was realized, and it continued to be used as an effective weapon in all the wars in the following years. This crucial effect made the electronic jamming concept more important in academic studies. On the other hand, some of the developments in the field of electronic warfare have been based on academic research about electronic jamming.

There are many studies on the different concepts of EW. Jamming events and effectively interrupting communication between enemy forces are important topics in the literature. Therefore, optimization studies have been conducted on the concept of effective jamming. One of the study topics is jamming architecture. The jamming architecture can be arranged for cognitive electronic warfare networks. In this network, the architecture is designed against unknown threat targets using game-based approaches [17]. Furthermore, there are decision-making studies for the jamming types. The studies for jamming types consider the cognitive electronic warfare scenarios and find the optimum jamming technique to maximize the effectiveness [18]. Although the initial studies to increase effective jamming focused on the radar targets, jamming of communication and intelligence networks is also crucial for the electronic warfare areas [19]. Moreover, the focus on these networks also paves the way for studying the networks that are assisted by Unmanned Aerial Vehicles (UAV) [20].

In addition to the jamming architecture and types, there are studies for the jamming effectiveness parameters. One of these parameters is received signal power. If the signal power is greater at the enemy receivers, then the jamming effectiveness is better [21]. Moreover, the Line-of-Sight (LOS) parameter is also considered in the literature. A channel between a transmitter and a receiver is highly dependent on the LOS between these electronics. Therefore, a clear LOS leads to better jamming at the enemy target receivers [22]. Another parameter is also the risk of detection by the enemy forces. The jammer action ceases when it is detected by the enemy forces. The jamming deployment is considered in two ways: on the attacker's side and on the other network [23]. Therefore, an attacked model can be improved by considering the risk of detection by the network [24].

In addition to the importance of the parameters, some studies use these parameters to select the locations of the jammers to maximize jamming effectiveness. The jammers can be located in the predefined grids to maximize the LOS coverage and jamming effectiveness [25]. However, the deployment of jammers through the grids may not give an optimal solution for every case. Therefore, the studies focus on the deployment of the jammers with stochastic methods. As a result, different types of optimization algorithms are studied for this problem, such as Ant Bee Colony (ABC) and Genetic Algorithm (GA) [26], [27]. In addition to these algorithms, machine learning models are studied in order to increase the effectiveness of jamming events [28]. These studies mostly focus on the aircraft jamming platforms such as Unmanned Aerial Vehicles [29]. However, the electronic warfare area may not allow the aircraft jamming platforms due to the enemy electronics. Therefore, the optimum deployment of stationary jammers and mobile jammer platforms such as trucks gain importance in this context. This thesis provides solutions for different types of problems for different jammers and target types.

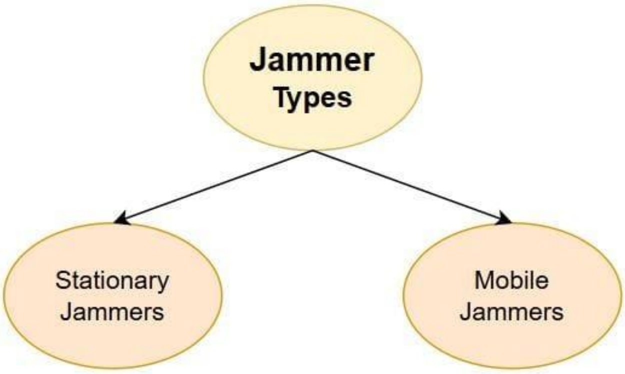

Figure 1.3. Types of Jammers

In the studies, the jammers are divided into two parts: stationary jammers and mobile jammers.

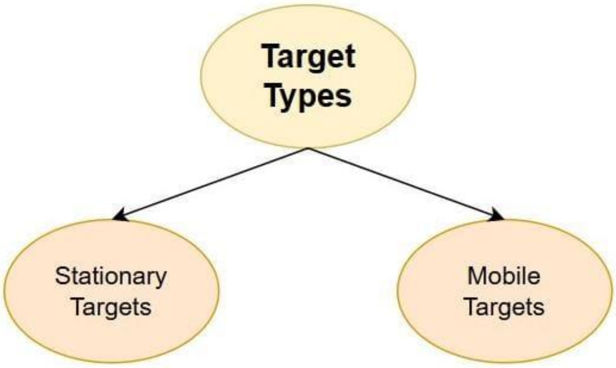

Figure 1.4. Types of Targets

The thesis problems include two types of targets: stationary targets and mobile targets.

In addition to the different types of jammer and target considerations, the thesis studies include real-world topological data, road map data, environmental data, and target parameters such as antenna height and receiving sensitivity. Therefore, these real-world variables are taken to the optimization process as prior knowledge. The optimization algorithm considers different types of well-defined parameters such as LOS, jamming signal level, and the risk of detection by enemy forces. These parameters are used to maximize the jamming effectiveness for the different thesis problems.

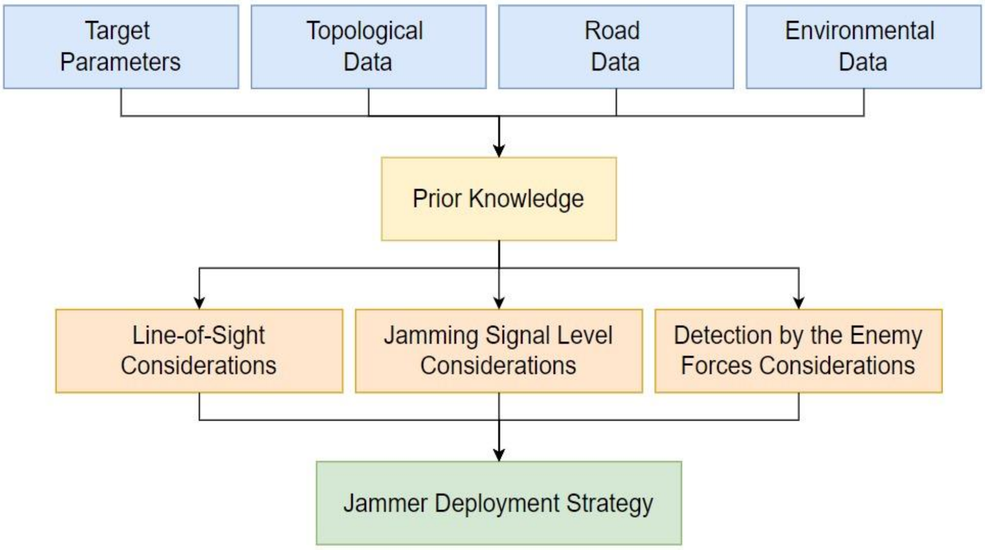

Figure 1.5. The Flow of Optimization Process

1.3 Research Contributions and Novelties

This thesis presents a comprehensive and robust optimization framework for electronic jammer deployment in diverse electronic warfare scenarios, addressing the challenges outlined in Problems 1, 2, 3, and 4. By introducing a mathematical model that integrates key considerations such as LOS, signal strength, and detectability by enemy forces, the study ensures that jammers are optimally positioned to maximize their effectiveness while minimizing the risk of detection. Beyond theoretical modeling, the thesis incorporates practical constraints, including terrain accessibility, deployment efficiency, and the presence of physical obstacles, making the findings highly applicable to real-world scenarios. Furthermore, to the best of the author's knowledge, there are no existing studies on jammer placement optimization that utilize real-world topological data, such as digital terrain elevation data (DTED). This unique aspect strengthens the practical relevance of the proposed methodology. Additionally, a novel approach is proposed to prioritize target areas based on their strategic importance, allowing for focused jamming operations at critical locations and enhancing overall operational effectiveness. The study addresses both stationary and mobile systems, highlighting challenges such as the role of road networks and real-time deployment in dynamic environments for mobile jammers.

A key contribution of this thesis, as outlined in Problem 5, is the development of an optimization strategy that simultaneously considers power allocation and jammer placement to disrupt enemy communications. While power allocation optimization has been explored in existing literature, no prior studies combine it with optimal jammer placement. The proposed model integrates LOS, signal strength, detectability by enemy forces, and transmitting power into a unified framework, addressing a significant gap in the field. By doing so, the study ensures not only the effectiveness of jamming but also resource-efficient operations, which are critical in resource-constrained environments.

Another novel aspect of the thesis, covered in Problem 6, is the focus on jammer placement optimization against self-localization systems. While a similar problem has been studied in the literature [30], previous research has been limited to two-dimensional optimization. This thesis extends the problem to three dimensions, offering a more realistic and comprehensive solution. To the best of the author's knowledge, this is the first study to address optimal jammer placement against self-localization systems in three-dimensional space. This contribution is critical in advancing the understanding and practical application of jamming strategies against emerging technologies like self-localization systems.

This research has significant implications for both military strategy and the broader domain of electronic warfare. By optimizing jammer deployment, the study directly enhances the effectiveness of electronic warfare operations, providing a decisive advantage in disrupting enemy communications. The findings demonstrate how the number of jammers required for effective coverage can be minimized, promoting resource efficiency, especially in resource-constrained environments. The development of a comprehensive optimization framework equips military planners with a valuable tool for decision-making. The ability to simulate various scenarios and constraints enables more informed and strategic choices in jammer deployment while addressing real-time operational challenges for mobile jammers and enhances the adaptability of these systems in dynamic battlefield conditions.

In summary, this thesis makes significant contributions to the academic literature on electronic warfare by introducing new methodologies and models for optimizing jammer deployment against communication networks and self-localization systems. By bridging the gap between theory and practice, it provides actionable insights and practical solutions that can be directly implemented in military operations, improving the flexibility, efficiency, and effectiveness of electronic warfare strategies.

1.4 Organization of the Thesis

This thesis focuses on optimizing the deployment of jammers to maximize the disruption of enemy communication systems in electronic warfare scenarios. The core of this optimization problem is to determine the optimal locations such as latitude and longitude, and the number of jammers required to achieve the desired jamming effect.

In this thesis, real-world data is used to make the study more applicable. In Chapter 2, the models and methods, as well as the data used in the thesis, are explained. These are the Digital Terrain Elevation Data (DTED) and road map data (OSM). In addition, the study considers three critical factors: LOS, signal level, and danger level, namely, detection by the enemy forces. These three concepts are also provided in this chapter in detail.

In Chapter 3, the most basic version of the thesis problem is studied. The problem in this chapter is named “Problem-0” since it is the basic version; namely, it focuses on placing the jammers into the predefined available positions. In this section, the problem definition, problem formulation, and solution technique for this problem are discussed. At the end of this chapter, the section for simulations and results is published.

In Chapter 4, the first main problem of the thesis study is published. The problem in this chapter is named “Problem 1”. In this problem, the study focuses on finding the best stationary jammer locations against stationary targets so that the jamming effectiveness is maximized. In this chapter, the problem definition, problem formulation, and solution technique are discussed. At the end of this chapter, many simulations are conducted, and the results of these simulations are demonstrated.

In Chapter 5, the second problem of the thesis study is published. The problem focuses on the mobile jammers and stationary targets and is named “Problem 2”. In this chapter, the differences between stationary and mobile jammers against stationary targets are discussed in the problem definition and problem formulation sections. In the solution technique section, the additional solution steps are defined. At the end of this chapter, the simulation results that are obtained in “Problem 1” are used as the simulation scenarios. Therefore, the simulations and results section is studied to show the differences between stationary jammers and mobile jammers for the optimal jammer deployment problem.

In Chapter 6, the third problem of the thesis study is published. This problem focuses on the stationary jammers against mobile targets, and it is named “Problem 3”. In this chapter, there are problem definition, problem formulation, solution technique, and simulations and results sections, similarly. In the problem definition and problem formulation sections, the similarities and differences between the previous problems are discussed. In the solution technique, the additional steps for the previous solutions are defined. At the end of the chapter, the simulations and results are published so as to investigate the performance of the solution algorithm for this problem.

In Chapter 7, the fourth problem of the thesis study is published. This chapter focuses on the mobile jammers against mobile systems and is named “Problem 4”. Similarly, this chapter includes problem definition, problem formulation, solution technique, and simulations and results sections. These sections define the problem in a verbal and mathematical way. In addition, the simulations and results section demonstrates the robustness and effectiveness of the proposed solution for this problem.

In Chapter 8, a new problem is introduced. The previous problems focused on disrupting the enemy communication networks by considering LOS, signal strength, and detectability by enemy forces. Power allocation is introduced to this problem. Therefore, this section aims to find the optimal jammer locations with the minimum number of jammers and optimal transmit power level. The problem definition and problem formulation sections define the problem in detail. The solution technique section improves an algorithm that also considers power allocation.

In Chapter 9, the last problem of the study is introduced. Unlike the other problems, this problem does not focus on disrupting the enemy communication networks. This problem aims to study for the communication systems which have the self-localization capability. A similar structure is kept in this chapter. The problem definition and problem formulation sections define the problem. In the solution technique section, a mathematical and geometrical solution is introduced. This solution includes propositions and develops an algorithm; therefore, these propositions and algorithms are defined in this section. At the end of this chapter, the simulations and results that show the requirements of different propositions are investigated.

In Chapter 10, the conclusion of the study is mentioned, and the future works are discussed. In addition, the Appendix section provides explanations of the different techniques that are used in the study.

CHAPTER 2

MODELS AND METHODS

In the optimization of jammer deployment for electronic warfare, understanding the underlying mechanisms that govern the behavior of electromagnetic signals is crucial. This section delves into two foundational concepts: Line-of-Sight and Signal Propagation Models, both of which are intimately connected to terrain data, particularly DTED. These models form the bedrock of effective jamming strategies, as they directly influence the ability of jammers to disrupt enemy communications. LOS determines whether a jamming signal can physically reach its intended target without obstructions, a determination that relies heavily on accurate terrain representation provided by DTED. Signal propagation models, on the other hand, predict how the signal will travel through various environmental conditions and terrains, again using DTED to account for the impact of terrain features. Together, these concepts, underpinned by DTED, are essential for designing jamming operations that are both powerful and precise, ensuring that jammers are placed in positions that maximize their impact while minimizing the risk of detection. By exploring these models in detail, this section aims to provide a comprehensive understanding of how electromagnetic signals behave in complex environments, laying the groundwork for the development of advanced jamming solutions.

2.1 Digital Terrain Elevation Data

Digital Terrain Elevation Data is a widely used format for representing the Earth's terrain in digital form, particularly for applications requiring precise topographical information. In this thesis, DTED plays a crucial role in accurately modeling the terrain, which is fundamental for optimizing the deployment of jammers in electronic warfare scenarios.

2.1.1 Overview of DTED

DTED is a raster-based elevation model used to describe the Earth's surface at a consistent spatial resolution. Each data point in a DTED file represents the elevation of the terrain at a specific geographic location, usually given in meters above mean sea level. The data is structured in a grid format, where each grid cell corresponds to a fixed geographical area, allowing for efficient processing and analysis [31].

The DTED standard was developed by the U.S. Department of Defense and is categorized into different levels of detail, typically known as DTED Level 0, Level 1, and Level 2 [32]:

- DTED Level 0: Provides a coarse resolution, typically with a post spacing (distance between elevation points) of approximately 1 kilometer. This level is useful for broad, large-scale analyses where fine detail is not necessary.
- DTED Level 1: Offers a medium resolution with a post spacing of approximately 100 meters. It is suitable for most military applications that require a balance between data volume and terrain detail.
- DTED Level 2: Provides a high resolution with a post spacing of approximately 30 meters. This level is often used in mission planning and operational scenarios where accurate terrain representation is critical.

2.1.2 Importance of DTED in Jammer Deployment

In the context of this thesis, DTED data is indispensable for several reasons [33]:

- Line-of-Sight Analysis: DTED data is essential for conducting LOS analysis between the jammer positions and the target areas. The LOS analysis requires an accurate representation of the terrain to determine whether there are any obstructions, such as hills or mountains, between the jammer and the target. The elevation data from DTED allows for precise calculation of these obstructions, ensuring that jammers are placed in positions where they can effectively transmit signals without being blocked by terrain features.

- Signal Propagation Modeling: Signal propagation models, which predict how radio waves travel over the terrain, rely heavily on accurate elevation data. DTED allows for the modeling of the signal's path as it is influenced by the terrain's contours, leading to more accurate predictions of signal strength at various target locations. This is particularly important in scenarios involving hilly or mountainous regions, where the terrain can have a significant impact on signal behavior.
- Terrain Accessibility: For mobile jammer systems, such as those mounted on trucks, DTED data is used to assess the accessibility of potential deployment locations. Steep slopes or rugged terrain may limit the ability of ground vehicles to reach certain areas, and these factors must be considered in the optimization process. DTED data provides the necessary information to evaluate and avoid such inaccessible areas during the planning phase.
- Deployment Simulation: DTED data enables the simulation of different deployment scenarios by providing a realistic representation of the terrain. This allows for the testing of various jammer placements and the evaluation of their effectiveness in a simulated environment before actual deployment.

2.1.3 Processing and Integration of DTED

In this study, DTED data is processed and integrated into the optimization algorithm as follows [34]:

- Data Acquisition: DTED files are obtained from relevant sources, typically in the form of binary or ASCII files that can be read by Geographic Information System (GIS) software or specialized terrain analysis tools.

- Data Preprocessing: The DTED data is preprocessed to align with the geographic coordinate system used in the optimization model. This may involve reprojecting the data, resampling it to match the resolution requirements, and cropping it to the area of interest.
- Incorporation into the Model: The elevation data from DTED is incorporated into the line-of-sight and signal propagation models, as well as any accessibility assessments. During the optimization process, the DTED data is queried to obtain elevation information for any given point within the study area.
- Visualization: The processed DTED data is also used to visualize the terrain in 3D, allowing for better interpretation of the results and more intuitive planning of jammer deployment strategies.

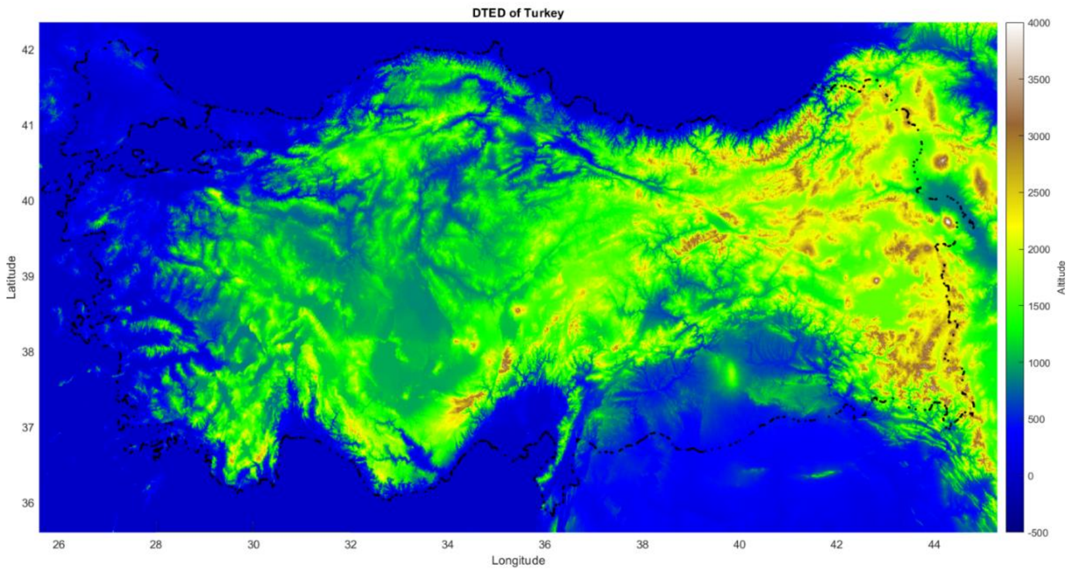

Figure 2.1. DTED Visualization of Turkey

2.2 Road Map Data

OpenStreetMap (OSM) is a collaborative project aimed at creating a free, editable map of the world. Similar to how DTED provides crucial topographical information, OSM data focuses on providing detailed geospatial information such as road networks, land use, building footprints, waterways, and other geographical features. The data is collected and maintained by a community of volunteers using GPS devices, aerial imagery, and other free sources, ensuring its availability and accessibility to a wide range of users [35].

In this study, OSM data plays a key role in defining road networks and operational boundaries, particularly in optimization problems that involve mobile systems such as jammer deployment. The road infrastructure extracted from OSM is essential for determining optimal paths for jammer movement and deployment logistics. The integration of OSM data allows the algorithm to evaluate road proximity and connectivity within feasible operational areas, enabling more efficient and practical movement of assets.

Unlike DTED, which provides elevation data and is crucial for determining terrain and LOS in communication systems, OSM data focuses more on human-made infrastructure such as roads, buildings, and boundaries. However, both datasets complement each other: OSM helps identify navigable routes for deployment, while DTED helps assess the terrain's impact on signal propagation.

By utilizing OSM in conjunction with DTED, this study ensures that both logistical and topographical factors are considered when optimizing jammer positions and movements, providing a comprehensive view of the operational environment. The open-source nature of OSM also means that it can be continuously updated and customized to fit the specific needs of the study [36].

After OSM data is extracted, it can be integrated into the study via Matlab. In this study, OSM data is used with DTED since the topographical map and roads are crucial parts of the optimization problems and models. So as to integrate the OSM data into DTED, the interpolation is conducted. Therefore, the sampling point of OSM data is matched with DTED. As a result, the roads are imported into the study with their topographical information. Throughout the thesis, the roads are visualized by black lines.

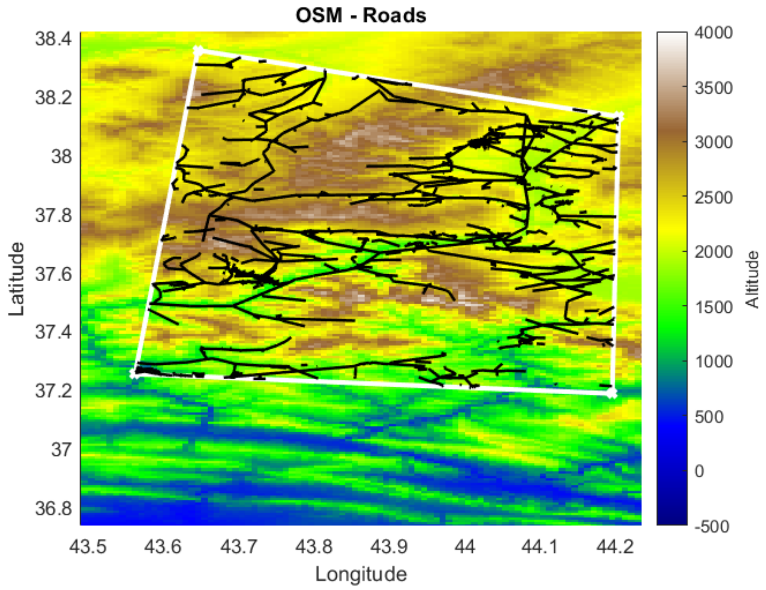

Figure 2.2. OSM Road Integration Visualization

2.3 Line-of-Sight

Line-of-Sight refers to the unobstructed straight path between two points in space, typically between a transmitter and a receiver, or in the case of electronic warfare, between a jammer and its target. For effective communication or signal transmission, the line of sight must be clear of any physical obstructions, such as buildings, trees, or terrain features, that could block or weaken the signal [37].

In the context of radio frequency (RF) communication, LOS is crucial because it ensures that the transmitted signal can reach the receiver directly without being diffracted, reflected, or absorbed by obstacles. Making a clear line of sight is essential for strong and reliable communication or jamming effectiveness [37].

There are many different uses of LOS in the literature [38]. In this study, LOS is not used in binary format; for example, LOS is one if there is a direct path between the jammer and target. Instead of this kind of usage, the LOS criteria are used as follows;

- The altitude information of the jammer location is found.
- A line is drawn between the jammer location and the target point (area).

- The altitude levels on this line are found.
- If there is no obstacle between the jammer location and the target point, LOS is taken as 0.
- If there is an obstacle between the jammer location and the target point, LOS is taken as the minimum required height for the jammer location so that there are no obstacles.

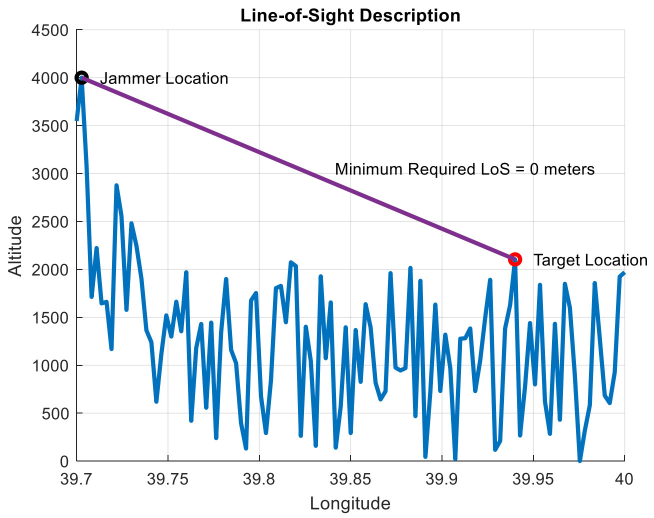

Figure 2.3. Clear Line-of-Sight Example

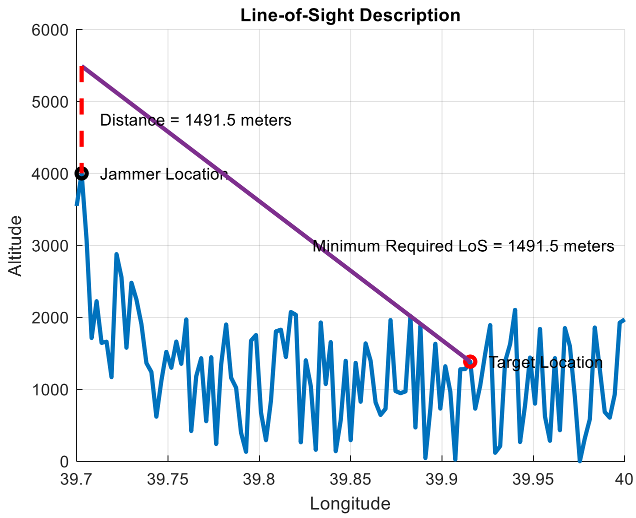

Figure 2.4. Unclear Line-of-Sight Example

The description figures are designed for the transmitter antenna height and receiver antenna height, which are 0 meters. If these antennas are above the ground, their heights should be introduced to the calculation.

2.4 Signal Propagation Models

Understanding the propagation characteristics of a mobile radio channel is crucial for designing any wireless (mobile) communication system in a specific area [39]. In terrestrial cellular radio systems, radio signals typically propagate through one or a combination of these three primary mechanisms: reflection, diffraction, and scattering [40], [41]. A key characteristic of the propagation environment is path loss. Path loss refers to the difference (measured in dB, decibel) between the effective transmitted power and the received power, and it may or may not take antenna gains into account [42].

Signal propagation models are mathematical representations and algorithms used to predict how electromagnetic signals travel through different environments. These models account for various factors that influence signal behavior, such as distance, frequency, terrain, atmospheric conditions, and obstacles like buildings or vegetation [43].

The purpose of signal propagation models is to estimate the strength, reach, and quality of a signal as it moves from a transmitter to a receiver. They help in understanding how the signal will be affected by factors like reflection, refraction, diffraction, scattering, and absorption. In the context of electronic warfare, these models are essential for determining the optimal placement and power levels of jammers to ensure that their signals effectively disrupt enemy communications over a given area. By simulating real-world conditions, signal propagation models enable more accurate and efficient planning of communication and jamming operations [44].

There are many signal propagation models. In this thesis, 4 of these models are examined.

2.4.1 Free Space Propagation Model

For the purposes of radiocommunication, free space is defined as a perfect vacuum that may be considered of infinite extent in all directions, so free space propagation is the propagation of a radio wave radiating in free space [45].

$$SL_R = -\left(32.45 + 20 \cdot log_{10}(f) + 20 \cdot log_{10}(d)\right) + G_T + G_R + 10 \cdot log_{10}(1000 \cdot P_T) \tag{2.1}$$

SL_R: Signal level at the receiver in dBm.

f: Frequency in MHz.

d: Distance between transmitter and receiver in km.

G_T: Gain of the transmitting antenna in dB.

G_R: Gain of the receiving antenna in dB.

P_T: Transmitting power in Watt.

2.4.2 Egli Propagation Model

This model is designed for the frequency range of 40 MHz to 900 MHz and a path distance from 0.1km to 60km. It is very suitable for irregular topography [46]. Egli is based on measured propagation paths and then reduced to a mathematical model. In the case of Egli, the model consists of a single equation for the propagation loss [47]

$$SL_R = -38 + 20 \cdot log_{10}(H_T \cdot H_R) + G_T + G_R - 20 \cdot log_{10}(f) - 40 \cdot log_{10}(d) + 10 \cdot log_{10}(1000 \cdot P_T) \tag{2.2}$$

SL_R: Signal level at the receiver in dBm.

f: Frequency in MHz.

d: Distance between transmitter and receiver in km.

G_T: Gain of the transmitting antenna in dB.

G_R: Gain of the receiving antenna in dB.

P_T: Transmitting power in Watt.

H_T: Height of the transmitting antenna in meters.

H_R: Heigth of the receiving antenna in meters.

2.4.3 Egli-Bullington Propagation Model

This model is designed for the frequency range of 20 MHz to 1 GHz and is an enhancement of traditional radio propagation models, particularly useful in predicting the path loss of signals in urban or rural areas over irregular terrain. The model combines the features of the Egli model with additional considerations from the Bullington model, making it more adaptable for complex environments where factors like diffraction and obstacles between the transmitter and receiver play a role [48].

$$SL_R = -68 + 20 \cdot log_{10}(H_T \cdot H_R) + G_T + G_R - 20 \cdot log_{10}(f) - 40 \cdot log_{10}(d) + 10 \cdot log_{10}(1000 \cdot P_T) \tag{2.3}$$

SL_R: Signal level at the receiver in dBm.

f: Frequency in MHz.

d: Distance between transmitter and receiver in km.

G_T: Gain of the transmitting antenna in dB.

G_R: Gain of the receiving antenna in dB.

P_T: Transmitting power in Watt.

H_T: Height of the transmitting antenna in meters.

H_R: Heigth of the receiving antenna in meters.

2.4.4 General Purpose Wide-Range Terrestrial Propagation Model

The ITU-R P.2001-5 (08/2023) Recommendation (International Telecommunication Union) provides an advanced propagation model tailored for predicting basic transmission loss in terrestrial radio systems over a broad frequency range, from 30 MHz to 50 GHz. The model is particularly useful for both short- and long-distance communication paths, spanning distances from 3 km to over 1000 km. Its main objective is to accurately predict transmission loss by integrating various propagation mechanisms, accounting for the effects of terrain, atmosphere, and environmental conditions that can affect signal propagation [49].

One of the central aspects of this model is its ability to handle complex propagation conditions by integrating multiple propagation mechanisms. These include diffraction**,** troposcatter, and anomalous propagation. Diffraction losses are a significant focus, especially when signals encounter obstacles like hills or buildings that block the direct line of sight. For these scenarios, the model incorporates methods like the Bullington diffraction model, which estimates transmission losses when the path is obstructed, allowing for more realistic predictions of signal degradation in non-line-of-sight (NLOS) conditions [49].

The model also addresses tropospheric scattering, or troposcatter, which occurs when radio waves are scattered by irregularities in the troposphere. This scattering becomes important for long-range communications, where signals travel beyond the horizon in non-line-of-sight conditions. Troposcatter allows signals to be received over long distances despite the lack of a direct signal path, making this mechanism critical for predicting propagation at distances greater than the line of sight would allow [49].

Another essential aspect of the ITU-R P.2001-5 model is the inclusion of gaseous absorption and precipitation fading. These factors become more prominent at higher frequencies, particularly above 10 GHz, where atmospheric gases and rain can significantly attenuate signals. The model incorporates these effects to ensure that predictions are accurate even in challenging environmental conditions, such as during heavy rainfall or in humid environments [49].

The model is highly versatile and can be applied in a range of communication scenarios, from designing terrestrial microwave links to ensuring reliable performance in mobile networks or broadcasting systems. Its adaptability is largely due to its ability to integrate a wide array of parameters, including terrain profiles, antenna heights, and climatic data, making it suitable for use in Monte Carlo simulations. These simulations are particularly important for long-term planning and interference studies, as they allow engineers to model the expected variability in signal strength and reliability over time [49].

In summary, the ITU-R P.2001-5 Recommendation offers a comprehensive and technically rigorous approach to predicting transmission loss for terrestrial communication systems operating within the 30 MHz to 50 GHz frequency range. By combining multiple propagation mechanisms and accounting for terrain, atmospheric, and environmental factors, the model provides accurate predictions of signal attenuation across diverse scenarios, making it an essential tool for telecommunications engineers engaged in system design, network optimization, and interference management [49].

2.4.5 Summation of Signal Levels

The summation of the signal levels that affect a target area is not a linear produce. This calculation requires the summation of the signal levels in dBm.

$$SL_t = 10 * \log_{10} \sum_{i=1}^{J} 10^{SL_{i,t}/10} \tag{2.4}$$

$SL_{i,t}$: Signal level from the i-th jammer to t-th target area in dBm.

SL_i: Total signal level at t-th target area in dBm.

Summation of signal levels is notated by $SignalSum$ for the rest of the study.

2.5 Danger Level

The concept of "Danger Level" likely refers to the risk or probability that a jammer can be detected and located by enemy forces, which could then lead to countermeasures such as jamming neutralization or physical attacks on the jammer's position. The "Danger Level" is a constraint that plays a critical role in determining the optimal placement of jammers in a given operational environment. The higher the Danger Level, the more likely the jammer's signal is detectable by enemy sensors, increasing the risk of being located and attacked [22].

2.5.1 Altitude Effect on Danger Level Concept

Terrain elevation and obstacles play a crucial role in determining the danger level. Jammers placed on high ground with clear LOS may provide better jamming effectiveness but are also more likely to be detected, thereby increasing their danger level. Conversely, jammers hidden behind terrain features might have a lower danger level but may suffer from reduced jamming efficiency [22].

The danger level criteria for altitude is found as follows;

1. The altitude information of the jammer location is found.
2. A line is drawn between the jammer's location and the target point (area).
3. The altitude levels on this line are found.

4. If there is no obstacle between the jammer location and the target point, then the point that has the maximum altitude level between the jammer location and the target point is found. The altitude difference between this point and the jammer location is the danger level.
5. If there is an obstacle between the jammer location and the target point, then the point that has the maximum altitude level among these obstacles is found. The intersection of this point and line is calculated. The altitude difference between the intersection point and the jammer location is the danger level.

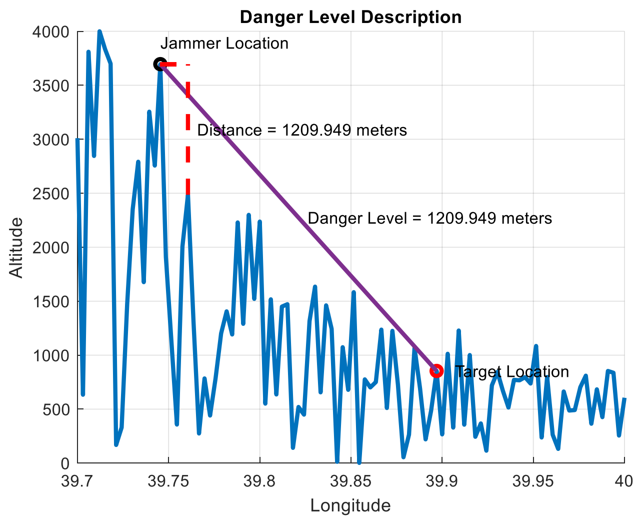

Figure 2.5. High Danger Level Example

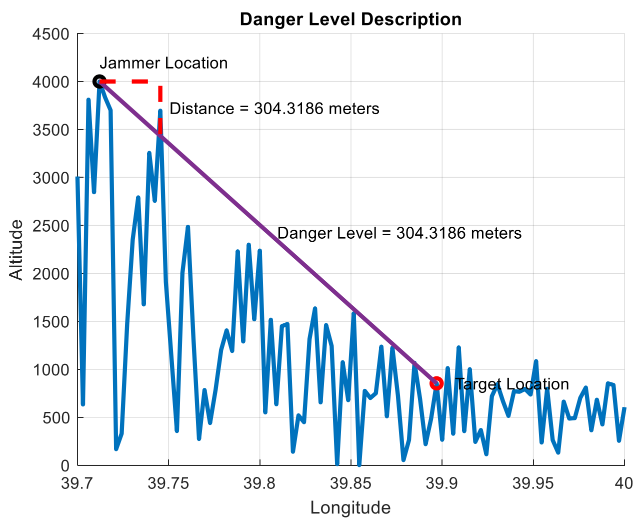

Figure 2.6. Low Danger Level Example

2.5.2 Distance Effect on Danger Level Concept

In addition to the altitude element of the danger level concept, the distance between the jammer and the target location also affects the total danger level value. If the distance between the jammer and the target location is high, then the detectability of the jammer location is low. As the distance value decreases, the detectability increases. Therefore, it should be considered as a part of the danger level calculation [50].

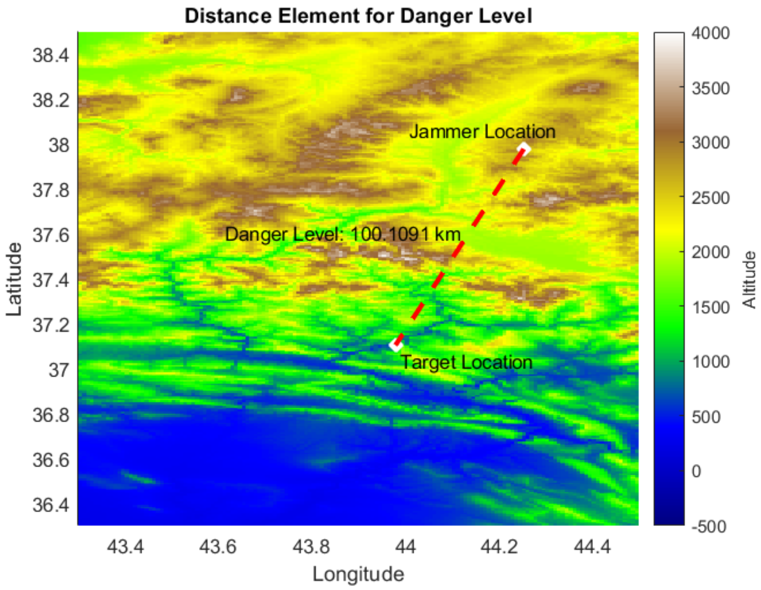

Figure 2.7. Distance Element Example on DTED

2.5.3 Time Effect on Danger Level Concept

In addition, the calculated danger level is factorized by a danger level coefficient. This coefficient is created as a piecewise exponential function. The piecewise exponential function describes that as time increases, the detectability of the jammer location increases exponentially. The function is created for a 30-minute period. When 30 minutes is up, the danger level coefficient arrives at 1, which is the maximum coefficient value.

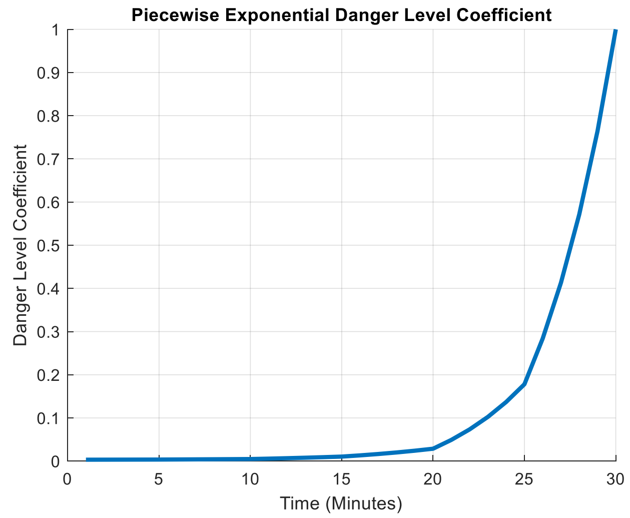

Figure 2.8. Danger Level Coefficient for 30 Minutes Period

Suppose the danger value is calculated as 500 meters from the topographical terrain data. It arrives 500 after 30 minutes when the jammer is set up in the area.

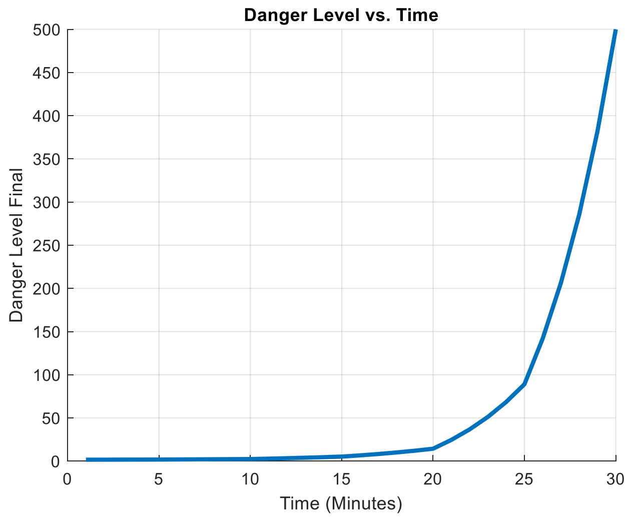

Figure 2.9. Danger Level Values for 30 Minutes Period

If the final value of a jammer exceeds the danger level at a time, then the jammer should be packed and moved to another location. At the new location of the jammer, the constraints should be satisfied, and jamming effectiveness should be maximized.

2.6 Parameter Calculations

In the section, Line-of-Sight of the chapter Models and Methods, the calculation of LOS is defined basically. In this section, this calculation is given as formulation. Therefore, the LOS between the jammer and a target point can be calculated using the equation given in this section.

$$LOS(P_i, t) = \max\left(\left(L(t) + H_{A_j}\right) - \left(Alt(P_i) + H_{G_i}\right)\right) \tag{2.5}$$

$L(t)$ is the continuous altitude function representing the geographical elevation between P_i and t.

$Alt(P_i)$ is the altitude of the i^{th} jammer in meters.

H_{G_i} is the height of the i^{th} jammer in meters.

H_{A_j} is the height of the j^{th} target in meters.

In the Signal Level section of the chapter Models and Methods, the calculation of the signal level is defined basically. In this section, this calculation is given as formulation.

The calculation of signal level is not straightforward. If there is a clear LOS, namely, there is no obstacle between the possible jammer deployment point and the target point, the Free-Space signal propagation model is used.

$$SL_R = -\left(32.45 + 20 \cdot log_{10}(f) + 20 \cdot log_{10}(d)\right) + G_T + G_R + 10 \cdot log_{10}(1000 \cdot P_T) \tag{2.6}$$

SL_R: Signal level at the receiver in dBm.

f: Frequency in MHz.

d: Distance between transmitter and receiver in km.

G_T: Gain of the transmitting antenna in dB.

G_R: Gain of the receiving antenna in dB.

P_T: Transmitting power in Watt.

On the other hand, the altitude difference between the jammer deployment point and the target point may not be high. If this altitude difference is less than 100 meters, the Free-Space signal propagation model is not used. In this case, Egli or Egli-Bullington signal propagation models are used according to the distance to the target point. If the distance between the possible jammer deployment point and the target point is greater than 35 kilometers, then the Egli model is used.

$$SL_R = -88 + 20 \cdot log_{10}(H_T \cdot H_R) + G_T + G_R - 20 \cdot log_{10}(f) - 40 \cdot log_{10}(d) + 10 \cdot log_{10}(1000 \cdot P_T) \tag{2.7}$$

SL_R: Signal level at the receiver in dBm.

f: Frequency in MHz.

d: Distance between transmitter and receiver in km.

G_T: Gain of the transmitting antenna in dB.

G_R: Gain of the receiving antenna in dB.

P_T: Transmitting power in Watt.

H_T: Height of the transmitting antenna in meters.

H_R: Heigth of the receiving antenna in meters.

Egli-Bullington model is feasible for the distance from possible jammer location and target is less than 35 kilometers case. After the simplifications are done into the models, it can be seen that the main difference between the Egli and Egli-Bullington models is the constant parameter.

$$SL_R = -68 + 20 \cdot log_{10}(H_T \cdot H_R) + G_T + G_R - 20 \cdot log_{10}(f) - 40 \cdot log_{10}(d) + 10 \cdot log_{10}(1000 \cdot P_T) \tag{2.8}$$

SL_R: Signal level at the receiver in dBm.

f: Frequency in MHz.

d: Distance between transmitter and receiver in km.

G_T: Gain of the transmitting antenna in dB.

G_R: Gain of the receiving antenna in dB.

P_T: Transmitting power in Watt.

H_T: Height of the transmitting antenna in meters.

H_R: Heigth of the receiving antenna in meters.

The possibility of clear LOS is examined for the signal level calculation. If there is no clear LOS, the model that is published by ITU, which is ITU-R P.2001-5 (08/2023) Recommendation, is used. This model is based on empirical data and is produced for wide-ranging applications.

In the section Danger Level of the chapter Models and Methods, the calculation of danger level is defined basically. In this section, this calculation is given as formulation. Therefore, the danger level from a target point to the possible location of the jammer deployment point can be calculated using the equation given in this section.

$$\begin{gathered} H(P_i, t) = \text{abs}\left(\max\left(L(t) - Alt(P_i)\right)\right) \text{ for all } t \in T, \\ \text{for each } i = \{1, \dots, J\} \end{gathered} \tag{2.9}$$

$$\widehat{DL}(P_i, t) = \begin{cases} H(P_i, t) \cdot \dfrac{G_i}{Dist(P_i, t')}, & H(P_i, t) > 1 \\ \dfrac{G_i}{Dist(P_i, t')}, & H(P_i, t) \leq 1 \end{cases} \tag{2.10}$$

$$DL = \frac{1}{J} \cdot \sum_{i=1}^{J} \widehat{DL}(P_i, t) \tag{2.11}$$

$L(t)$ is the continuous altitude function representing the geographical elevation between P_i and t.

T is the set of target areas.

$Alt(P_i)$ is the altitude of the i^{th} jammer in meters.

$Dist(P_i, t')$ is the distance between i^{th} jammer and t' in meters. t' is the center location of the corresponding target area of t. The distance metric is in meters.

G_i denotes the transmit power of i^{th} jammer in watt and it is strictly positive.

CHAPTER 3

PROBLEM 0: OPTIMUM DEPLOYMENT ON PREDEFINED LOCATIONS

The first problem of the study is optimum deployment on predefined locations. Therefore, problem definition, problem formulation, solution technique, simulations, and results are investigated for the first problem in this section.

3.1 Problem Definition

Problem 0 is the simplest version of deploying jammers on a map in a way that is optimal under given constraints. In this problem, the main aim is jamming the enemy target area with the jammers by locating them in the predetermined areas. The predetermined areas can be considered as military bases or military guard posts. Military bases and military posts are established at certain intervals, especially on country borders. Therefore, it is easy and fast to place jammers in these places. This way, defined as Problem 0, can be used to jam the target enemy areas located beyond the borders or in areas close to these bases and posts. Briefly, the optimum jammer deployment problem with predetermined deployment points and a predetermined target area involves strategically placing jammers from a set of fixed deployment locations to maximize the interference on a predefined target area while adhering to operational constraints. This problem is a key concern in electronic warfare, where the objective is to neutralize or disrupt enemy communication systems without revealing the jammers' locations to enemy forces.

In this problem, predetermined deployment points are a fixed set of geographical coordinates where jammers can be placed. The selection of which points to use and how many jammers to deploy must be optimized to achieve the desired jamming effect. These points may vary in elevation, accessibility, or environmental conditions, affecting the signal propagation and line-of-sight to the target area.

The target area is a specific geographical zone where the jammers aim to degrade the effectiveness of communication systems. The problem is to ensure that the signal emitted by the jammers sufficiently covers the target area to prevent the effective operation of enemy systems, taking into account propagation losses and interference requirements.

The goal is to maximize a certain performance criterion, typically:

- Maximizing signal strength in the target area, ensuring adequate jamming power reaches all parts of the target.
- Minimizing detection risk, meaning the jammer placement should be optimized such that the jammers themselves remain concealed or protected from enemy detection and attack.
- Minimizing cost or resource usage, where deploying fewer jammers or choosing low-risk locations is preferred.

Since there is a limited number of jammer location points, this problem does not lead to a global optimum point on a map. Therefore, the solution to the problem is to provide the best locations for jammers that meet the constraints.

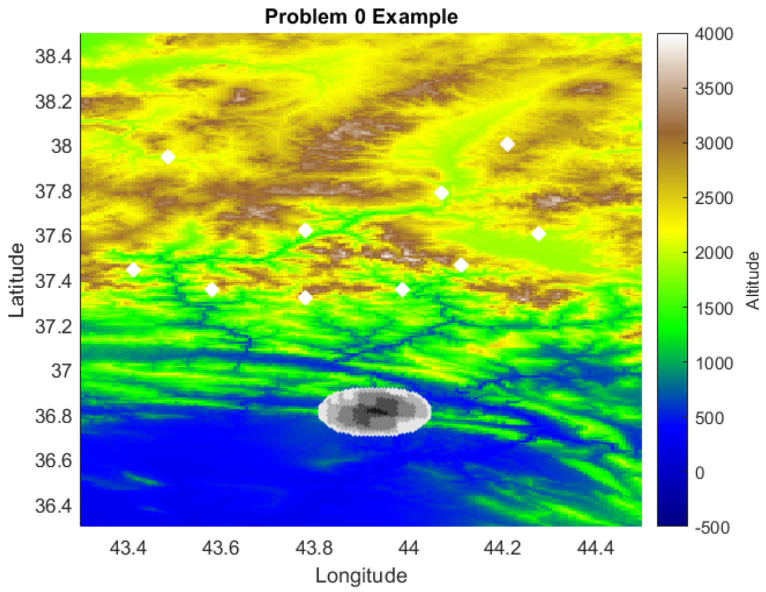

Figure 3.1. Problem 0 Visualization

In the visualization of Problem 0, white points represent the military bases and military posts. The black and gray shaded area is the enemy target area that should be jammed. As in the explanation, the jammers can be deployed only on the white points given in the visualization. Therefore, there are 10 possible locations for the jammers. The required number of jammers and the military bases and posts that are used should be found by the optimization algorithm.

3.2 Problem Formulation

In this problem, there are two main optimization unknowns.

The first unknown is the locations of the jammers, namely, the latitude and longitude coordinates of the jammers. This unknown demonstrates that the selected predefined sites. The selection of the predefined sites is important to increase the effectiveness of jamming activity in terms of the signal level and provide a clear LOS. When choosing the locations of the jammers, the terrain features should also be considered.

In this section, the following notations are used to define the geographical coordinates of the jammers;

$$P_j = \left(x_j, y_j\right), j = 1,2, \dots, J \tag{3.1}$$

x_j: Latitude of the j-th jammer.

y_j: Longitude of the j-th jammer.

J: Total number of jammers used in the solution.

The second unknown is the number of jammers that presents the minimum required number of jammers that satisfies the constraints of the optimization problem. The number of jammers cannot be greater than the number of predefined jammer location points. Therefore, the most basic problem, “Problem-0”, does not guarantee that there is an absolute convergence to the solution. Throughout this section, J is used to represent the total number of jammers where J is a positive integer.

3.2.1.1 Objective Function

The objective of the problem is to minimize the total LOS and maximize the signal level by selecting the predefined sites. Therefore, the objective function requires both the LOS and signal-level concepts.

$$F(P_i, J) = \min_{\{P_i\,,\,J\}} (LOS_{Total} - SL_{Total}) \tag{3.2}$$

Total LOS and signal level can be calculated as the following equations;

$$LOS_{Total} = c_1 \cdot \frac{1}{J} \cdot \sum_{i=1}^{J} \left(\int_T \min\, (LOS(P_i, t) dt \right) \tag{3.3}$$

$$SL_{Total} = c_2 \cdot \int_T \left(\sum_{i=1}^{J} SL(P_i, t) \right) dt \tag{3.4}$$

$$0 \leq c_1, c_2 \leq 1 \tag{3.5}$$

Where, $P_i \in A$ and $c_1 + c_2 = 1$.

$P_i = (x_i, y_i)$ represents the coordinates of the i-th jammer in the deployment set of points A.

A is the set of points in which jammers can be deployed.

t shows a target area, which is an element of T.

T represents the set of target areas.

J is the minimum number of jammers to satisfy the constraints.

c_1 is the coefficient that represents the importance of LOS.

c_2 is the coefficient that represents the importance of signal level.

3.2.1.2 Constraints

There are 3 constraints for this basic version of the optimum jammer deployment problem. The initial constraint is designed for the places where jammers can be deployed.

$$P_i \in A \text{ for all } i = 1,2, \dots, J$$

A is the set of points where jammers can be placed and defined before the optimization algorithm starts. This set includes predefined points such as the military guards and military posts.

The second constraint aims to ensure the signal level is higher than the enemy sensitivity at the target area [51]. The targets that should be jammed are receivers, and the goal is to prevent the activities of these receivers. These receivers have sensitivity thresholds. If the jamming signal exceeds this sensitivity threshold, the enemy electronics cannot work in a proper way. Therefore, the signal level must be greater than the sensitivity of the enemy electronics.

$$\int_T SL(P_i, t)dt \geq S(t) \text{ for all } t \in T \tag{3.6}$$

$S(t)$ is the sensitivity threshold at the target area t.

T is the set of target areas.

The last constraint is the LOS between the jammer places and the target areas. In this thesis, the LOS is not used in a binary format. Instead of binary format, the calculations of the LOS give a continuous set of values. The higher LOS value means worse clearance, while the lower LOS value means better clearance. Therefore, LOS should be a part of the constraints. In addition, the transmitter antennas have a height from the ground. The LOS is combined with this height value and becomes a part of the constraints.

$$\frac{1}{J}\cdot\sum_{i=1}^{J} LOS(P_i, t) \leq 5 \cdot H_{G_i} \text{ for all } t \in T \tag{3.7}$$

H_{G_i} is the height of the i^{th} jammer in meters. The coefficient 5 makes a flexibility to this constraint. In addition, t represents the target area, which is an element of all target areas set T.

The optimization process is not evaluated on a continuous area. Therefore, the deployment possibilities are limited. Namely, the combinations of the predefined jammer deployment points are limited. Therefore, this situation may lead to a non-convergence of the problem. The non-convergence means that there may be any combination that satisfies the constraints. The other problems, which are defined from "Problem 1" to "Problem 4", are designed for this reason.

3.3 Solution Technique

The solution to this problem is straightforward. Since the possible locations of the jammers are predefined and do not include a continuous area, there are a limited number of combinations. Therefore, the solution does not use stochastic methods instead of deterministic methods.

3.3.1.1 Gathering Possible Solutions and Evaluations

For the solution of this problem, the combinations of the predefined points are evaluated initially. This evaluation gives all possible solutions.

$$M = \binom{N}{J} \tag{3.8}$$

M is the total number of possible solutions.

N is the number of predefined locations for jammer placements.

J is the number of jammers that are used in the optimal solution.

Therefore, there should be M number of cost function and constraints evaluations for the cases of J number of jammers are used.

3.3.1.2 Handling Non-Convergence Problem

Any combination of the jammer deployments when J numbers of jammers are used may not satisfy the constraints. Therefore, there is a non-convergence problem for J number of jammers. In this case, the total number of jammers is increased, $(J \rightarrow J + 1)$.

However, the possible predefined locations are limited. If there is no convergence while the number of jammers is equal to the number of possible locations, this means that there is no optimal solution satisfying the constraints. In this case, the deployment with the minimum cost function value is taken as the best possible solution.

3.4 Simulations and Results

In this section, the solution to this problem is tested in various scenarios. The scenarios aim to show the performance of the solution under different conditions. On the other hand, some of the scenarios are designed to demonstrate there may not be a convergence. These scenarios show the importance of other problems and their solutions. The general information about the scenario definition figures is the following;

- The points on the map that are colored with white represent the jammer location points.
- The black/gray elliptic areas (black/gray points) are the enemy/target areas that are wanted to be jammed.

   - These black elliptic areas have different colors. These colors refer to the priority level. The black parts have the most priority, and the whiter areas have less priority.
- The red points are the solutions. Namely, if the jammers are placed in the red points, the constraints are satisfied with the minimum cost value. If there is no red point, then there is no solution that satisfies all of the constraints.

3.4.1 Scenario-1

Table 3.1 Characteristics of Scenario-1

Characteristics	Explanations
Number of Feasible Points	10
Altitude Level of Feasible Points Relative to the Target Area	High
Number of Target Areas	1
Antenna Height (m)	25
Sensitivity Level (dBm)	-90

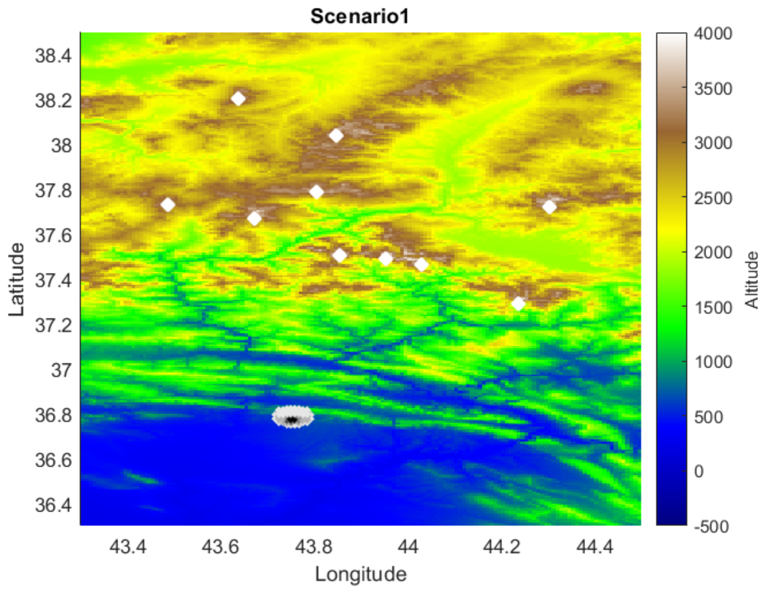

Figure 3.2. Scenario-1 Visualization

The first scenario demonstrates the ideal case for the problem. There are many feasible points, and all the points have greater altitude levels relative to the target area. In addition, there is only one target area, and the solution should deal with one target area. Therefore, this scenario provides general information about how the solution performs under the best possible conditions. The optimization algorithm for this scenario provides the following results.

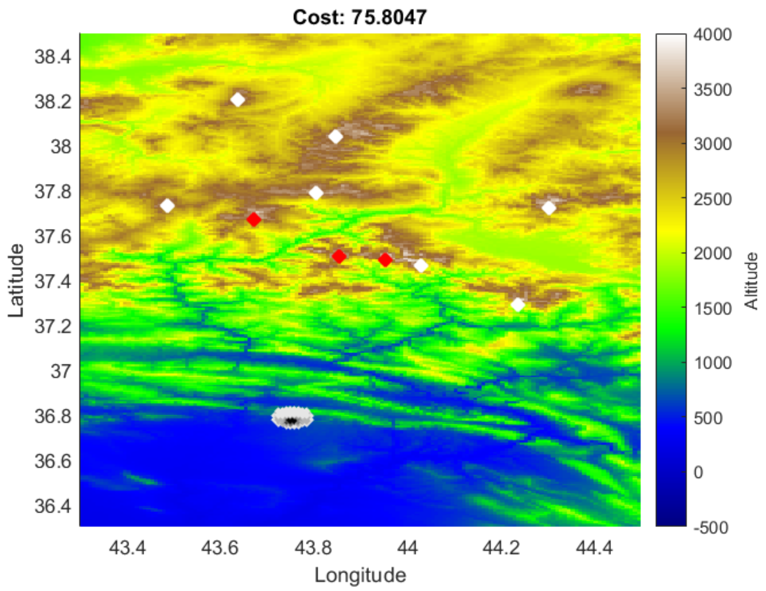

Figure 3.3. Scenario-1 Solution

The optimization algorithm finds the optimum solution with 3 numbers of jammers. These jammers are placed the nearest possible locations to the enemy target area. The cost value is around 76.

3.4.2 Scenario-2

Table 3.2 Characteristics of Scenario-2

Characteristics	Explanations
Number of Feasible Points	10
Altitude Level of Feasible Points Relative to the Target Area	Low

Table 3.2 (continued)

Number of Target Areas	1
Antenna Height (m)	40
Sensitivity Level (dBm)	-90

In this scenario, the relative altitude of the jammer deployment points is decreased. The number of target areas is kept the same so as to see the effect of altitude level changes on the solution. This scenario demonstrates that if the number of jammers is increased, then the altitude levels problem can be solved or not.

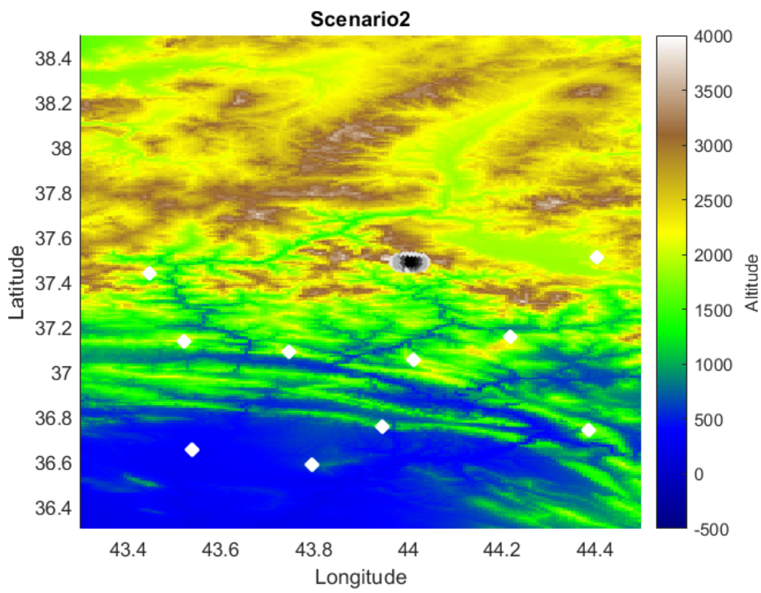

Figure 3.4. Scenario-2 Visualization

The optimization algorithm for this scenario provides the following results. The optimization algorithm finds the optimum solution with six numbers of jammers. Some of the jammers are close to the target area. These jammers increase the signal level at the target area. On the other hand, the rest of the jammers are away from the target area. These locations provide better LOS since there is no high hill between the target area and themselves. The cost value is around 250.

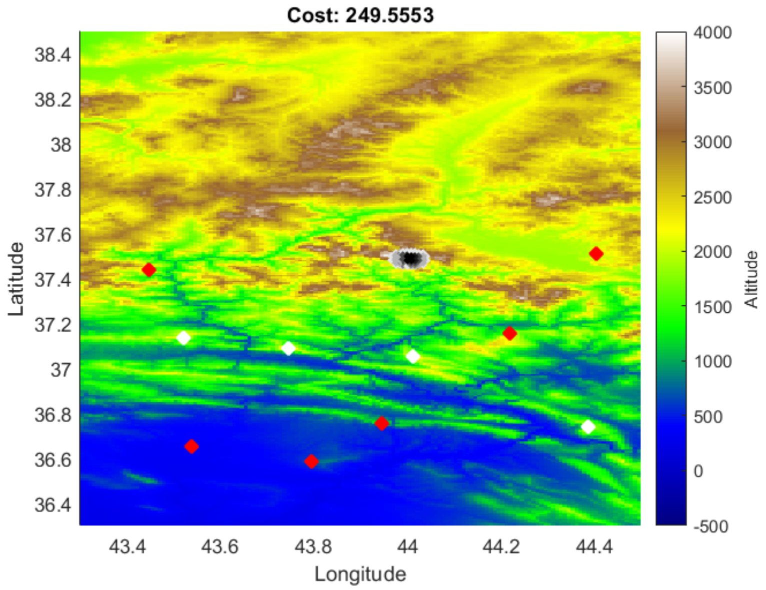

Figure 3.5. Scenario-2 Solution

3.4.3 Scenario-3

Table 3.3 Characteristics of Scenario-3

Characteristics	Explanations
Number of Feasible Points	10
Altitude Level of Feasible Points Relative to the Target Area	High
Number of Target Areas	3
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

In this scenario, the number of target areas is increased, and there are multiple target areas. The target areas are distributed to the different parts of the map. Therefore, the jammers should be deployed so that they can handle all the target areas. This scenario shows the capability of managing multiple target areas problem.

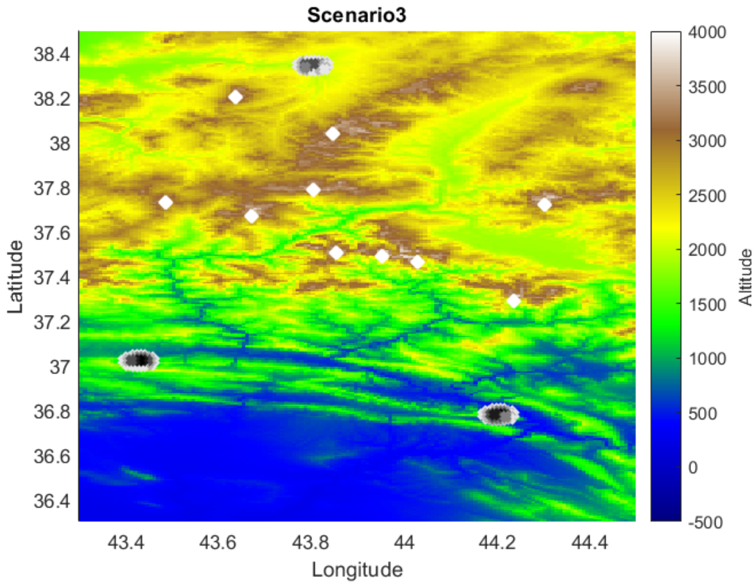

Figure 3.6. Scenario-3 Visualization

The optimization algorithm for this scenario provides the following results.

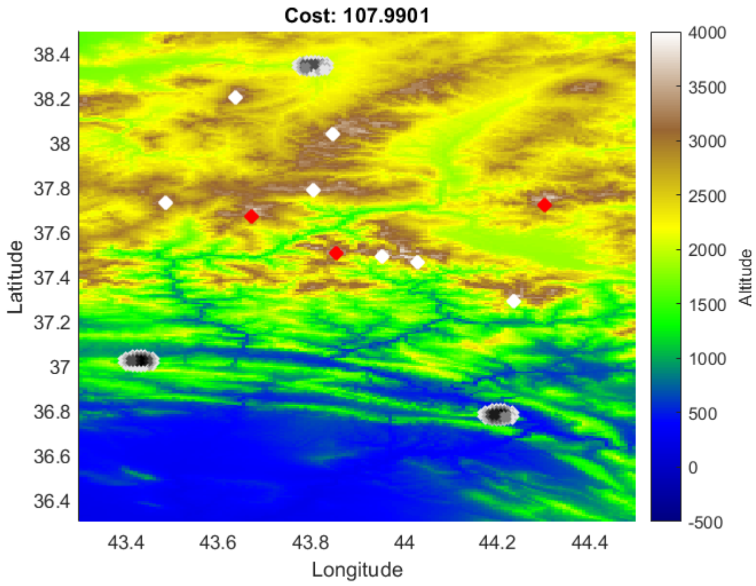

Figure 3.7. Scenario-3 Solution

The optimization algorithm finds the optimum solution with three numbers of jammers. These jammers are placed at the highest possible locations according to the enemy target area so as to achieve clear LOS and better signal levels. The cost value is around 108.

3.4.4 Scenario-4

Table 3.4 Characteristics of Scenario-4

Characteristics	Explanations
Number of Feasible Points	10
Altitude Level of Feasible Points Relative to the Target Area	Mixed
Number of Target Areas	3
Antenna Height (m)	30
Sensitivity Level (dBm)	-90

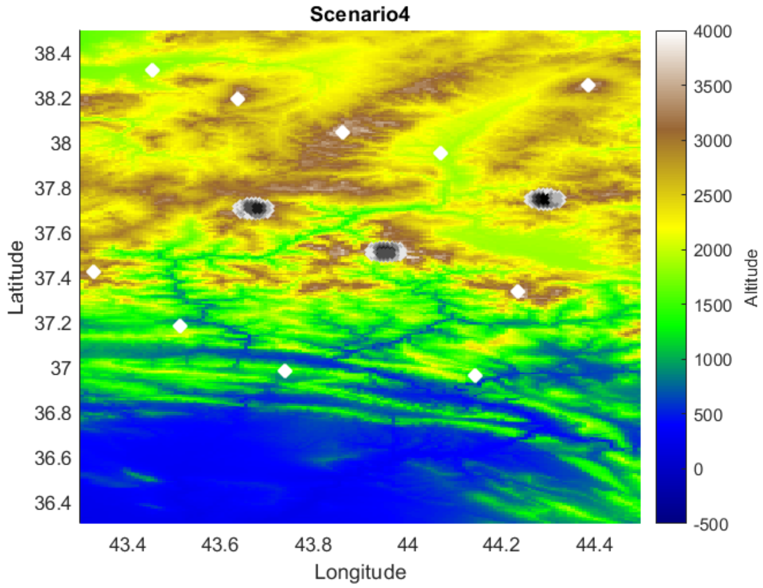

Figure 3.8. Scenario-4 Visualization

In this scenario, the altitude levels are low with respect to the target areas. In addition, there are three targets that are distributed to the different parts of the map. This scenario aims to show the behavior of the solution under hard conditions. In addition, the feasible points are placed around the target areas, and it provides better conditions for the problem. The optimization algorithm for this scenario provides the following results.

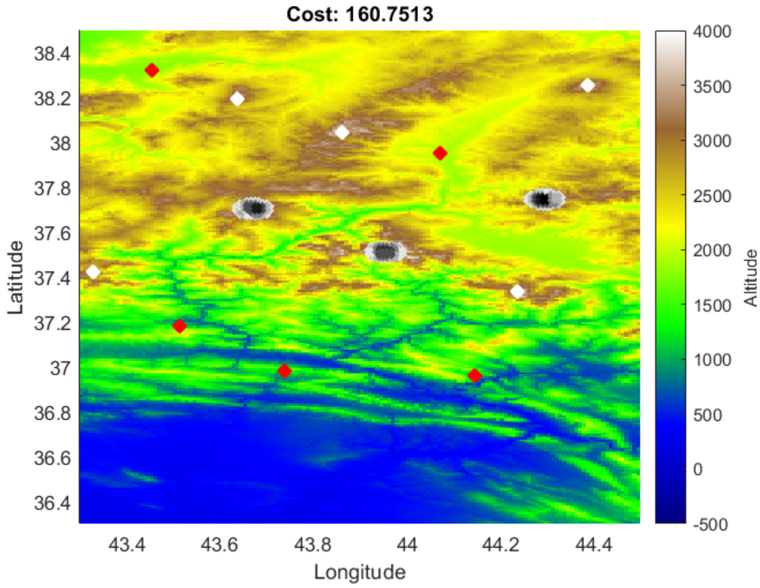

Figure 3.9. Scenario-4 Solution

The optimization algorithm finds the optimum solution with 5 number of jammers. Since the possible jammer locations are distributed around the target areas, many of the jammers affect all the target areas highly. Therefore, instead of 6 jammers, five jammers are required for this solution, unlike Scenario 2. In addition, the altitude levels of the jammer locations are better than the Scenario 2.

3.4.5 Scenario-5

Table 3.5 Characteristics of Scenario-5

Characteristics	Explanations
Number of Feasible Points	10
Altitude Level of Feasible Points Relative to the Target Area	Low
Number of Target Areas	3

Table 3.5 (continued)

Antenna Height (m)	25
Sensitivity Level (dBm)	-90

This scenario is the hardest and last part of this section. Like the fourth scenario, there are multiple targets and the altitude levels of the feasible points are lower than the target areas. In addition, the feasible points are not distributed around the target areas; therefore, the signal level and LOS constraints may not be satisfied. The aim of the scenario is to make the convergence of predefined problem fails and show the necessities of the other problems.

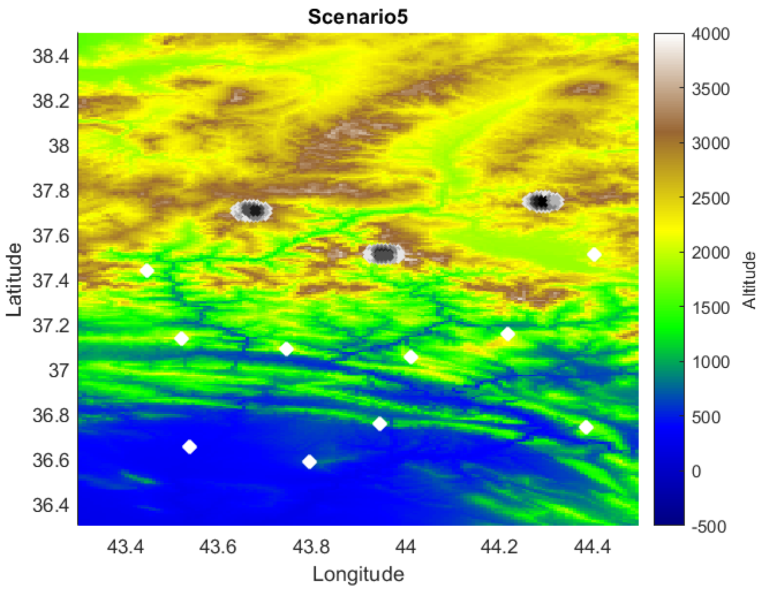

Figure 3.10. Scenario-5 Visualization

The optimization algorithm for this scenario provides the following results, for which no solution exists.

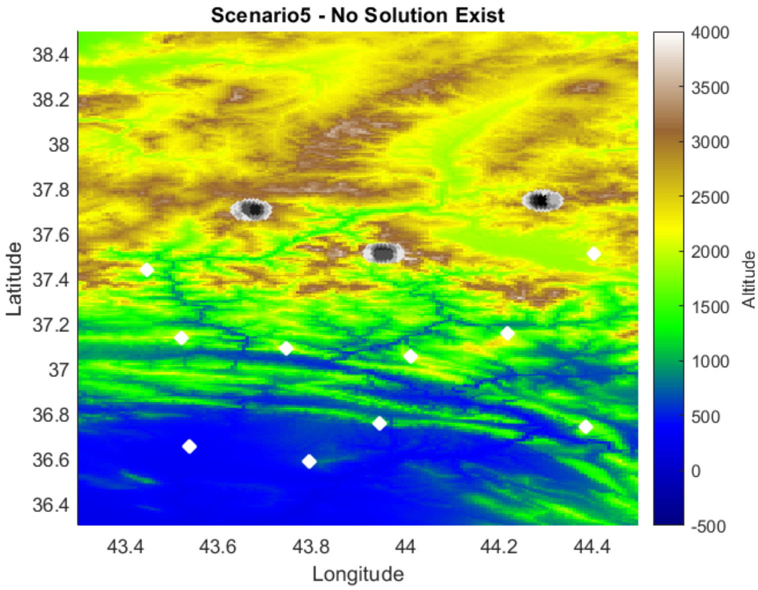

Figure 3.11. Scenario-5 Solution

Any of the set of jammers cannot satisfy the constraints. Therefore, there is no solution for this scenario.

According to Scenario 5, this problem requires a new problem, which is the existence of a continuous feasible area for jammer deployment. The rest of the study focuses on continuous feasible areas.

CHAPTER 4

PROBLEM 1: STATIONARY JAMMERS AND STATIONARY TARGETS

This section focuses on the optimization of stationary jamming systems, where jammers are positioned at fixed locations to maximize the disruption of enemy communication signals. The optimization process involves determining the most effective placement of these jammers while taking into account various factors such as terrain, LOS, signal strength, and the risk of detection by enemy forces.

The problem is formulated to balance the need for effective jamming coverage with operational constraints, including avoiding restricted zones and minimizing vulnerabilities. The solution technique leverages an advanced optimization algorithm, Particle Swarm Optimization (PSO), to iteratively refine jammer placement. Key aspects of the optimization process, including population initialization, velocity updates, and handling cases of non-convergence, are thoroughly addressed [52].

This section also presents different scenarios that test the performance of the optimization model under varying conditions, providing detailed insights into how the stationary systems perform across different environments and constraints. Through this structured approach, the study aims to derive robust and effective solutions for deploying stationary jammers in complex operational settings.

4.1 Problem Definition

In this problem, the objective is to determine the optimal locations for jammer deployment within continuous operational areas, which are represented as polygons. Unlike in the previous problem (Problem 0), where possible deployment locations were predefined, the jammers in this scenario can be deployed anywhere within the polygons. These polygons may exhibit varying geometrical properties, such as being convex or concave, and can be either connected or disconnected, providing a complex and flexible operational area for deployment.

Additionally, the polygons may contain restricted zones, representing areas within which jammer deployment is not allowed due to operational, environmental, or safety concerns. These polygons are considered as the feasible operational region, and within these areas, the jammers must find their optimal positions to maximize jamming effectiveness.

A unique challenge in this scenario involves the presence of roads within the operational region. Since the jammers are not restricted to being deployed at fixed military bases or posts, their final placement should consider the proximity to roads for ease of transportation and deployment. If the solution points are near roads, the jammers can be easily moved and deployed, reducing logistical challenges. However, jammers may also be deployed far from roads if doing so leads to a significant increase in jamming effectiveness. Therefore, the optimization must balance the ease of deployment with operational effectiveness, considering both signal coverage and logistical feasibility.

In addition to these factors, the detectability of the jammers by enemy forces plays a significant role in the optimization process. The jammers must be placed in such a way that they minimize the risk of being detected and attacked by enemy forces. This adds another layer of complexity to the objective function, as the solution must consider not only signal strength and coverage but also the concealment and safety of the jammers. This requires optimizing for minimal detectability, taking into account factors such as terrain, foliage, and other natural covers that might reduce the risk of detection.

The objective function must now balance several key factors:

- Maximizing jamming effectiveness over the target area, which includes maximizing signal strength and ensuring comprehensive coverage.

- Minimizing cost or resource usage, where deploying fewer jammers is preferred.
- Minimizing the risk of detection by enemy forces, which involves choosing locations that are more difficult to detect, potentially hidden from enemy sensors or reconnaissance.
- Minimizing logistical challenges, by preferring locations that are near roads for easier transportation and deployment, unless more distant locations significantly improve operational effectiveness.

Solving this problem requires the use of optimization algorithms that can handle the continuous search space and multiple conflicting objectives.

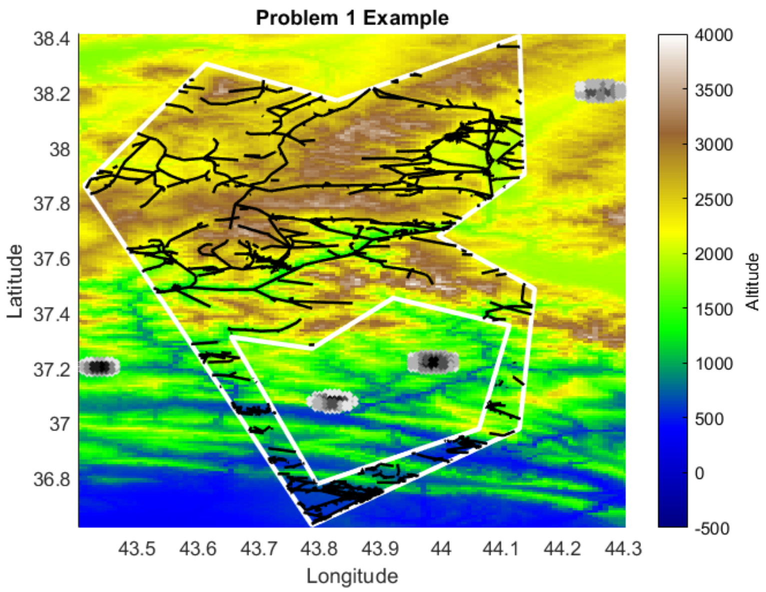

Figure 4.1. Problem 1 Visualization

In the visualization of Problem 1, the outside white borders are the feasible region for jammer deployment. However, there is another white border inside this feasible region. The inside white border represents the restricted area where jammers cannot be deployed. The black and gray shaded areas are the enemy target areas that should be jammed. There are four different enemy target areas in this example. In addition, the black lines demonstrate the roads in the feasible region.

4.2 Problem Formulation

In the context of optimizing jammer deployment for electronic warfare, there are two main optimization unknowns.

The first unknown is the jammer locations, namely, the latitude and longitude coordinates of the jammers. This unknown represents the specific geographic coordinates where each jammer will be positioned. The locations of the jammers are crucial to ensure adequate coverage and effective jamming of enemy communication systems. Variations in jammer locations can significantly impact both LOS and signal levels, which are important for achieving optimal jamming performance. Determining these coordinates involves balancing multiple factors, including LOS requirements, signal strength, terrain features, and potential obstacles. The placement must be strategically optimized to maximize the effectiveness of the jamming operation while adhering to all relevant constraints.

Throughout this section, the following notations are used to represent the geographical coordinates of the jammers;

$$P_j = \left(x_j, y_j\right), j = 1,2, \ldots, J \tag{4.1}$$

x_j: Latitude of the j-th jammer.

y_j: Longitude of the j-th jammer.

J: Total number of jammers used in the solution.

The second unknown is the optimal number of jammers. This unknown represents the total number of jammers required to achieve effective coverage and disruption of enemy communication targets. The number of jammers directly influences the jamming capacity and the ability to cover all prioritized target areas. An insufficient number of jammers may result in inadequate coverage and reduced effectiveness, while an excessive number may lead to unnecessary resource expenditure [53]. Determining the optimal number involves considering factors such as signal strength requirements, deployment constraints, and the need to meet specific jamming objectives within the allocated budget and operational limits. Throughout this section, J is used to represent the total number of jammers, where J is a positive integer.

4.2.1.1 Objective Function

The objective of the problem is to minimize the total LOS and maximize the signal level information for the jammers deployed in the target areas. Therefore, the objective function is constructed by considering LOS and signal level with the parameters of jammer locations and the total number of jammers.

$$F(P_i, J) = \left(\min_{\{P_i\,,\,J\}}(LOS_{Total} - SL_{Total})\right) \cdot K \tag{4.2}$$

Total LOS and signal level can be calculated as the following equations;

$$LOS_{Total} = \frac{1}{|T|} \cdot \frac{1}{J} \cdot \sum_{j=1}^{|T|} \left(\sum_{i=1}^{J} \left(\int_{T_j} \min\,(LOS(P_i, t)dt \right) \right) \tag{4.3}$$

$$SL_j = \int_{T_j} \left(\sum_{i=1}^{J} SL(P_i, t) \right) dt \tag{4.4}$$

$$SL = SignalSum\left(SL_j \circ SL_j\right) \text{ for } j = 1,2, \dots, |T| \tag{4.5}$$

$$SL_{Total} = \frac{1}{|T|} \cdot \sqrt{SL} \tag{4.6}$$

Where, $P_i \in A$.

$P_i = (x_i, y_i)$ represents the coordinates of the i-th jammer in the deployment area A.

A is the continuous area in which jammers can be deployed.

T is the set of target areas.

T_j represents the continuous set of points within a target area, which is an element of the set T.

$|T|$ shows the number of elements in the set T.

J is the minimum number of jammers to satisfy the constraints.

K is the punishment coefficient according to the proximity of the jammers. K value is defined in the constraints as it is mostly dependent on constraints.

$A \circ B$ notation represents the elementwise multiplication.

4.2.1.2 Constraints

For the problem formulation, there are five constraints. The first constraint is about the feasible jammer deployment area. Therefore, the first constraint ensures that the jammers are placed within the continuous area A.

$$P_i \in A \text{ for all } i = 1,2,\ldots,J$$

The second constraint is about the signal level thresholds. Since the targets for the problem are receivers and the main aim is to jam these receivers, the jammer signal level must be greater than the sensitivity of the receivers.

$$\int_T SL(P_i, t)dt \geq S(t) \text{ for all } t \in T \tag{4.7}$$

$S(t)$ is the sensitivity threshold at the target area t.

T is the set of target areas.

The third constraint is about LOS height. The LOS values are calculated in a sophisticated way in the study. However, very high values may lead to no signal propagation. Therefore, the LOS constraint is combined with the maximum height of the transmitter and ensures that it is within the maximum reachable height.

$$\frac{1}{J} \cdot \sum_{i=1}^{J} LOS(P_i, t) \leq 5 \cdot H_{G_i} \text{ for all } t \in T \tag{4.8}$$

H_{G_i} is the height of the i^{th} jammer in meters. The coefficient 5 makes a flexibility to this constraint. In addition, t represents the target area, which is an element of all target areas set T.

Another constraint is the danger level. Since the danger level parameter represents the detectability by the enemy forces, there also should be a constraint. This constraint does not directly put a threshold. The constraint ensures that the optimum locations with minimum danger level for the jammers with the number of J jammers or the number of $J + 1$ jammers. It checks the optimum solution for the number of $J + 1$ jammers when the algorithm converges an optimum solution with a number of J jammers.

$$\min_{\{P_i\,,J\}} \left(DL(P_{opt},J_{opt}), DL(P_{opt}{}',J_{opt} + 1)\right) \tag{4.9}$$

J_{opt} is the number of jammers to which the algorithm converges.

$P_{opt}{}'$ is the new optimum solution that uses $J_{opt} + 1$ number of jammers.

The last constraint is about the proximity of jammers to each other. In the objective function, there is a coefficient of K. This coefficient should be arranged according to this constraint.

$$K = \begin{cases} \infty, & Dist(P_i, P_j) < 1000 \text{ meters} \\ \dfrac{2500}{Dist(P_i, P_j)}, & 1000 \text{ meters} \leq Dist(P_i, P_j) < 2500 \text{ meters} \\ 1, & Dist(P_i, P_j) \geq 2500 \text{ meters} \end{cases} \tag{4.10}$$

Where, $P_i, P_j \in A$.

$Dist(P_i, P_j)$ represents the distance between the i^{th} jammer, and its closest neighbor j^{th} jammer in meters. According to this constraint, the distance between any two jammers must not be less than 1000 meters. If the distance is between 1000 meters and 2500 meters, the coefficient decreases as the distance increases. Otherwise, the coefficient is taken as one and does not affect the other parameters.

4.3 Solution Technique

In this section, the solution technique that is used to find optimum jammer placements is explained.

4.3.1 Optimization Algorithm and Parameter Selection

In this study, Modified Particle Swarm Optimization (MPSO) was selected as the optimization algorithm due to several key advantages that make it particularly suitable for solving complex problems like jammer placement in electronic warfare scenarios. MPSO is a population-based, metaheuristic algorithm that excels in finding optimal solutions in highly dimensional and complex search spaces, which is critical for determining effective jammer locations [54].

MPSO is well-suited for exploring the entire search space and avoiding local optima, which is crucial in complex terrains where the best jammer placements may not be immediately apparent. This global search capability ensures that the algorithm does not get trapped in suboptimal configurations, leading to more robust solutions [55].

The problem of optimizing jammer placement involves non-linear relationships between signal strength, line of sight, and terrain elevation. MPSO's ability to handle nonlinear, multimodal optimization problems makes it an ideal choice for this application [55].

MPSO is known for its relatively fast convergence compared to other population-based algorithms, such as genetic algorithms. This is important in scenarios where computational efficiency is critical, allowing for quicker solutions without sacrificing optimization accuracy. MPSO does not rely on gradient information, which is beneficial because the optimization problem in this study does not have a simple, differentiable objective function. MPSO can efficiently handle complex, discontinuous, or noisy objective landscapes like the one in this jamming optimization problem. In addition, MPSO is flexible and scalable, meaning it can be adapted to different types of constraints and objectives [56]. In this study, MPSO is able to handle multiple constraints, such as avoiding restricted zones, maintaining line-of-sight requirements, and optimizing signal coverage, making it versatile for the range of scenarios explored.

There are six main parameters for MPSO, and these parameters affect the performance of the algorithm. Therefore, parameter selection is crucial for the study. The first parameter is population size. The population size in MPSO refers to the number of particles (potential solutions) that are simultaneously considered in each iteration of the algorithm. A larger population size allows the algorithm to explore a broader solution space but also increases the computational burden [57]. The population size is set to be 5% of the total number of possible jammer location points.

$$\text{Population Size} = (\text{Total Possible Location Points}) \times 0.05 \qquad (4.11)$$

This percentage strikes a balance between exploration and computational efficiency, ensuring that enough potential solutions are evaluated without overwhelming the computational resources. By relating the population size to the number of possible locations, the approach adapts to the complexity of the specific problem instance.

The second parameter is the number of maximum iterations. The maximum iteration parameter dictates the number of times the MPSO algorithm will update the positions of the particles. This is a critical factor in determining the convergence of the algorithm [58]. The maximum number of iterations is set to 20 in the solution. $(\# \text{ of Iterations} = 20)$

While 20 iterations provide a reasonable compromise between solution quality and computation time, it is acknowledged that this choice could be made more parametric or adaptive, potentially based on the convergence rate observed during initial runs or on problem-specific characteristics.

The other parameter is the cognitive parameter, c_1. The cognitive parameter influences the extent to which a particle is influenced by its own best-known position. It represents the individuality of each particle, driving the exploration of new areas based on past experiences [59]. The cognitive parameter is chosen as 2 in the solution. $(c_1 = 2)$

A value of 2 for the cognitive parameter provides a moderate influence from the particle's own experience, encouraging individual exploration without overemphasizing it. This choice helps maintain diversity in the search space, preventing premature convergence to suboptimal solutions.

Another parameter, the social parameter c_2, is the counterpart of the cognitive parameter. The social parameter governs the influence of the best-known positions of all particles on each individual particle's movement. It represents the social aspect of the swarm, promoting convergence toward the global best solution [59]. The social parameter is set to 2. ($c_2 = 2$)

A higher value for the social parameter ensures that particles are strongly guided toward the best solution found by the swarm, while a lower value leads to less exploitation. The selection of 2 establishes a balance between exploring the map and exploiting the global best solution.

The fifth parameter is the constriction factor, K. The constriction factor is used to prevent the velocities of the particles from growing too large, which could lead to instability in the search process. It controls the balance between exploration and exploitation [59]. The constriction factor is chosen as adaptive to the iteration number.

$$K = \left(10 - \frac{\text{Iteration}}{\text{Maximum Iteration}}\right) \cdot 0.008333 \tag{4.12}$$

The constant coefficient in the constriction factor selection is connected with DTED. Since DTED is a sampling of the earth with the altitude levels of the samples, the sample spacing is used in the constriction factor. The sample spacing is given as a constant coefficient to the constriction factor selection. In addition, the adaptive selection of this parameter provides less movement at the end of the iterations and more movement at the initial steps of the algorithm.

The last parameter is inertia weight, W. Inertia weight represents the influence of the previous velocity values on the current velocity values. To increase the controllability of the MPSO algorithm, inertia weight can be used to tune the global and local search capability. As the inertia weight increases, the tendency to explore the new space increases. Therefore, the particles of the swarm have longer steps in the space. As the inertia weight decreases, particles will have a tendency to dedicate local exploitation.

$$W_0 = \frac{\text{Maximum Iteration} - \text{Iteration}}{\text{Maximum Iteration}} \tag{4.13}$$

W_0 is the minimum inertia weight and it is adaptive according to the current iteration number and total number of iterations.

$$\widehat{W_i} = \text{rand}() \cdot \frac{\text{Cost}_\text{i} - \min\left(\text{Cost}_\text{Swarm}\right)}{\min\left(\text{Cost}_\text{Swarm}\right)} \tag{4.14}$$

W_i is the inertia weight of the i^{th} particle of the swarm.

$\text{Rand}()$ represents a scalar value drawn from the uniform distribution in the interval of (0,1) [60].

Cost_i is the cost value gathered by the i^{th} particle of the swarm.

Cost_Swarm demonstrates the all cost values calculated by all particles of the swarm.

$$\widetilde{W_i} = \frac{\widehat{W_i}}{\left(\sum_\text{Swarm} W\right) \big/ \text{Population Size}} \tag{4.15}$$

The inertia weight of the i^{th} particle is divided into the mean of the inertia weight values of the swarm.

$$W_i = \begin{cases} W_0, & \widetilde{W_i} < W_0 \\ \widetilde{W_i}, & \widetilde{W_i} \geq W_0 \end{cases} \tag{4.16}$$

If the inertia weight of i^{th} particle is less than the inertia weight threshold; the value is equalized with the minimum inertia weight value.

4.3.2 Population Initialization

In order to initialize the population, the priority levels for the feasible jammer deployment area should be produced. Therefore, the first step in initializing the population involves gathering precise altitude information for every possible jammer location. This data could be sourced from DTED. Then, the mean altitude value of the entire feasible jammer deployment area is calculated. The locations with altitudes higher than this mean are prioritized because higher elevations generally offer better line-of-sight conditions, which is important for jamming effectiveness. The second step is to determine the proximity of jammers to the target areas. Since the crucial data is calculated to create priority levels, the population initialization coefficients can be produced. Each potential location point is assigned a priority score based on its altitude, proximity to target areas, and whether it falls within or outside restricted zones. Points within restricted zones are given zero or very low priority. Based on the priority scores, an initial population is selected. The size of this population is 5% of the total possible locations, chosen to balance between diversity in the search space and computational efficiency.

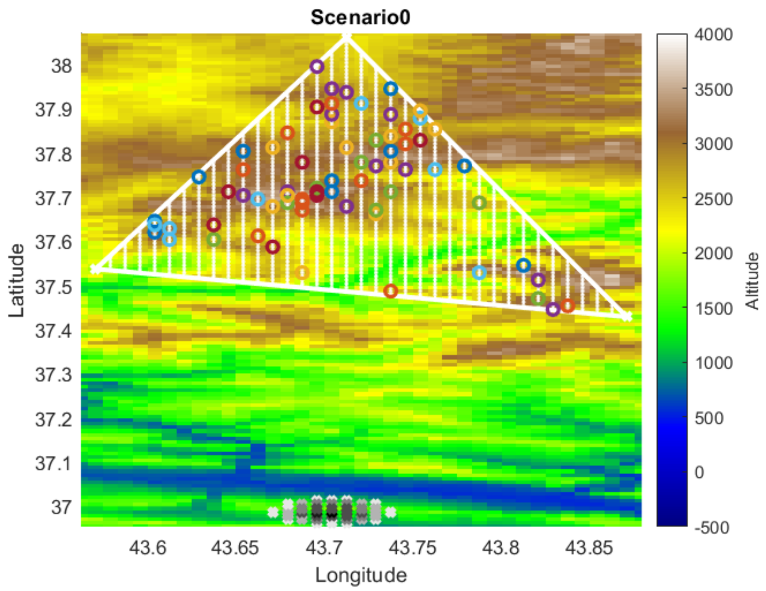

Figure 4.2. Population Initialization on the Map

In the example of Scenario-0, there is an initial population with 25 particles, which corresponds to 5% of the total number of possible jammer deployment locations. All of the circles that have the same color represent the jammer locations for a particle.

4.3.3 Evaluation of the Initial Population

The evaluation of the (initial) population part checks whether the constraints are met. Each particle, which represents a jammer location, is checked against predefined constraints. These constraints are the geographical, signal, line-of-sight, danger level, and proximity constraints. The geographical constraint ensures that the particle's position remains within allowable jammer placement areas. The signal constraint guarantees that the signal levels at the enemy target areas exceed their sensitivity thresholds. LOS constraint also confirms that a clear line-of-sight exists between the particle's position and the target areas. In addition, the danger level constraint provides that the solution has less danger level by not increasing the number of jammers so many. Lastly, the proximity constraint verifies that each jammer of a particle has a distance to its neighbor of at least 500 meters.

In this step of the solution, the particles that do not satisfy the constraints are eliminated from the population. Therefore, there are only feasible solutions that can move to the next iterations.

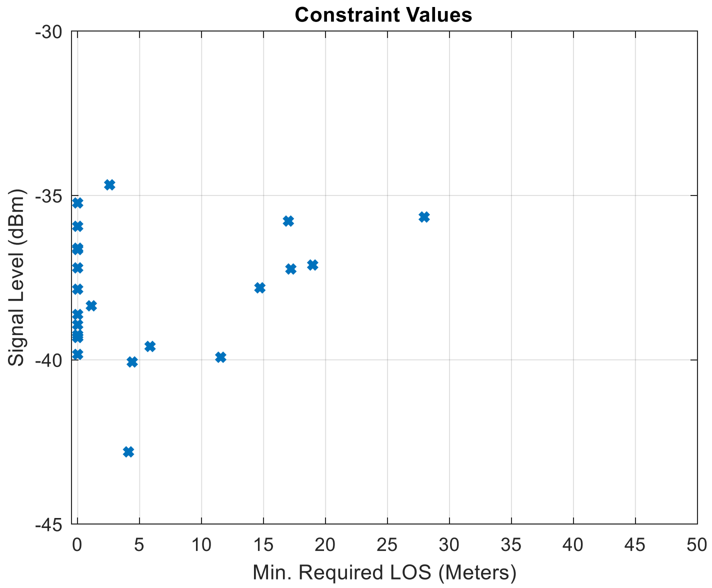

Figure 4.3. Signal Level and Minimum Required LOS Constraint Evaluation

In this example, the signal level values are approximately between -35 dBm and -45 dBm. The minimum required Line-of-Sight values are between 0 meters, which represents a clear LOS, and 30 meters.

After finding a particle that meets the constraints of the problem, the cost function of this particle should be evaluated. Since the LOS metric is used as the minimum required height so that there is a clear LOS between the jammer location and target area, the cost function wants to minimize the required height. On the other hand, if the jamming signal at the target area is higher, then the jamming effectiveness is higher. Therefore, the cost function wants to maximize the jamming signal strength at the target area. As a result, the local best for each particle and a temporary global best for the population are identified.

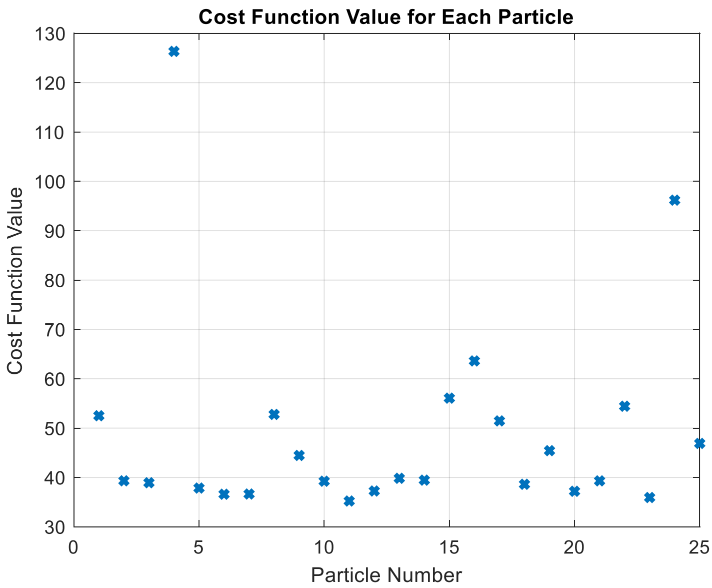

Figure 4.4. Cost Function Values for each Particle in the Example

In addition, the cost function is also affected by the proximity to the roads. The proximity to the roads is not defined as the constraint for the problem; however, the deployment time of the jammers decreases and the jammers can be easily portable if they are close to the roads. Therefore, there is a 5% decrease for the cost function values, if the jammers are away from the roads up to 500 meters.

4.3.4 Velocity Update and Iterations

The velocity of each particle is updated based on its current velocity, the difference between its current position and its local best position, and the difference between its position and the global best position [54]. This update is also affected by the parameters of the algorithm. The cognitive parameter controls the particle's tendency to return to its own best-known position and self-learning [59]. The social parameter increases the particle's tendency to follow the best-known position in the swarm [59]. The scaling constriction factor prevents the particles from overshooting optimal solutions. It is crucial in fine-tuning the localization adjustments of the jammers [59]. The inertia weight increases the balance between the exploration and the exploitation. It controls the effect of the previous velocity on the current velocity [61]. In addition, the dynamic adjustments of the constriction factor and inertia weight also gain convergence controllability to the algorithm.

After the velocity values are updated for the particles, the new position can be determined. Since the DTED is sampled data, bicubic interpolation is applied to the topographical map. By doing so, it is ensured that a more continuous search space is gathered. Namely, the movements of the particles are not strictly limited to the predefined grid points, but the intermediate positions of the map can be considered. Therefore, the search resolution is more finer.

The particles may have a tendency to go outside of the feasible area. Therefore, the outsider particles that cross the borders are to be handled and taken into the borders. If a particle moves outside the allowable jammer placement area, it's re-positioned to the nearest valid location, satisfying the search remains within permissible boundaries.

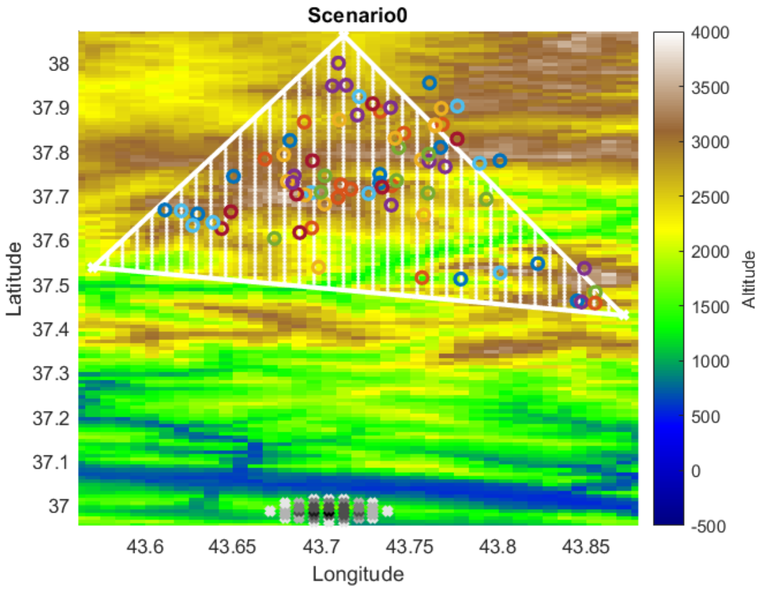

Figure 4.5. The New Positions of the Particles for Example Scenario

The outsider fixing process takes the particles that cross the borders into the border points that are close to the outsider particles.

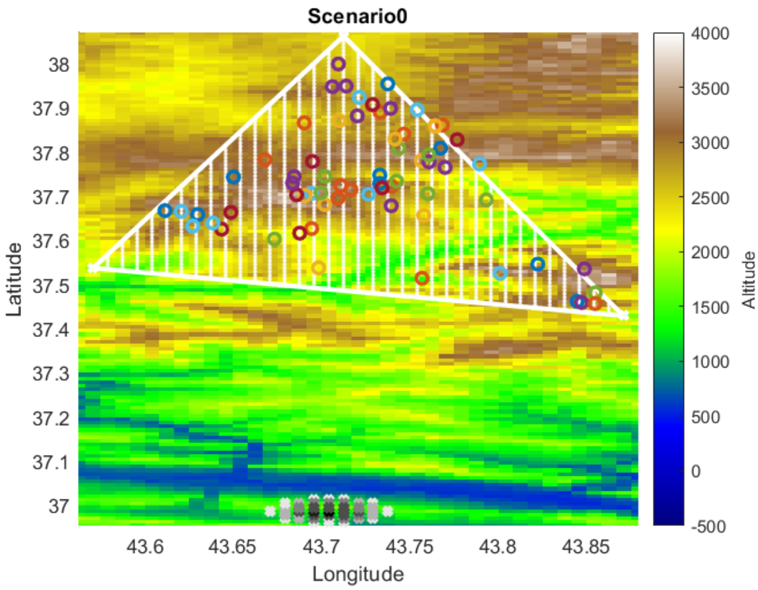

Figure 4.6. Outsider Handling for Example Scenario

After the velocities are updated and the particles have their new positions, the constraints and cost values should be re-evaluated. By doing so, the algorithm iterations continue to refine the search to an optimal solution. For each iteration, the local and global best positions are also updated if the current positions of particles offer improved cost function values.

4.3.5 Handling Non-Convergence Problem

The problem seeks the optimum jammer deployment in the feasible area with the minimum number of jammers. However, some of the regions do not converge an optimal solution with a small number of jammers. The increase in the number of jammers leads to a higher signal level in the target area and a lower minimum required mean LOS. Therefore, the number of jammers that are used in optimization is increased if the PSO fails to find a feasible solution within the initial search boundaries due to constraints, $(J \rightarrow J + 1)$.

Although there is no convergence to a feasible solution, the algorithm has the cost values that are calculated from the previous iteration. Therefore, the initial population includes the particles that have the lowest cost function value with respect to the other particles. By doing so, the information gathered from previous iterations can be used. Namely, the particle that gives the minimum cost value when there are J jammers are used, and a new jammer is introduced to the particle.

On the other hand, increasing jammers may lead to many number of used jammers, and this causes too much resource consumption. Another technique for non-convergence problem is boundary expansion. Therefore, the area is expanded by 2 kilometers if the algorithm fails to find a feasible solution within the initial search boundaries. As a result, this technique makes the feasible region constraint more flexible.

$$P_i \in A \text{ for all } i = 1,2, \dots, J$$

$$P_i \in A' \text{ for all } i = 1,2, \dots, J$$

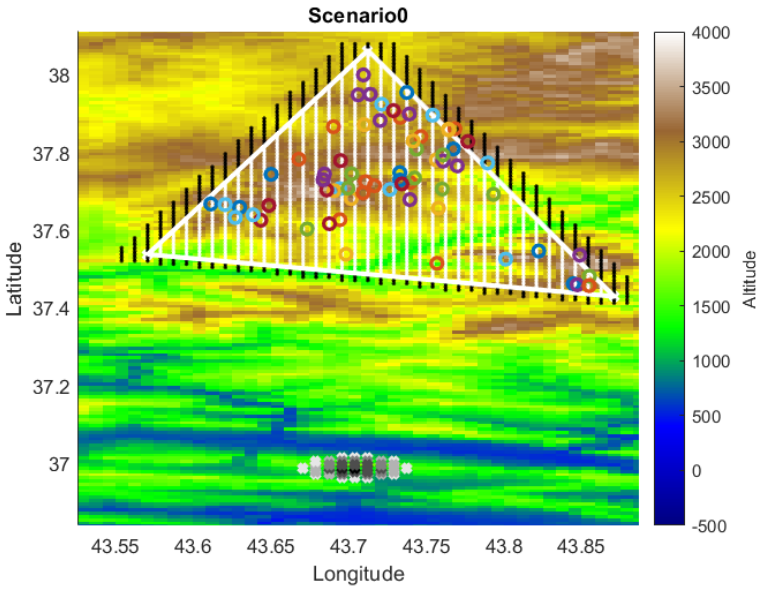

Figure 4.7. Boundary Expansion for the Example Scenario

The new area that is represented with the dashed white lines is the extension of the map for the non-convergence problem. Thus, the area between the dashed white lines and solid white lines is the amount of expansion.

$$A' - A = \{\text{Amount of Expansion}\} \tag{4.17}$$

If the boundary expansion is applied to the problem, the number of jammers is not increased. So, the algorithm should be re-initialized using the best solutions from the previous run as starting points for the new search. This approach leverages the partial optimization from previous runs, ensuring that the algorithm doesn't start from scratch but builds on previous knowledge.

On the other hand, the algorithm converges with a high level of detectability. In this case, the algorithm tries to find a new optimal solution with a number of $J + 1$ jammers instead of J jammers. It is obviously known that, there would be a new optimal solution for increased number of jammers. Therefore, the algorithm chooses the solution with less danger level among J jammers and of $J + 1$ jammers cases.

4.3.6 Fine-Tuning the Solution

Fine-tuning refers to the process of refining the solution found by the Modified Particle Swarm Optimization algorithm within a small localized region, typically in the form of a circle around the solution. This region is defined based on the solution provided by MPSO, and fine-tuning focuses on making small adjustments within this confined area to further minimize the cost function and improve the accuracy of jammer placement [62].

After MPSO has identified an optimal solution, the algorithm’s global search phase is no longer necessary, as the solution space has already been narrowed down. Fine-tuning within a small circle allows for precise adjustment of the jammers, refines the local optimum point, and constrains the search space. Small, localized changes in jammer positions can help improve their effectiveness in terms of coverage, signal strength, and avoidance of detection by enemy forces. By limiting the search area to a small circle, the gradient-based optimization can explore small-scale variations more thoroughly, helping to converge more quickly on a refined local minimum [63]. Focusing the fine-tuning process within a small circular region ensures that the adjustments remain relevant to the original solution, preventing unnecessary exploration of distant suboptimal points [62].

After obtaining the solution from MPSO, fine-tuning involves defining a circular region around the solution in which the gradient-based optimization algorithm can operate. The radius of this circle defines the range in which the gradient-based optimization will make small tweaks to the jammer positions, ensuring that the optimization process is focused and efficient. This method allows for further minimization of the objective function (such as reducing signal loss or meeting a more precise danger level) while maintaining computational efficiency.

4.4 Simulations and Results

In the complex landscape of electronic warfare, the optimization of jammer deployment requires careful consideration of various environmental and strategic factors [30]. This section presents a series of scenarios designed to test the robustness and flexibility of the proposed optimization model. Each scenario varies key parameters such as the number and size of jammer deployment areas, the number and size of target areas, and the number and size of restricted zones or obstacles. Additionally, the altitude of the jammer deployment areas—whether high or low—adds another layer of complexity, influencing signal propagation and line-of-sight conditions. The existence of road networks, ranging from dense to light, further impacts the deployment, particularly for the next sections, such as mobile jammers cases. By altering these parameters, the scenarios simulate a wide range of real-world conditions, providing a comprehensive evaluation of the model's effectiveness in achieving optimal jammer placement across different terrains and operational constraints. The general information about the scenario definition figures is the following;

- The polygons that are surrounded with white lines represent the jammer location areas. If there is an additional surrounding area with white lines, it represents the restricted zones.
- The black/gray elliptic areas (black/gray points) are the enemy/target areas that are wanted to be jammed.
    - These black elliptic areas have different colors. These colors refer to the priority level. The black parts have the most priority, and the whiter areas have less priority.
- The blue areas are lakes; namely, obstacles.
- The black lines are roads.
- The red points are the solutions. Namely, if the jammers are placed in the red points, the constraints are satisfied with the minimum cost value.

The second figures in each scenario illustrate the distribution coefficients of population initialization across the jammer deployment areas within the optimization framework. This distribution is a crucial element in the initial phase of the optimization process, as it determines the starting positions of potential solutions (jammers) within the search space. In this context, “population” refers to the set of potential solutions generated at the start of the algorithm, with each individual representing a possible configuration of jammer placements. The distribution coefficients that are shown in the figures indicate how likely it is for these initial placements to occur in various parts of the deployment areas. This distribution is not uniform; instead, it is influenced by the specific characteristics of the deployment areas, such as their size, shape, distance from the target areas, and any constraints present (e.g., restricted zones or obstacles like lakes).

4.4.1 Scenario-1

Table 4.1 Characteristics of Scenario-1

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	High
Number of Restricted Zones	0
Distribution of Restricted Zones	-
Number of Target Areas	1
Density of Road Networks	Normal
Antenna Height (m)	15
Sensitivity Level (dBm)	-75

The first scenario represents the ideal case situation since the relative altitude of the feasible region is high, there is no restricted zone inside feasible regions, and there is one target area. This scenario provides general information about how the algorithm performs under the best possible conditions.

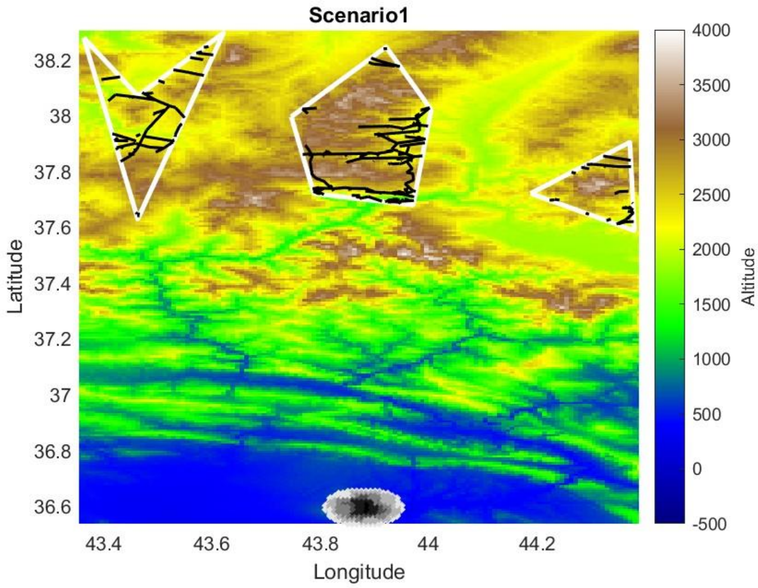

Figure 4.8. Scenario-1 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.2 Optimal Jammer Locations for Scenario-1

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.743613	37.720666	38.050319	37.803666
Longitude	43.848166	44.345333	43.918318	43.882333

The optimization algorithm finds the optimum solution with four numbers of jammers. These jammers are placed at the highest locations according to the enemy target area. The cost value is around 90.

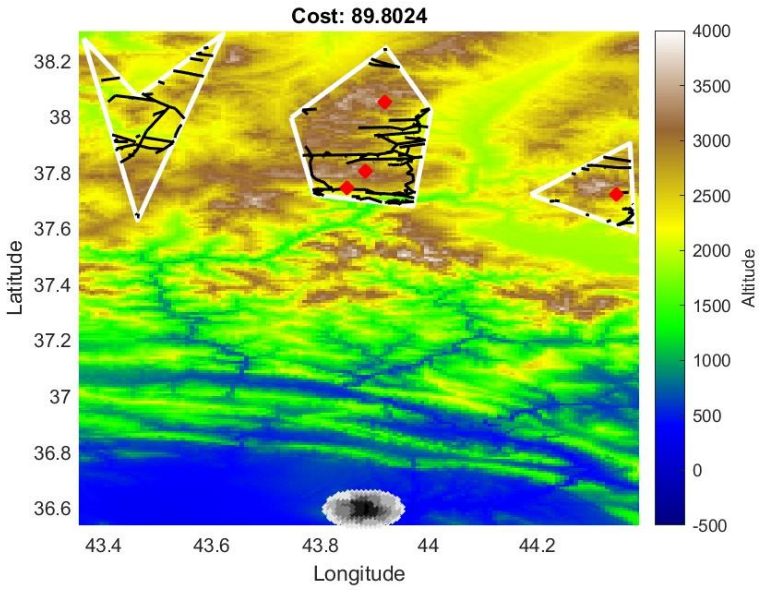

Figure 4.9. Scenario-1 Solution

In addition to the final result, the numerical results for each iteration are obtained.

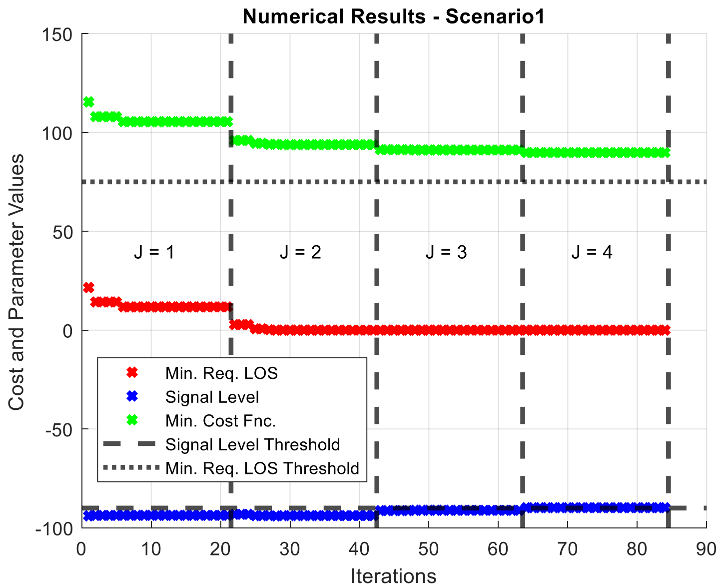

Figure 4.10. Numerical Results for Scenario-1

The antenna height is taken as 15 meters in this scenario. Therefore, the threshold for the minimum required LOS is 75 meters. In addition, the sensitivity threshold is taken as -90 dBm in this scenario. After the fourth jammer is added to the particles of the swarm, the signal level constraint is satisfied, and the algorithm converges the solution with four jammers. LOS constraint is satisfied for all of the iterations. In this scenario, this figure is provided to show that the algorithm converges with a solution. Therefore, this figure for other scenarios has not been published.

4.4.2 Scenario-2

Table 4.3 Characteristics of Scenario-2

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	Low
Number of Restricted Zones	0
Distribution of Restricted Zones	-
Number of Target Areas	1
Density of Road Networks	High
Antenna Height (m)	35
Sensitivity Level (dBm)	-90

In this scenario, the effect of altitude can be observed since the altitude level of the target area is higher than the feasible regions. In addition, the LOS is not clear due to the position of the target area. This scenario demonstrates the performance of the algorithm under hard altitude problem conditions.

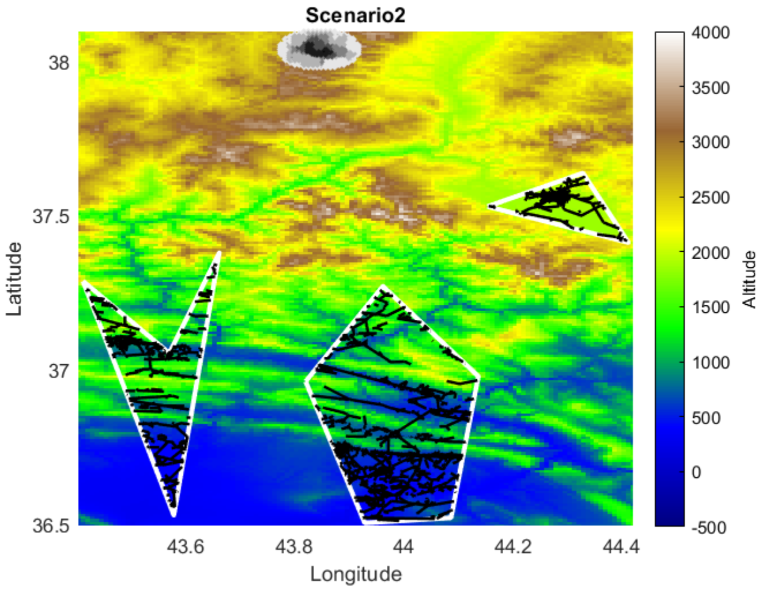

Figure 4.11. Scenario-2 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.4 Optimal Jammer Locations for Scenario-2

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.211333	37.385461	36.983633	37.302266
Longitude	43.523666	43.669432	43.848620	43.977446
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.000461	36.922534	37.529019	37.486328
Longitude	44.069133	44.096451	44.276366	44.301467

The optimization algorithm finds the optimum solution with 8 number of jammers. Two of these jammers are located in the quadrangle area, two of them are inside the triangle area, and the rest of the jammers are inside the pentagon region. Since the distance between the target area and feasible regions is high and the altitude levels of feasible regions are low, eight jammers are required.

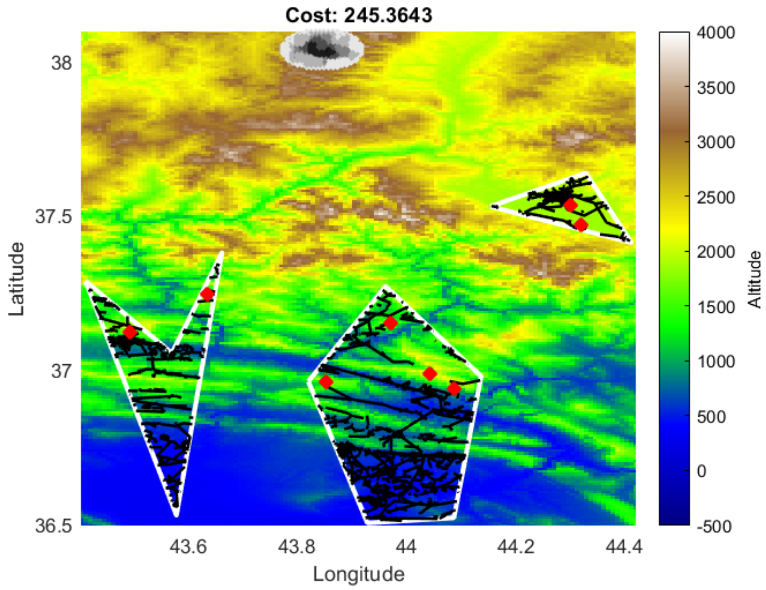

Figure 4.12. Scenario-2 Solution

4.4.3 Scenario-3

Table 4.5 Characteristics of Scenario-3

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	High
Number of Restricted Zones	3
Distribution of Restricted Zones	One inside each feasible region
Number of Target Areas	1
Density of Road Networks	Low
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

In this scenario, a new challenge that significantly reduces the flexibility of jammer placement is introduced. Inside each feasible jammer deployment polygon, there is a restricted area. In order to see the effect of the restricted zones, the other parameters are chosen as good conditions, such as altitude and the position of the target area.

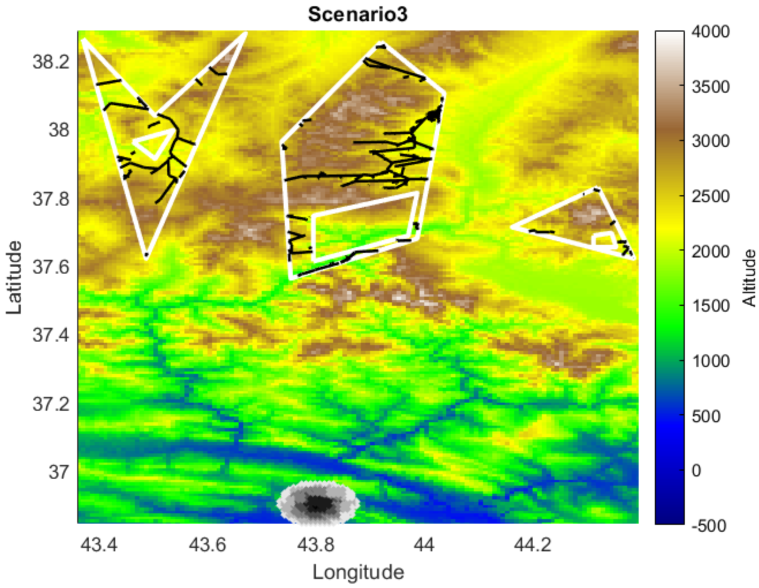

Figure 4.13. Scenario-3 Visualization

The optimization algorithm for this scenario provides the following results. There are five jammers, and the locations of the jammers, namely, the numerical results for the optimal jammer locations, are given in the table.

Table 4.6 Optimal Jammer Locations for Scenario-3

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**	**Jammer 5**
Latitude	37.793927	37.835333	37.827799	37.841792	37.736000
Longitude	43.833016	43.951264	43.842541	43.870049	44.292706

The optimization algorithm finds the optimum solution with 5 number of jammers. These jammers are placed at the highest locations according to the enemy target area. Four of the jammers are placed directly north of the target area. One of the jammers is placed east of the target area. This jammer satisfies the constraints for the east side of the target area. The cost value is around 90.

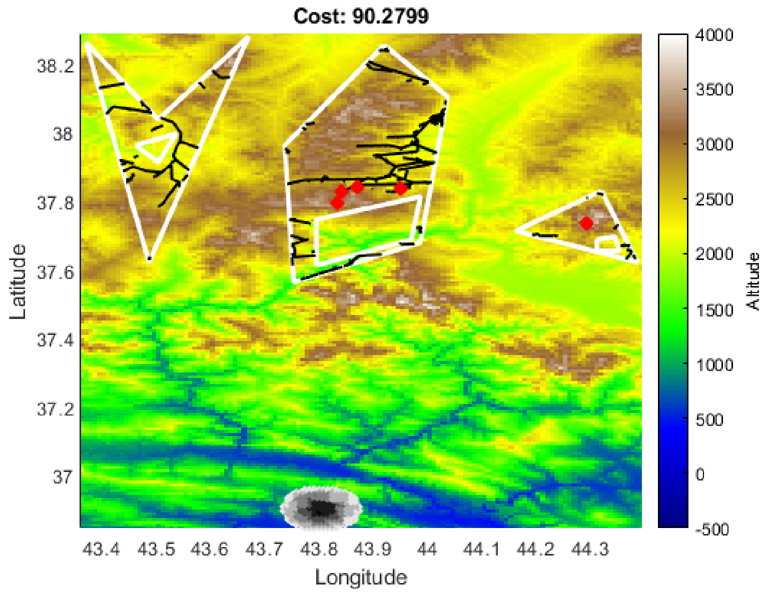

Figure 4.14. Scenario-3 Solution

4.4.4 Scenario-4

Table 4.7 Characteristics of Scenario-4

Characteristics	**Explanations**
Number of Feasible Regions	3
Types of Feasible Regions	Convex quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	Low
Number of Restricted Zones	3
Distribution of Restricted Zones	One inside each feasible region
Number of Target Areas	1
Density of Road Networks	High

Table 4.7 (continued)

Antenna Height (m)	15
Sensitivity Level (dBm)	-90

After testing the jammer deployment with restricted zones and good conditions, the altitude levels of feasible regions are decreased. Therefore, like “Scenario-2”, the conditions become worse.

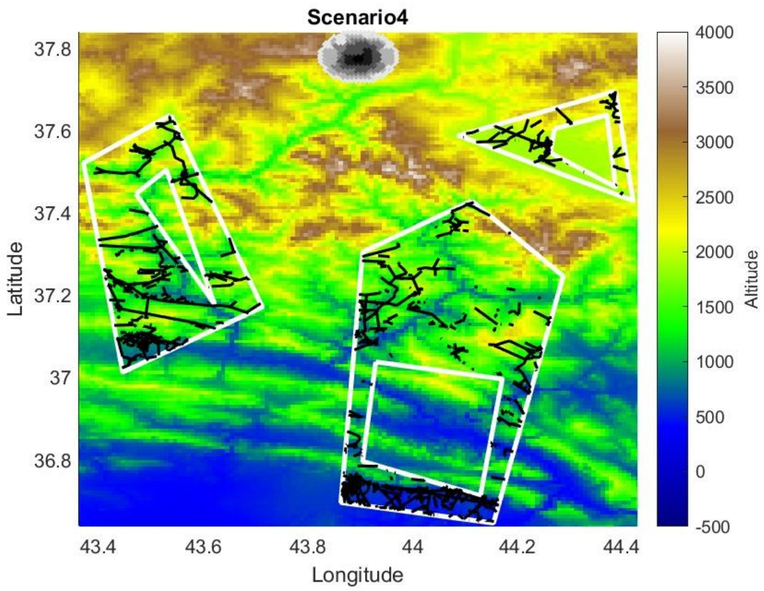

Figure 4.15. Scenario-4 Visualization

The optimization algorithm for this scenario provides the following results.

Table 4.8 Optimal Jammer Locations for Scenario-4

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	37.590000	37.390955	37.194000
Longitude	43.505000	43.600833	44.014000
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.182388	37.228666	37.176886
Longitude	43.989458	43.514500	43.528023

The optimization algorithm finds the optimum solution with six numbers of jammers. Many of the jammers are placed near to the roads. Four of the jammers are located in the west of the target area, and the others are deployed in the east. On the other hand, there is no jammer inside the triangular feasible region due to the altitude levels and the detectability constraints. All these jammers cover the target area completely. The cost value is around 121.

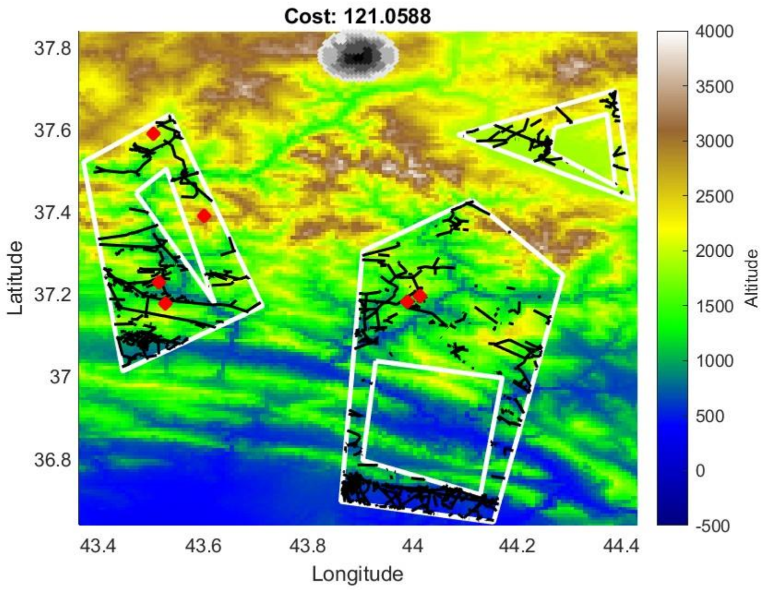

Figure 4.16. Scenario-4 Solution

4.4.5 Scenario-5

Table 4.9 Characteristics of Scenario-5

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	High
Number of Restricted Zones	1

Table 4.9 (continued)

Distribution of Restricted Zones	A lake inside the convex pentagon
Number of Target Areas	2
Density of Road Networks	Normal
Antenna Height (m)	10
Sensitivity Level (dBm)	-90

The algorithm is tested under different altitude and restriction conditions. In this scenario, a new target area is introduced to the problem, and there are two different target areas. These target areas are located on the same side, south, of the feasible regions. Locating at the same side provides an easier challenge to the problem according to the locating different sides. In addition, the altitude levels of the feasible regions are better than the target areas. Therefore, this scenario represents two target areas problem under good conditions.

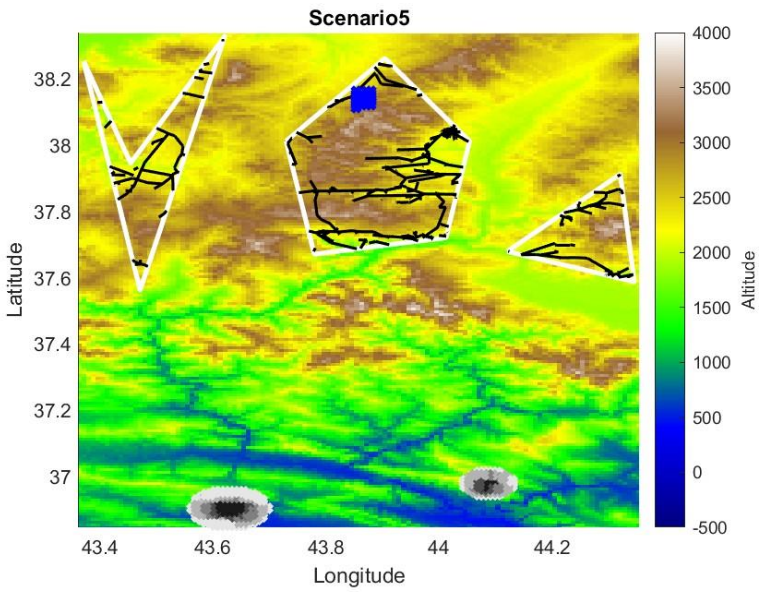

Figure 4.17. Scenario-5 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.10 Optimal Jammer Locations for Scenario-5

	Jammer 1	Jammer 2	Jammer 3
Latitude	37.741072	37.742000	37.750000
Longitude	43.857857	43.902813	44.303000

The optimum solution requires three numbers of jammers. Two of the jammers are placed near the roads and in the closest locations to the target areas. One of the jammers is located at the west of the target areas, and it is mainly responsible for the west-sided target area. There is no jammer inside the quadrangle region. The reasons are the altitude levels and the distance to the target area. The cost value is around 60.

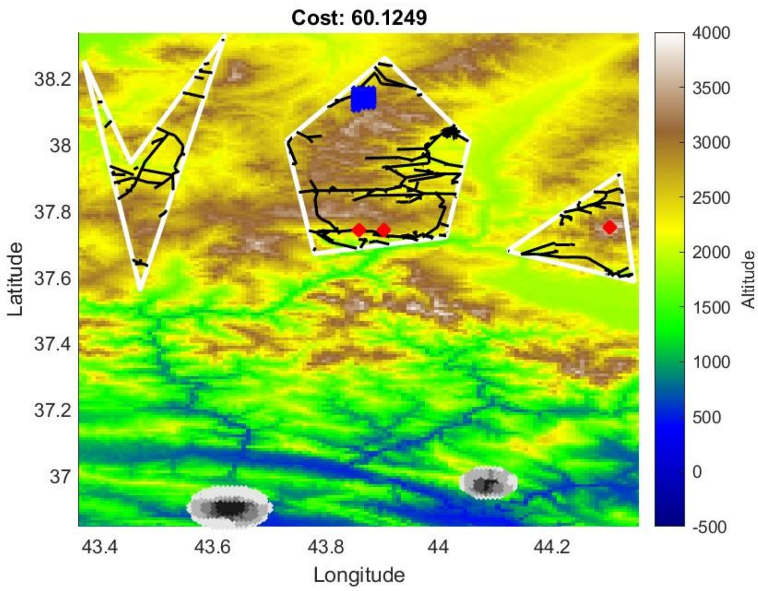

Figure 4.18. Scenario-5 Solution

4.4.6 Scenario-6

Table 4.11 Characteristics of Scenario-6

Characteristics	Explanations
Number of Feasible Regions	3

Table 4.11 (continued)

Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	High
Number of Restricted Zones	1
Distribution of Restricted Zones	A lake inside the convex pentagon
Number of Target Areas	2
Density of Road Networks	Normal
Antenna Height (m)	10
Sensitivity Level (dBm)	-90

In this testing scenario, there are again two target areas; however, the target areas are located on different sides of the feasible regions. One of the target areas is on the southwest, and the other is on the northeast side of the problem map. The altitude values of the feasible regions' difficulty stay the same so as to discover the effect of two target areas with different sides.

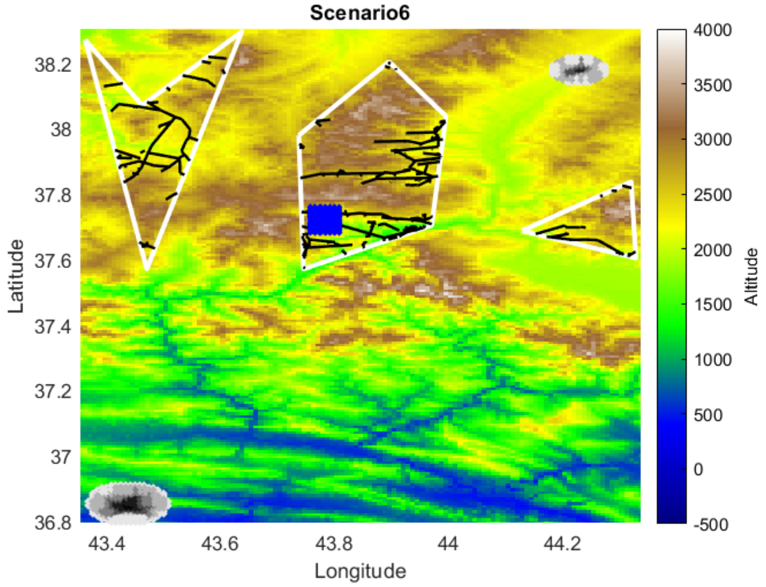

Figure 4.19. Scenario-6 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.12 Optimal Jammer Locations for Scenario-6

	Jammer 1	Jammer 2	Jammer 3
Latitude	37.811357	37.790985	38.107166
Longitude	43.866166	43.804531	43.900333

The optimization algorithm finds the optimum solution with three numbers of jammers. Two of the jammers are mainly responsible for the target areas, which are at the south-east and the north-west of the map, respectively. One of the jammers is located at the center of the pentagon feasible region and provides a jamming signal for both of the target areas. All of the jammers are located at the highest locations of the feasible region. The cost value is around 55.

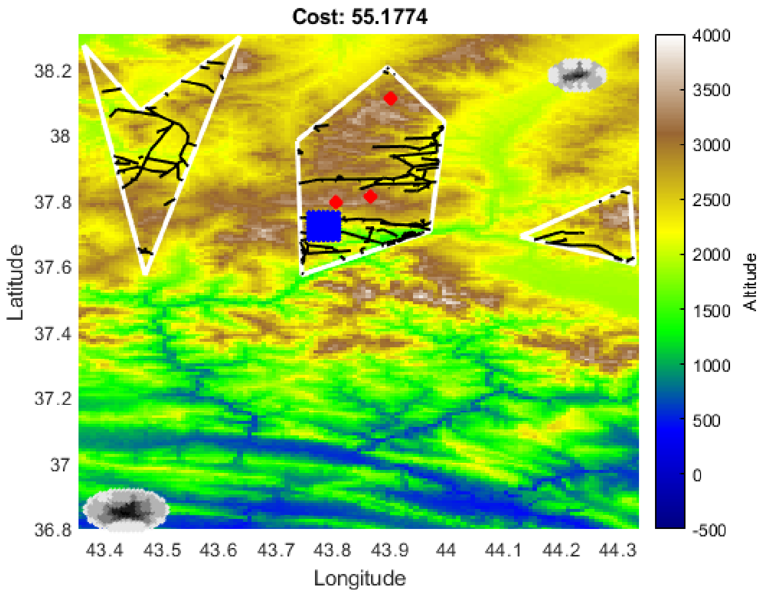

Figure 4.20. Scenario-6 Solution

4.4.7 Scenario-7

Table 4.13 Characteristics of Scenario-7

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	Low
Number of Restricted Zones	1
Distribution of Restricted Zones	A lake inside the convex pentagon
Number of Target Areas	2
Density of Road Networks	High
Antenna Height (m)	35
Sensitivity Level (dBm)	-90

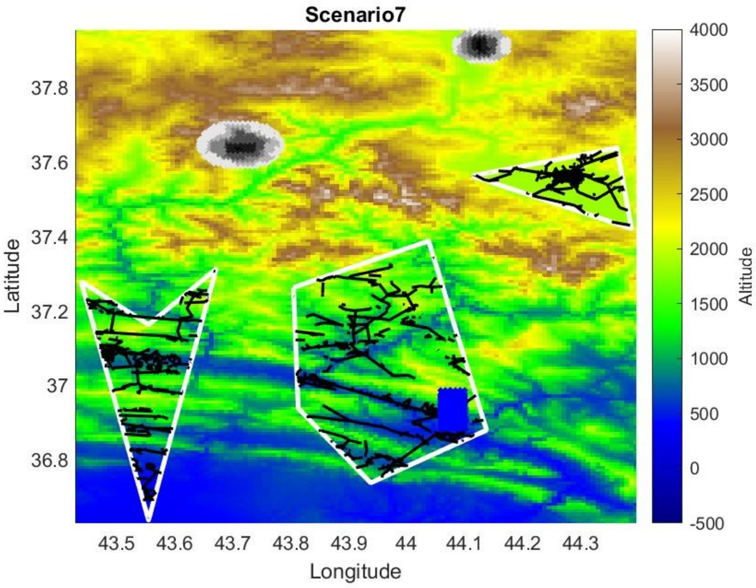

Figure 4.21. Scenario-7 Visualization

In this case, the target areas have greater altitude values than the jammer deployment areas. Therefore, the scenario tests the two target areas problem under hard conditions. In order to realize the aim of the scenario, the target areas are located on the same side of the feasible regions. The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.14 Optimal Jammer Locations for Scenario-7

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	37.560320	37.151458	37.256450
Longitude	44.133333	43.530351	43.939794
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.079547	37.544100	37.054166
Longitude	43.534333	44.334772	43.580544

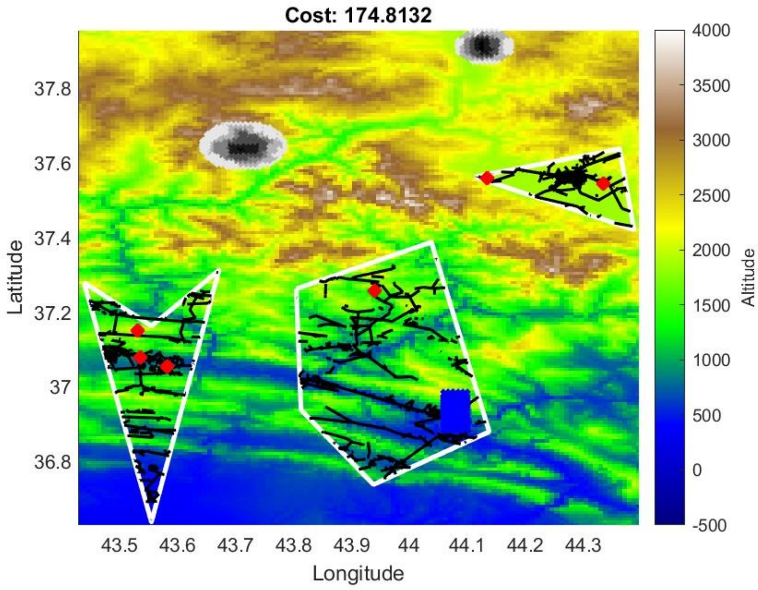

Figure 4.22. Scenario-7 Solution

The optimization algorithm finds the optimum solution with six numbers of jammers. Two of the jammers at the east are mainly responsible for the target area, which is in the south-east. Three of the jammers are located at the concave quadrangle feasible region, providing the jamming signal for the target on the west side. The last jammer located in the pentagon is responsible for both of the target areas. The cost value is around 174 since the locations of the jammer deployment regions increase the difficulty of the problem.

4.4.8 Scenario-8

Table 4.15 Characteristics of Scenario-8

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	Low
Number of Restricted Zones	1
Distribution of Restricted Zones	A lake inside the convex pentagon
Number of Target Areas	2
Density of Road Networks	High
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

This scenario is the hardest one among the scenarios that have no large restricted zone areas. The positioning of the target areas on different sides of the feasible regions and the low altitude levels of jammer deployment areas increase the challenge in the scenario. Therefore, this scenario demonstrates the optimization performance under hard conditions.

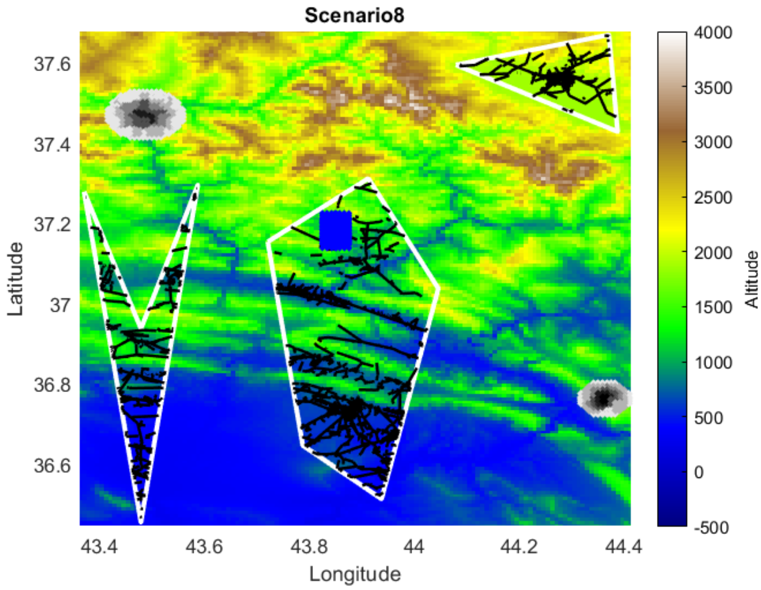

Figure 4.23. Scenario-8 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.16 Optimal Jammer Locations for Scenario-8

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	36.973210	37.147333	36.690390
Longitude	43.499570	43.909666	43.888937
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.087833	37.021225	36.959746
Longitude	43.773123	43.857157	43.886675

The optimization algorithm finds the optimum solution with six numbers of jammers. Any of the jammers are located in the feasible region on the northeast side of the map since this feasible region is away from the target areas, although this feasible region has greater altitude values than the other feasible regions.

In addition, one of the jammers is located in the concave quadrangle area, and it is responsible for the target area located on the northwest side of the map.

On the other hand, there are five jammers in the pentagon region. These jammers are responsible for both of the target areas. The cost value is gathered around 209.

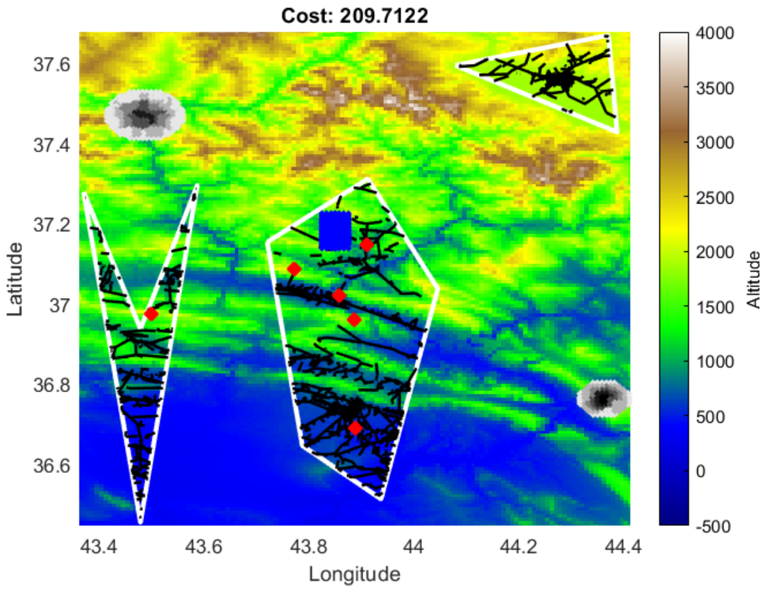

Figure 4.24. Scenario-8 Solution

4.4.9 Scenario-9

Table 4.17 Characteristics of Scenario-9

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	High
Number of Restricted Zones	4
Distribution of Restricted Zones	One inside each feasible region and a lake inside the concave quadrangle
Number of Target Areas	2

Table 4.17 (continued)

Density of Road Networks	Low
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

In this scenario, the large restricted areas are introduced under two target areas case. The jammer deployment flexibility can be examined in this case against two target areas. In order to see the aim of the scenario, the other conditions, such as altitude levels and positioning of target areas, are kept favorable.

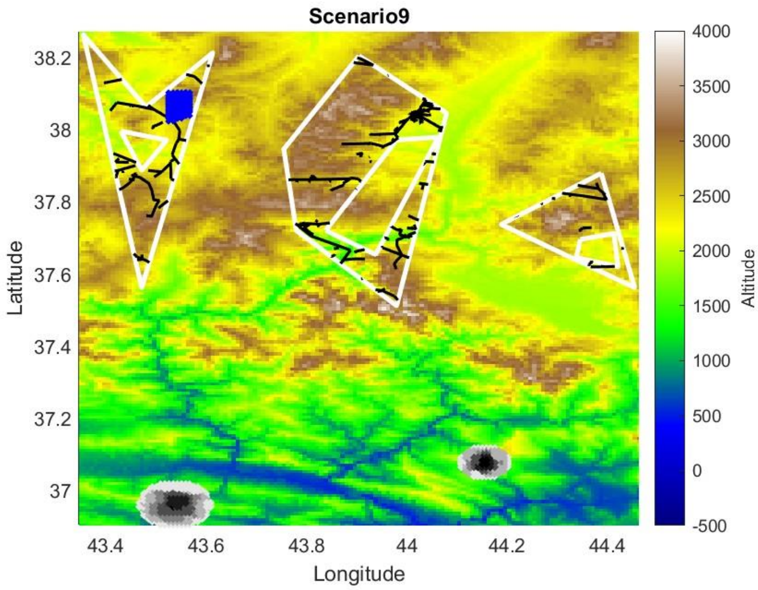

Figure 4.25. Scenario-9 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.18 Optimal Jammer Locations for Scenario-9

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.607857	37.920361	37.783157	37.748833
Longitude	43.963530	43.849189	43.483404	44.307573

The optimization algorithm finds the optimum solution with four numbers of jammers. Two of the jammers at the west and east are responsible for the target areas at the west and east, respectively. Two of the jammers located in the pentagon region help to jam both of the target areas. The cost value is around 61.

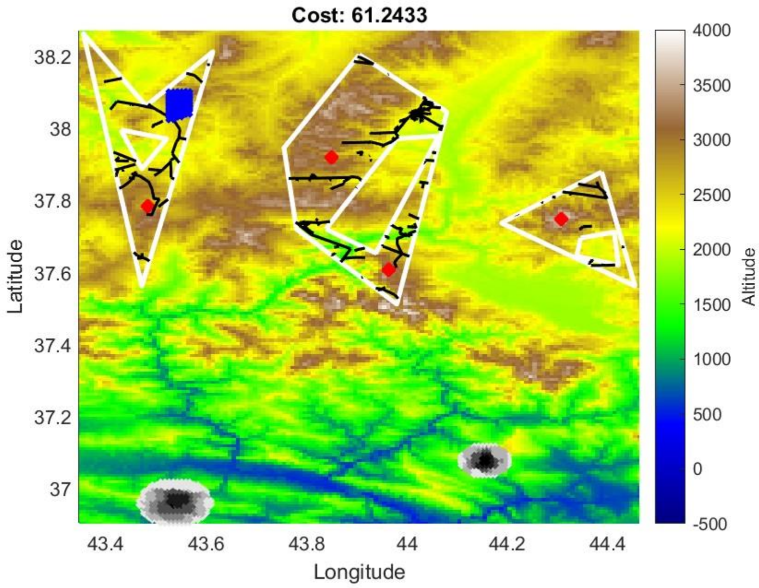

Figure 4.26. Scenario-9 Solution

4.4.10 Scenario-10

Table 4.19 Characteristics of Scenario-10

Characteristics	Explanations
Number of Feasible Regions	3
Types of Feasible Regions	Concave quadrangle, Triangle, Convex pentagon
Altitude Level of Feasible Regions Relative to the Target Area	Similar
Number of Restricted Zones	4
Distribution of Restricted Zones	One inside each feasible region and a lake inside the convex pentagon

Table 4.19 (continued)

Number of Target Areas	2
Density of Road Networks	Low
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

Like the "Scenario-6", the target areas are deployed at the different sides of the feasible regions for the case of introducing the restricted zones. This time, one of the target areas is located northwest, and the other is southeast. In this case, the altitude levels of the feasible regions are not necessarily greater than the target areas. Therefore, this scenario tests the performance of two target areas located on different sides under normal conditions.

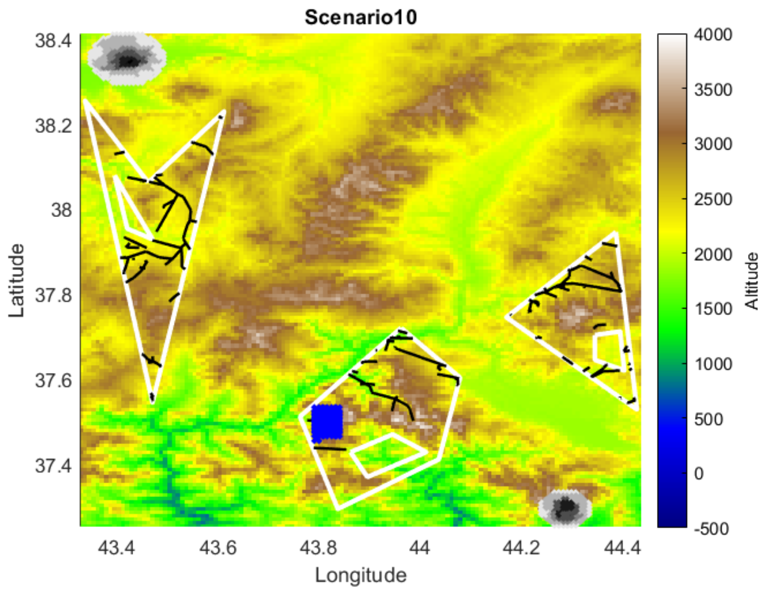

Figure 4.27. Scenario-10 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.20 Optimal Jammer Locations for Scenario-10

	Jammer 1	**Jammer 2**
Latitude	37.746450	37.733730
Longitude	43.480465	44.295064

The optimization algorithm finds the optimum solution with two numbers of jammers. The jammer at the west is responsible for the target area at the west. In addition, the jammer at the east is responsible for the target area at the east.

Since the altitude levels are greater for the feasible regions and some of the feasible regions are close to the target areas, two jammers are required to converge an optimal solution. The cost value is around 60.

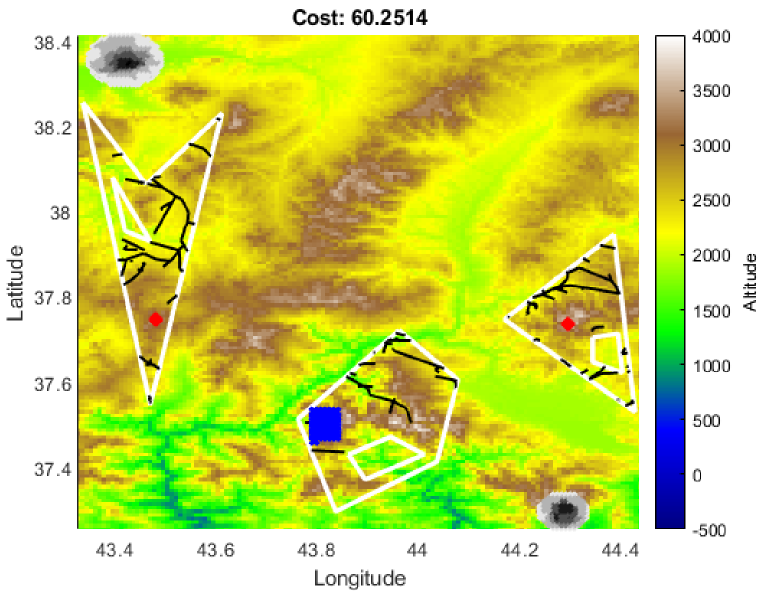

Figure 4.28. Scenario-10 Solution

4.4.11 Scenario-11

Table 4.21 Characteristics of Scenario-11

Characteristics	Explanations
Number of Feasible Regions	2
Types of Feasible Regions	Convex quadrangle, Concave hexagon
Altitude Level of Feasible Regions Relative to the Target Area	High
Number of Restricted Zones	1
Distribution of Restricted Zones	A lake inside the concave hexagon
Number of Target Areas	4
Density of Road Networks	High
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

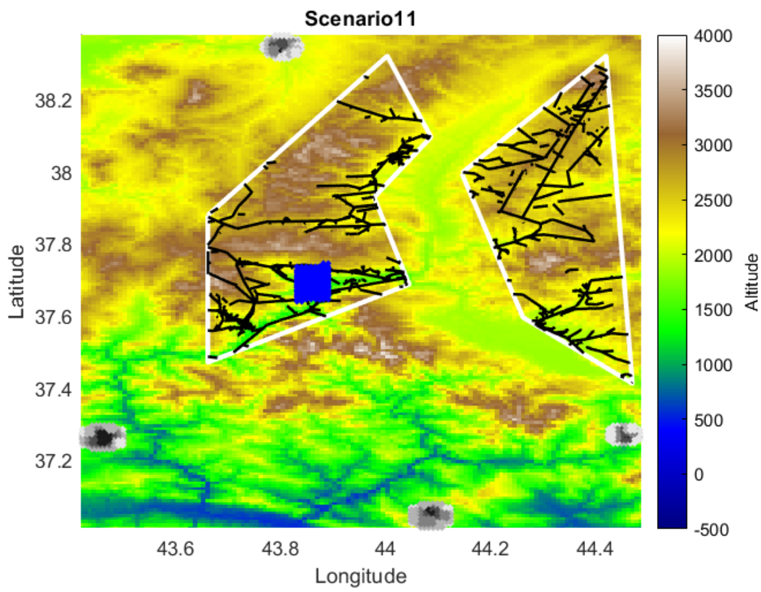

Figure 4.29. Scenario-11 Visualization

This time, there are two feasible regions where the jammers can be deployed. On the other hand, the amount of target areas is increased excessively. Since the number of target areas is increased, their locations are distributed on the map. Therefore, not all of the target areas are on the same side of the map. In this scenario, the optimization algorithm should deal with many target areas while the target areas are not close to each other. The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.22 Optimal Jammer Locations for Scenario-11

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.495215	38.139820	37.581166	37.561547
Longitude	44.404706	43.920722	43.665163	44.369557
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.768012	38.007908	37.711624	37.785913
Longitude	43.712748	43.845372	43.681889	43.810309

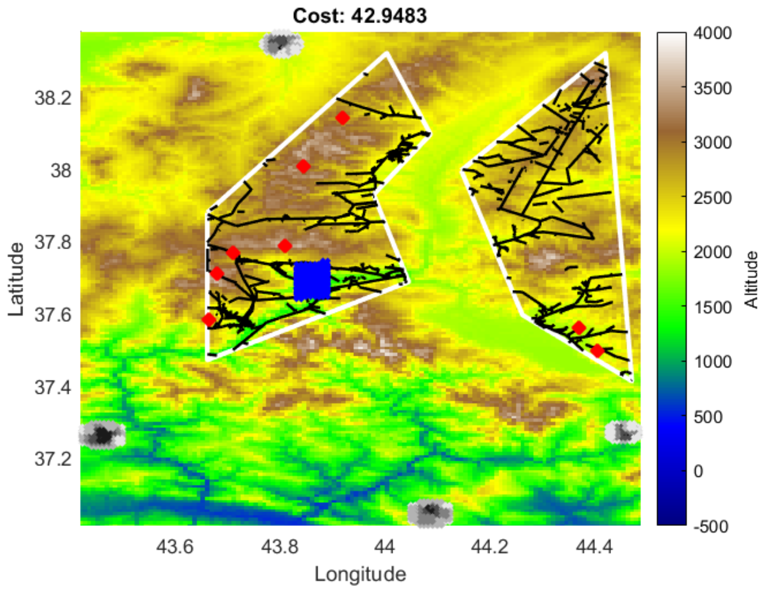

Figure 4.30. Scenario-11 Solution

The optimization algorithm finds the optimum solution with 8 number of jammers. The jammers at the west are deployed to the high grounds. On the other hand, the jammers in the quadrangle area are very close to the target area to satisfy the signal level constraint. Since there are four target areas, the jammers are separated into feasible regions. The cost value is around 43.

4.4.12 Scenario-12

Table 4.23 Characteristics of Scenario-12

Characteristics	Explanations
Number of Feasible Regions	2
Types of Feasible Regions	Convex quadrangle, Concave hexagon
Altitude Level of Feasible Regions Relative to the Target Area	Mixed
Number of Restricted Zones	1
Distribution of Restricted Zones	A lake inside the convex quadrangle
Number of Target Areas	4
Density of Road Networks	High
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

In this scenario, a trade-off between the high altitude levels and distance to the target areas is aimed to test. Therefore, there are two feasible regions. One of them is located at a high ground but far away from the target areas. The other is close to the target areas but has low altitude levels. There are still four target areas, and they are close to each other so as to see the performance of the algorithm for the distance-altitude trade-off problem.

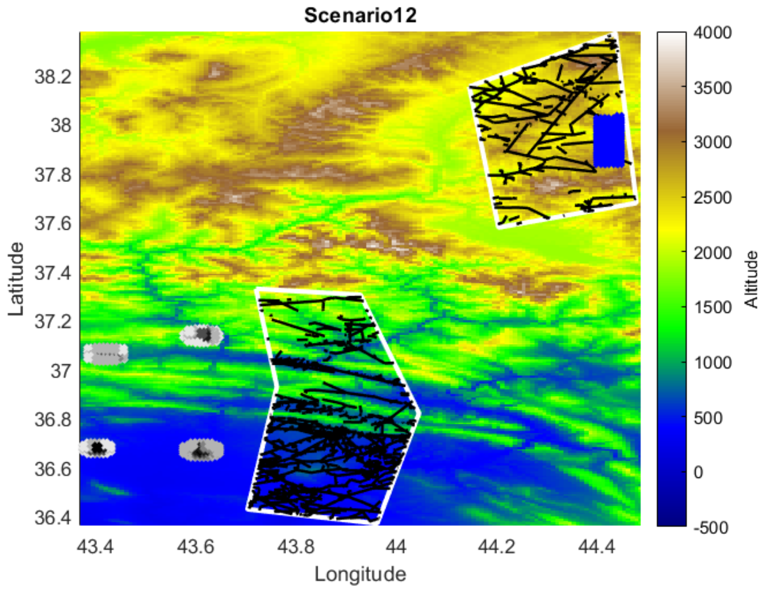

Figure 4.31. Scenario-12 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.24 Optimal Jammer Locations for Scenario-12

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	36.758290	37.211097	36.745322	37.211033
Longitude	43.981184	43.742666	43.830482	43.878564
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.250114	36.794409	37.145705	36.963367
Longitude	43.766266	43.844790	43.787568	43.836008

The optimization algorithm finds the optimum solution with 8 number of jammers. All of these jammers are located at the nearest feasible region, although the other regions have greater altitude values. The reason behind this is the signal level at the target areas. The jammers are also located at the highest regions in the hexagon region. The cost value is around 42.

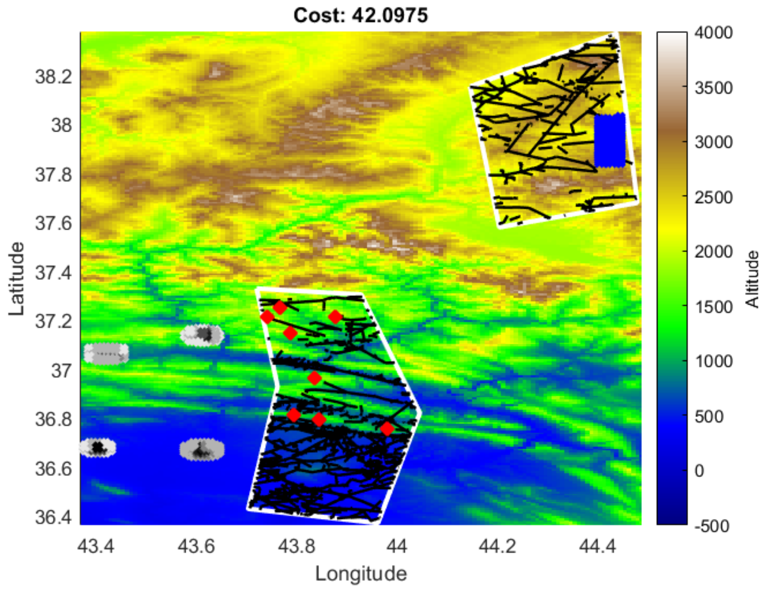

Figure 4.32. Scenario-12 Solution

4.4.13 Scenario-13

Table 4.25 Characteristics of Scenario-13

Characteristics	Explanations
Number of Feasible Regions	1
Types of Feasible Regions	A connected region with two polygons
Altitude Level of Feasible Regions Relative to the Target Area	High
Number of Restricted Zones	3
Distribution of Restricted Zones	One inside the feasible region and two lakes inside the feasible region
Number of Target Areas	4
Density of Road Networks	High
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

In this scenario, the feasible region almost consists of two separated polygons like "Scenario-11". However, there is a connection area between these two polygons. Therefore, the feasible region is a connected polygon. In addition, there is a large restricted zone, and target areas are located on different sides of the feasible region. Therefore, the scenario tests the performance of the algorithm under a large, connected feasible region.

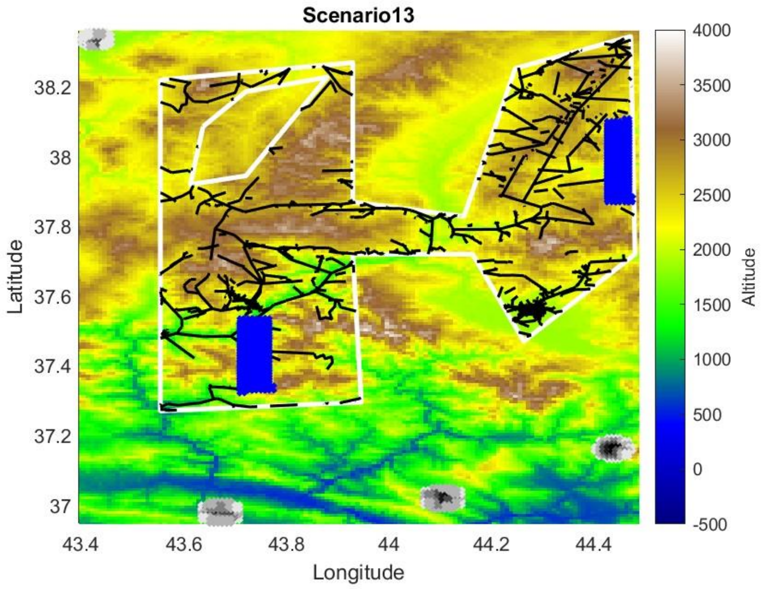

Figure 4.33. Scenario-13 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.26 Optimal Jammer Locations for Scenario-13

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	37.369166	38.153166	37.745889
Longitude	43.892532	43.587333	44.300193
	Jammer 4	**Jammer 5**	-
Latitude	37.712355	37.517666	-
Longitude	43.717300	43.852695	-

The optimization algorithm finds the optimum solution with 5 number of jammers. The target area located on the northwest side of the map is mainly covered by the jammer located at the northwest of the feasible region. Another target area, which is located southeast of the map, is also mainly covered by the nearest jammer. The other three jammers cover the other two target areas and also help to cover the northwest and southwest target areas. The cost value is around 43.

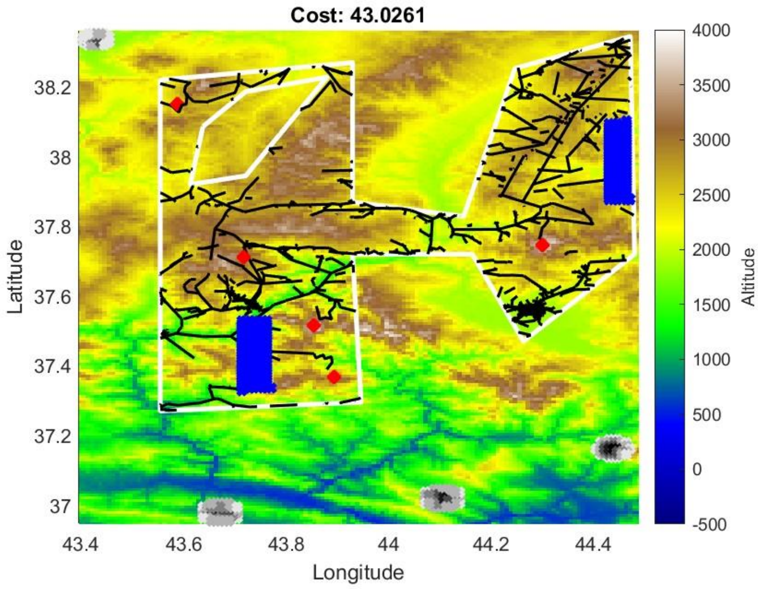

Figure 4.34. Scenario-13 Solution

4.4.14 Scenario-14

Table 4.27 Characteristics of Scenario-14

Characteristics	Explanations
Number of Feasible Regions	2
Types of Feasible Regions	Two convex quadrangles
Altitude Level of Feasible Regions Relative to the Target Area	Mixed
Number of Restricted Zones	3

Table 4.27 (continued)

Distribution of Restricted Zones	One inside each feasible region and a lake inside a concave quadrangle
Number of Target Areas	4
Density of Road Networks	Normal
Antenna Height (m)	10
Sensitivity Level (dBm)	-90

In this scenario, the target areas are distributed in different locations with different altitude values. Therefore, one of the target areas has high ground, two of them are on the normal altitude values, and the last one has a low altitude value. In this problem, the diversity in altitude values of the target areas is tested.

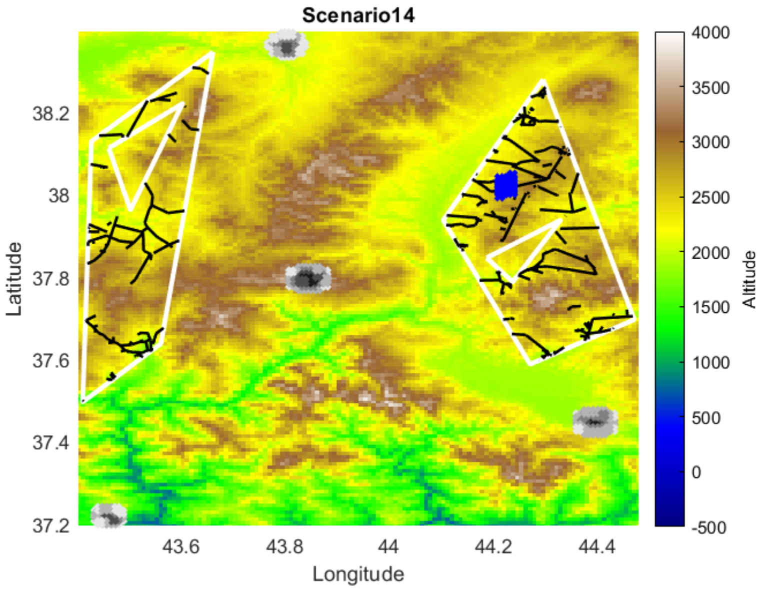

Figure 4.35. Scenario-14 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.28 Optimal Jammer Locations for Scenario-14

	Jammer 1	Jammer 2	Jammer 3
Latitude	37.749300	37.647507	37.734482
Longitude	43.473562	43.465490	44.360150
	Jammer 4	**Jammer 5**	-
Latitude	37.761073	37.749833	-
Longitude	43.503957	44.306071	-

The optimization algorithm finds the optimum solution with 5 number of jammers. The target areas are separated into the different parts of the map. The target area located at the center of the map has a high altitude value. Therefore, the jammers are located at the highest locations of the feasible regions. In the solution, two of the jammers are close to each other. The distance between these two jammers is nearly 3 kilometers. Therefore, the solution does not include the proximity punishment.

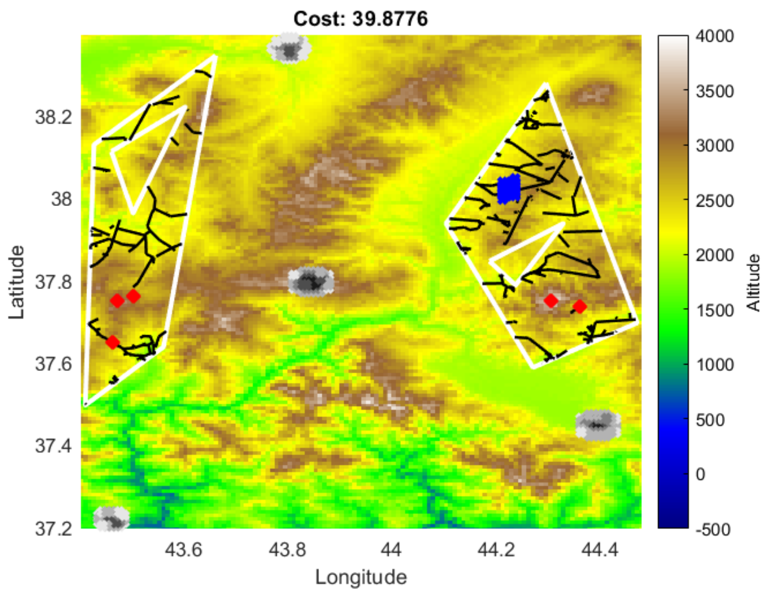

Figure 4.36. Scenario-14 Solution

4.4.15 Scenario-15

Table 4.29 Characteristics of Scenario-15

Characteristics	Explanations
Number of Feasible Regions	1
Types of Feasible Regions	A large polygon
Altitude Level of Feasible Regions Relative to the Target Area	Mixed
Number of Restricted Zones	2
Distribution of Restricted Zones	One inside the feasible region and a lake inside the polygon
Number of Target Areas	4
Density of Road Networks	High
Antenna Height (m)	10
Sensitivity Level (dBm)	-90

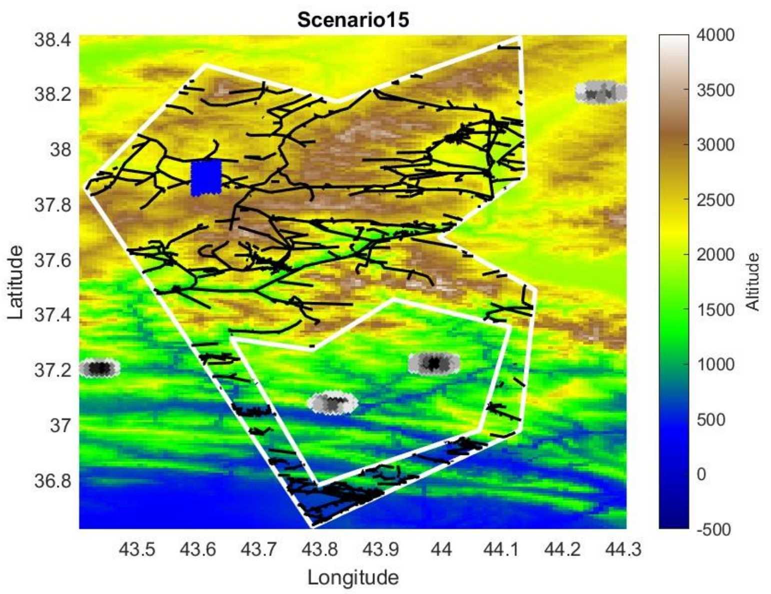

Figure 4.37. Scenario-15 Visualization

The last scenario includes a large feasible region. The restrictions inside the feasible region are also enormous. Since there is a big restricted area, two of the target areas are located inside this restricted area. In addition, two of the target areas are located at the different sides of the feasible region. In this problem, the feasible region has higher and lower altitude values together. The aim of this scenario is to test the behavior of the optimization algorithm when there are target areas inside of the feasible region. The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 4.30 Optimal Jammer Locations for Scenario-15

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	38.138583	37.347966	37.521270
Longitude	44.099893	43.801044	43.854423
	Jammer 4	**Jammer 5**	**-**
Latitude	37.697836	37.788254	-
Longitude	43.682155	43.805124	-

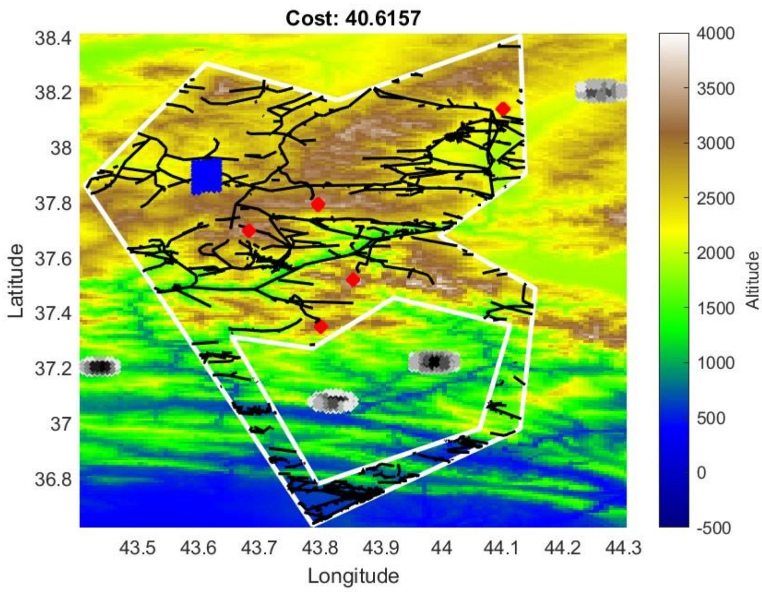

Figure 4.38. Scenario-15 Solution

The optimization algorithm finds the optimum solution with 5 number of jammers. This scenario includes target areas both inside and outside of the feasible region. Two of the jammers mainly cover the target areas inside of the feasible region. On the other hand, one of the jammers focuses on the northeast located target area. The target area located at the west of the map is covered by four center jammers.

CHAPTER 5

PROBLEM 2: MOBILE JAMMERS AND STATIONARY TARGETS

Stationary jammers and stationary targets problem is defined, formulated, and tested in the previous section. However, the jammers can be mobile, and their mobility provides better solutions and protection. In the context of electronic warfare, the enemy can detect the locations of the jammers and attack the jammers [64]. Therefore, the jammers should move from another location where they can still jam the enemy target areas. As a result, mobile jammers and stationary target problem should be considered.

5.1 Problem Definition

In this problem, the objective is to determine the optimal movement if the jammers are detected by enemy forces and the final positions for mobile jammers within a set of feasible operational regions, represented as polygons. The jammers have the capability of moving throughout the operational area in response to detection risks posed by enemy forces. The mobility of the jammers provides them with the ability to perform counter-movements aimed at minimizing their detection risk, while still maintaining effective jamming coverage over a stationary target.

Similar to the previous problem (Problem 1), the feasible regions for jammer deployment are defined by polygons, which can be either convex or concave, and they may also be connected or disconnected. Additionally, these polygons may contain restricted zones, where the jammers are prohibited from entering, such as areas with high-risk exposure, environmental concerns, or operational constraints. These restricted zones create additional barriers that the jammers must avoid during both deployment and movement.

A key aspect of this problem is the consideration of roads within the operational area. Since the jammers are mobile, their ability to move effectively within the operational region is constrained by the presence of roads. Roads are essential for facilitating jammer movement, as the jammers must navigate along the roads to reposition themselves to new optimal locations. The optimization problem must consider the proximity of jammers to roads, balancing ease of movement with jamming effectiveness. While roads enable efficient mobility, the jammers may need to move farther from the roads if doing so significantly increases the overall jamming performance.

The mobility of the jammers introduces dynamic optimization into the problem. The jammers must continuously adjust their positions to evade detection by enemy forces, who may be employing countermeasures to locate and neutralize them. The challenge is to maintain optimal jamming coverage of the stationary target while ensuring that the jammers remain undetected or out of range of enemy threats. This creates a trade-off between the jammers' movement efficiency (based on road proximity) and stealth (reducing the likelihood of detection).

The objective function must now balance several key factors:

- Maximizing jamming effectiveness over the target area, which includes maximizing signal strength and ensuring comprehensive coverage.
- Minimizing cost or resource usage, where deploying fewer jammers is preferred.
- Minimizing the risk of detection by enemy forces, which involves choosing locations that are more difficult to detect, potentially hidden from enemy sensors or reconnaissance.
- Minimizing movement time by using roads for efficient travel between positions.

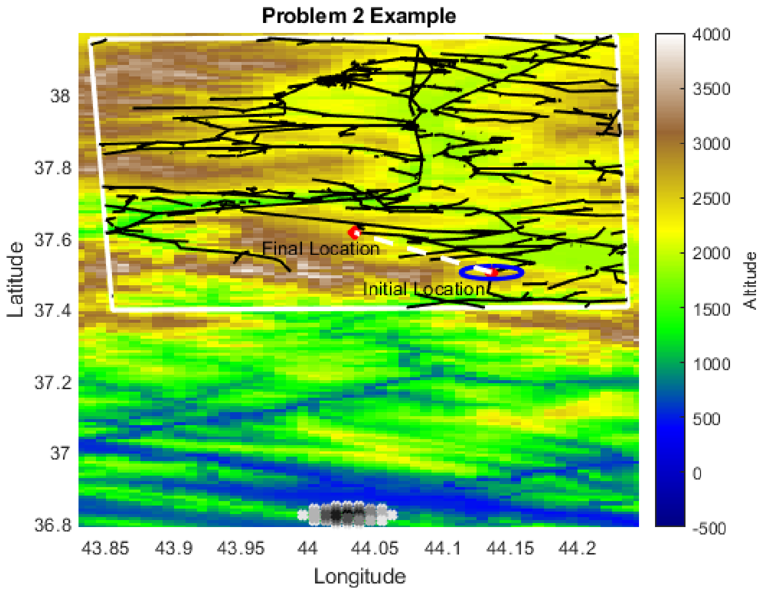

Figure 5.1. Problem 2 Visualization

In this visualization, the red dots represent the jammer deployment points. When the jammer is deployed into the initial location, its detectability is increased in the blue-circled area. Therefore, the jammer should move out to the blue circle area. As a result, it finds a final location that meets the optimization constraints, and the mobility of the jammer is used to decrease the detectability while still meeting the constraints.

5.2 Problem Formulation

The problem is mainly similar to the stationary jammers and stationary targets problem. There are two unknowns for the problem.

The first unknown is the final geolocation points of the mobile jammers in terms of latitude and longitude. This unknown should be updated when the friend jammers are detected by the enemy forces. Therefore, the solution for this unknown should be up-to-date. In addition, the geolocation of the jammers should be updated by considering the LOS requirements, signal level thresholds, terrain features, and potential obstacles.

Throughout this section, the following notations are used to represent the geographical coordinates of the jammers;

$$P_j = (x_j, y_j), j = 1,2, \dots, J \tag{5.1}$$

x_j: Latitude of the j-th jammer.

y_j: Longitude of the j-th jammer.

J: Total number of jammers used in the solution.

The other unknown is the number of jammers in the optimum solution. In the case of mobile jammers, the initial solution may not be maintained, and jammers may need to move. As a result, the new solution may require more jammers to satisfy the constraints. Therefore, the number of jammers is an unknown for the problem, and it is represented by J throughout this section, where J is a positive integer. In the solution, a minimum number of jammers should be used so as to keep the consumption to a minimum.

5.2.1 Objective Function

The objective of the study is to minimize the total LOS between the jammers and target areas and maximize the jamming signal level at the target areas. Constraints can also be satisfied while minimizing the total cost. In addition, the locations of the jammers should be away from each other in order to decrease the detectability by the enemy forces. Therefore, the objective function is constructed by considering the mentioned parameters.

$$F(P_i, J) = \left(\min_{\{P_i, J\}} (LOS_{Total} - SL_{Total})\right) \cdot K \tag{5.2}$$

Total LOS and signal level can be calculated as the following equations;

$$LOS_{Total} = \frac{1}{|T|} \cdot \frac{1}{J} \cdot \sum_{j=1}^{|T|} \left(\sum_{i=1}^{J} \left(\int_{T_j} \min\left(LOS(P_i, t)dt\right)\right)\right) \tag{5.3}$$

$$SL_j = \int_{T_j} \left(\sum_{i=1}^{J} SL(P_i, t) \right) dt \tag{5.4}$$

$$SL = SignalSum\left(SL_j \circ SL_j\right) \text{ for } j = 1,2, \dots, |T| \tag{5.5}$$

$$SL_{Total} = \frac{1}{|T|} \cdot \sqrt{SL} \tag{5.6}$$

Where, $P_i \in A - A'$.

$P_i = (x_i, y_i)$ is the coordinates of the i-th jammer in the deployment area $(A - A')$.

A is the continuous area in which jammers can be deployed. On the other hand, A' is the continuous area in which jammers cannot be deployed due to the detectability risks. Therefore, $(A - A')$ refers to the set of geolocation that is inside the area A and outside the area A'.

T is the set of target areas.

T_j represents the continuous set of points within a target area, which is an element of the set T.

$|T|$ shows the number of elements in the set T.

J is the minimum number of jammers to satisfy the constraints.

K is the punishment coefficient according to the proximity of the jammers. K value is defined in the constraints as it is mostly dependent on constraints.

$A \circ B$ notation represents the elementwise multiplication.

5.2.2 Constraints

The problem has five constraints. The first constraint considers the feasible jammer deployment area. Thus, the locations of the jammers should be inside the feasible region A and outside the detected area A'. In addition, the detected jammers should stay on the same road with the initial road.

$$P_i \in (A - A') \text{ for all } i = 1,2, \dots, J$$

$$P_j \in R_j \text{ for all detected jammers}$$

P_j represents the jammers that are detected by the enemy forces.

R_j demonstrates the connected road of j-th jammer.

Although the detected jammers move to another location from their initial best locations, the jamming signal level at the target areas should be greater than the sensitivity level of the enemy electronics. This constraint is similar to the signal level constraint in "Problem 1".

In addition, the LOS is important for this problem similarly. Therefore, the arrived location of the mobile jammers should ensure the LOS constraint of the problem. This constraint is similar to the LOS constraint in "Problem 1".

Since the detected jammers are moved to another location, their danger level decreases. However, when these jammers are set up in their new locations, the danger level starts to increase. Therefore, the new locations should have the minimum initial danger level values. The aim is to keep the initial danger level at a minimum; thus, the danger level constraint is similar to "Problem 1".

The last constraint is about the proximity of jammers. The arrived location of the mobile jammers should be very close to the other jammers. If they are close to each other, the detectability risk increases. Therefore, the proximity constraint is similar to the constraint in "Problem 1".

5.3 Solution Technique

In this section, the solution technique that is used to find the optimum jammer placements for mobile systems is explained. If a jammer is not detected by the enemy forces, the location of this jammer does not change. Therefore, this problem focuses on the jammers that are detected by the enemy forces.

MPSO is used as the optimization algorithm. The parameters of the optimization algorithm are kept the same as the solution technique of "Problem 1". In addition, the evaluation of the populations that are produced throughout the optimization process is done in a similar way to "Problem 1". Moreover, the velocity updates in each iteration are the same as in "Problem 1". At the end of the solution, a fine-tuning process is applied to the solution. The fine-tuning process is the same as the "Problem 1". Therefore, the parameter selection, evaluation of constraints and cost functions, and velocity update iterations are passed in this section.

However, the creation of the initial population and handling a non-convergence problem are different from "Problem 1". Thus, these two steps are explained in this section of the study.

Moreover, the mobile jammers should move on the roads. Therefore, if a jammer is detected by the enemy forces, it can go only on the roads. So as to process this constraint, an algorithm that finds the fully connected roads is used.

5.3.1 Finding Connected Roads

In this step of the solution, the roads that are represented with black lines in the scenarios are considered. If a jammer is detected by the enemy forces, then it should be moved to another location. This location should be on the same connected road with the initial location.

However, the detected jammers may not be deployed near the roads at the initial deployment. If a jammer is not on the road, the closest road is accepted as the jammer's road. Therefore, the fully connected road should be calculated according to this road.

On the other hand, the road map may not include all of the roads. Therefore, if the distance between two roads is less than 250 meters, these two roads are accepted as they are connected.

5.3.2 Initial Population

In order to initialize the population, the results gathered from the solution of "Problem 1" are used. Namely, if there is a jammer that is detected by the enemy forces and there are many other jammers that are not detected, then the jammers that are not detected are kept as part of the initial solution. The other jammer, which is detected, should be reinitialized by the algorithm.

In the same way as "Problem 1", the priority levels of feasible regions are used. As a result, particles that are not detected stay in their positions, and the particles that are detected are re-initialized by the algorithm. A circle with 5 5-kilometer radius is calculated, and the re-initialization is produced out of this circle due to the detectability issues.

5.3.3 Handling Non-Convergence Problem

The problem is designed to achieve the optimum jammer deployment in a feasible area with the minimum number of jammers. Due to the detection issues, the optimal solution may be corrupted. Therefore, there may not be another solution that ensures the constraints with the same number of jammers. This problem leads to a non-convergence of the optimization. In order to handle this problem, a new jammer can be added to the particle. Namely, the number of jammers is increased so as to maintain the jamming event effectively, $(J \rightarrow J + 1)$.

On the other hand, increasing jammers may lead to many number of used jammers, and this causes too much resource consumption. Another technique for non-convergence problem is moving not-detected jammers to other locations. Therefore, if MPSO fails to find an optimum solution with $J + 1$ number of jammers, the other jammers can be moved. If these jammers are moved to another location, this location should be out of the circle with 5 kilometers, which represents the high danger level valued area.

$$P_i \in (A - A') \text{ for all } i = 1,2, \ldots, J$$

$$P_j \in (A - A') \text{ for all } i = 1,2, \ldots, J$$

P_i represents the jammers that are detected by the enemy forces.

P_j demonstrates the jammers that are not detected; however, they are moved to another location to maintain the jamming activity effectively.

5.4 Simulations and Results

In this section, the scenarios for mobile jammers and stationary targets are simulated. The simulations aim to test the robustness and flexibility of the optimization algorithm. The scenarios are constructed by considering the complex landscape of electronic warfare. Therefore, the enemy can detect the jamming signal transmitter and attack this jammer.

The scenarios are chosen from the scenarios of "Stationary Jammers and Stationary Targets". The reason is that using the feasible solutions, which are gathered in this section, are the initial conditions of mobile jammers. Therefore, 10 of the scenarios are taken from the previous section.

All of the scenario figure information is the same with the "Stationary Jammers and Stationary Targets". In addition to this information, the blue circles in this section represent the detected area by the enemy forces. Therefore, the detected jammers should move out of this area and any jammers cannot enter in this area. Moreover, there are magenta points on the solution figures. These points represent the new position of the detected jammers or the new jammers that are added to the solution particle. The new positions and new jammers are indicated with the texts that are near the magenta points.

5.4.1 Scenario-1

Table 5.1 Characteristics of Scenario-1

Characteristics	Explanations
Number of Total Jammers	4
Number of Detected Jammers	1
Number of Target Areas	1
Difficulty Level of the Scenario	Low
Density of Road Networks	Normal

The first scenario is also the first scenario of "Problem 1". This scenario represents the ideal case situation for mobile jammer problems since there are enough roads to deploy the mobile jammer into its new location, and the feasible regions have greater altitude values than the target area. In this scenario, one of the four jammers is detected by the enemy forces. This jammer cannot remain jamming event in the area represented with the blue circle due to the risk of enemy forces' attacks. For the initial deployment of jammers, the cost function is around 90.

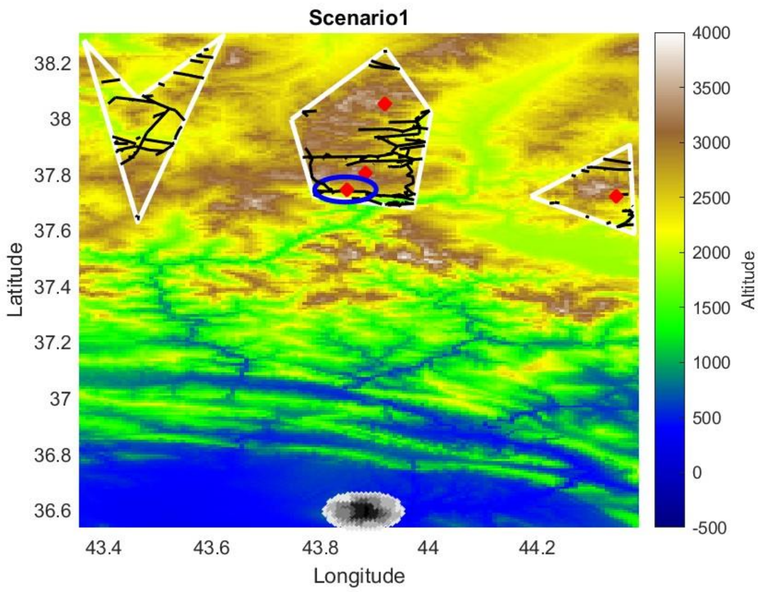

Figure 5.2. Scenario-1 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 5.2 Optimal Jammer Locations for Scenario-1

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.720666	38.050319	37.803666	37.823278
Longitude	44.345333	43.918318	43.882333	43.943875

The optimization algorithm finds a new position for the detected jammer. The new position has a high altitude value like the previous position. However, the cost function increases to around 110 since the new position of the jammer is further to the target area, and the LOS is not as clear as the previous position.

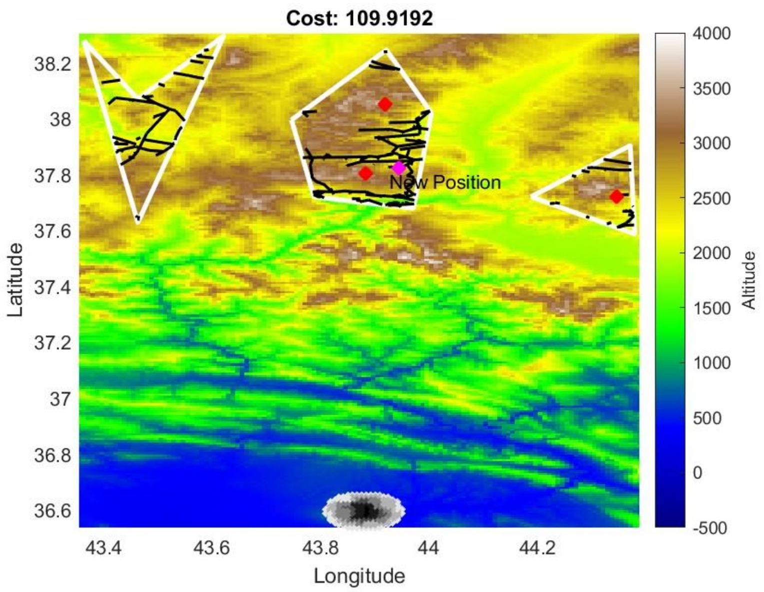

Figure 5.3. Scenario-1 Solution

5.4.2 Scenario-2

Table 5.3 Characteristics of Scenario-2

Characteristics	Explanations
Number of Total Jammers	6
Number of Detected Jammers	1
Number of Target Areas	1
Difficulty Level of the Scenario	High
Density of Road Networks	Normal

This scenario is the harder version of the first scenario, and it is “Scenario-4” of “Problem 1”. This time, the altitude levels of the feasible region are lower than the altitude level of the target area. One of the six jammers is detected, and it cannot be placed in the blue-circled area on the map. For the initial deployment of jammers, the cost function is around 121.

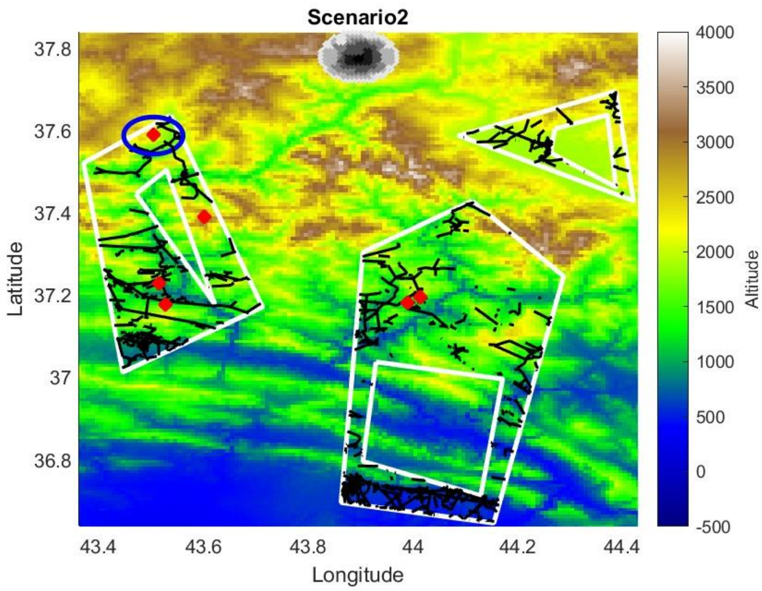

Figure 5.4. Scenario-2 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 5.4 Optimal Jammer Locations for Scenario-2

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.390955	37.194004	37.182388	37.228666
Longitude	43.600833	44.014050	43.989458	43.514504
	Jammer 5	**Jammer 6**	**Jammer 7**	**-**
Latitude	37.176886	37.472249	37.643677	-
Longitude	43.528023	43.561714	44.281696	-

The optimization algorithm finds a new position for the detected jammers; however, it requires one more jammer to continue jamming the target area effectively. The second jammer has a clear LOS and is responsible for maintaining the LOS constraint. The cost function value increases to around 134 since the previous location of the jammer is close to the target area and has a high altitude value.

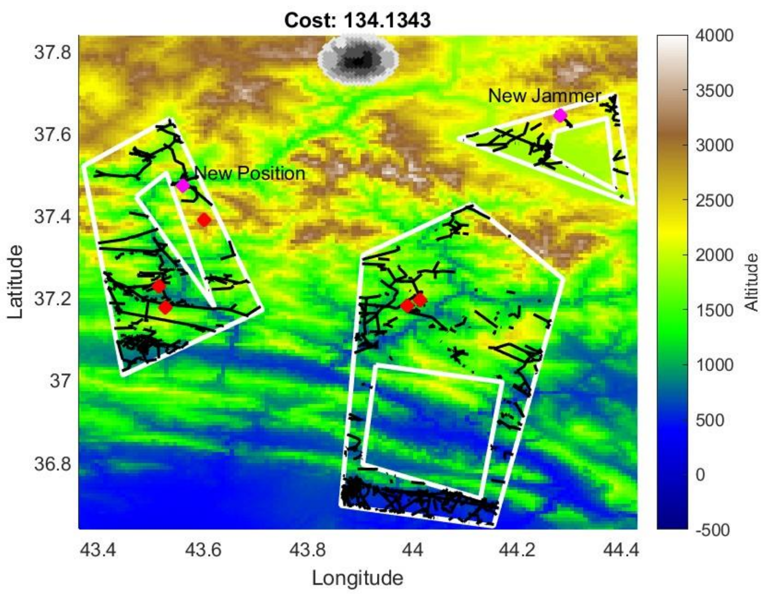

Figure 5.5. Scenario-2 Solution

5.4.3 Scenario-3

Table 5.5 Characteristics of Scenario-3

Characteristics	Explanations
Number of Total Jammers	3
Number of Detected Jammers	2
Number of Target Areas	2
Difficulty Level of the Scenario	Low
Density of Road Networks	Normal

This scenario is taken from “Scenario-5” of “Problem 1”. When there is no detection by the enemy forces, the solution requires three jammers. However, the enemy forces can detect two of the jammers inside the pentagon region over time. Therefore, two of the jammers should be moved to another location so as to minimize the detection by the enemy forces. In this scenario, the difficulty is not as hard as in the previous scenario since the altitude levels of the feasible region are high. The initial cost function value (before the movements of the jammers) is around 60.

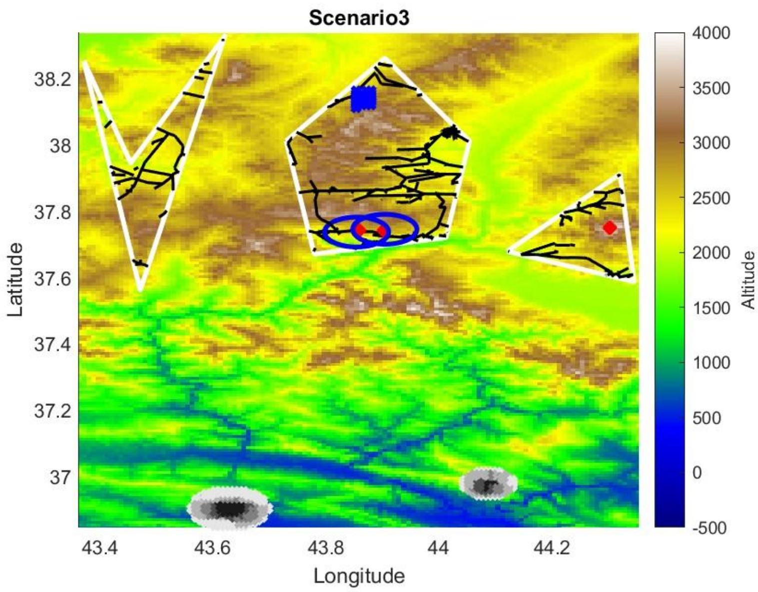

Figure 5.6. Scenario-3 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 5.6 Optimal Jammer Locations for Scenario-3

	Jammer 1	Jammer 2	Jammer 3
Latitude	37.750187	37.833558	37.829719
Longitude	44.303072	43.851461	43.928430

The optimization algorithm finds the solution without the addition of a new jammer to the particle.

The new positions of the jammers are at the north of the previous locations. Since the altitude levels are high and there are clear LOS through the target areas, the cost function does not increase much. On the other hand, the jammer that is not detected still provides clear LOS and, therefore, a substantially higher signal level. The new cost function value is still around 61.

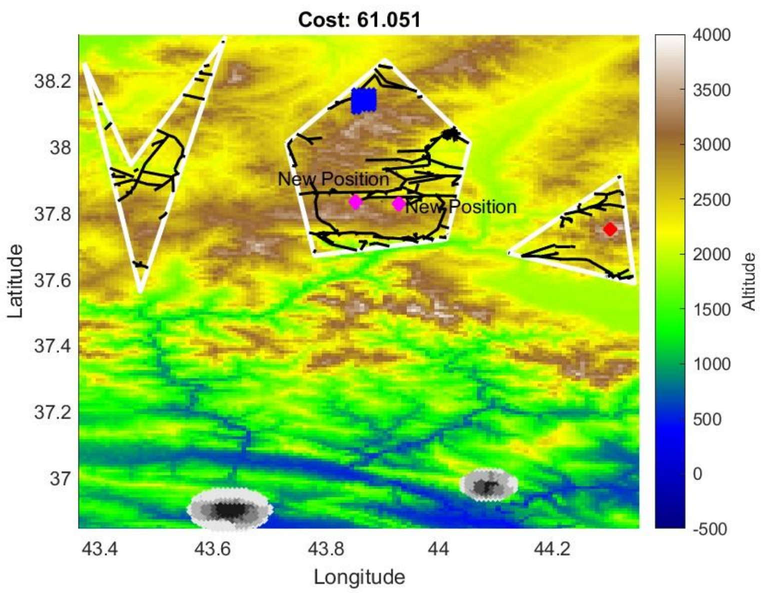

Figure 5.7. Scenario-3 Solution

5.4.4 Scenario-4

Table 5.7 Characteristics of Scenario-4

Characteristics	Explanations
Number of Total Jammers	6
Number of Detected Jammers	2
Number of Target Areas	2
Difficulty Level of the Scenario	High
Density of Road Networks	Normal

This scenario is the harder version of the two target areas scenarios since the feasible regions have lower altitude values. In this scenario, two of the jammers are detected by the enemy forces, and they are located in different feasible regions. Therefore, they should move to their feasible regions. The before movement cost function value is around 175.

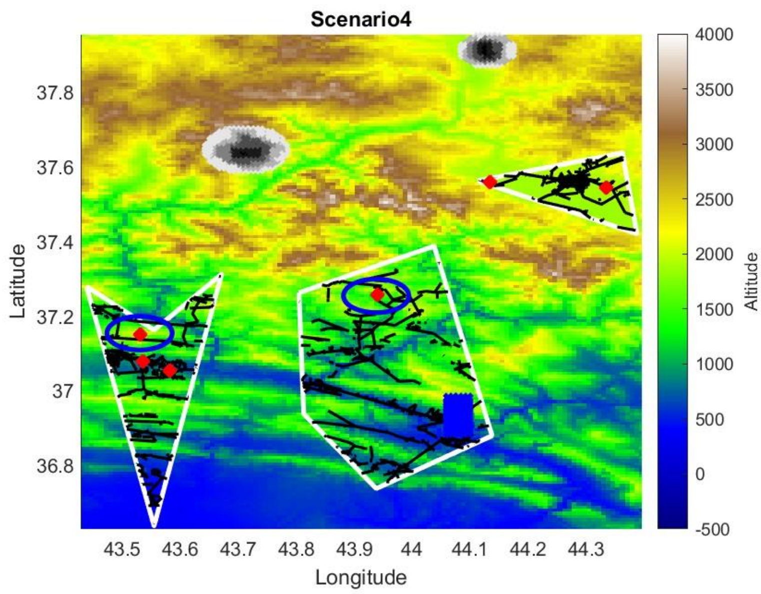

Figure 5.8. Scenario-4 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 5.8 Optimal Jammer Locations for Scenario-4

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.560173	37.079547	37.544107	37.054166
Longitude	44.134383	43.534333	44.334772	43.580500
	Jammer 5	**Jammer 6**	**Jammer 7**	**-**
Latitude	37.228571	37.216634	36.976190	-
Longitude	43.644539	44.008295	43.538695	-

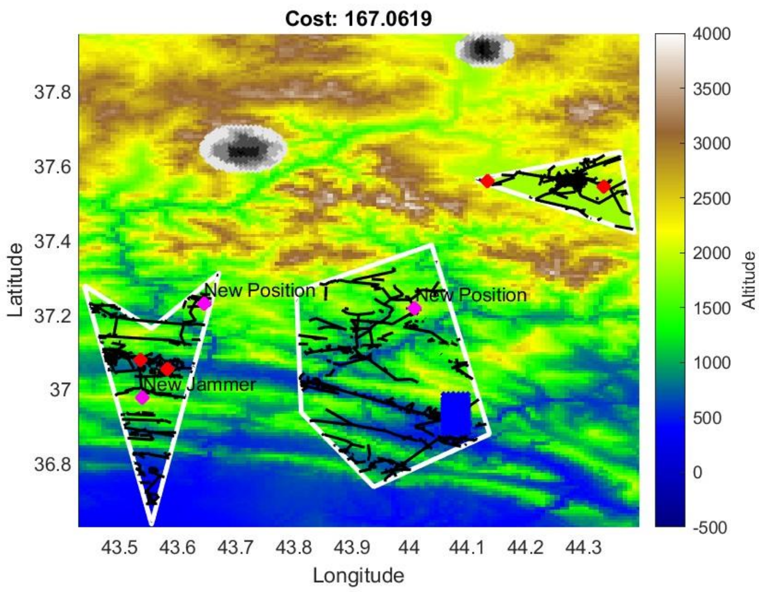

Figure 5.9. Scenario-4 Solution

The optimization algorithm finds a new solution with the addition of one extra jammer to the particle. Since the previous jammers are located close to the target area around the west side of the map, the signal level decreases if the distance increases between the target area and new jammer locations. The detected jammer, which is located in the pentagon region, goes away from the target area. Therefore, a new jammer is required. In order to keep the minimum required LOS and signal level constraints satisfied, the new jammer is located at the high ground and as close as possible to the west side target area. The new cost function is around 167. The addition of new jammers decreases the cost function below the previous value.

5.4.5 Scenario-5

Table 5.9 Characteristics of Scenario-5

Characteristics	Explanations
Number of Total Jammers	4
Number of Detected Jammers	2
Number of Target Areas	2
Difficulty Level of the Scenario	Low
Density of Road Networks	Low

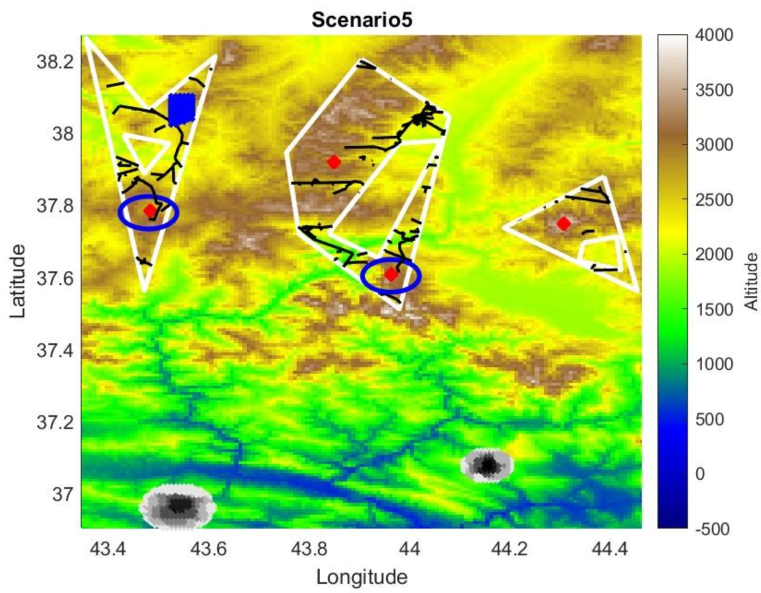

Figure 5.10. Scenario-5 Visualization

This scenario is taken from the “Scenario-9” of the “Problem 1”. In this scenario, the density of the roads is decreased. In addition, two of the jammers that are closest to the target areas are detected by the enemy forces. On the other hand, the altitude values of the feasible regions are high. Therefore, relocating the positions of the jammers is not hard. The cost function value of the stationary scenario is around 61. The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 5.10 Optimal Jammer Locations for Scenario-5

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.920361	37.748833	37.837264	37.668409
Longitude	43.849189	44.307573	43.434439	43.955240

The optimization algorithm finds the solution without adding any extra jammers to the particle. Both of the jammers still have high altitude values at their new positions. Therefore, the LOS and signal level constraints are satisfied easily. In addition, the small changes in the altitude values and the distance between new jammer positions and target areas lead to a small change in cost function value. The new cost function is around 63.

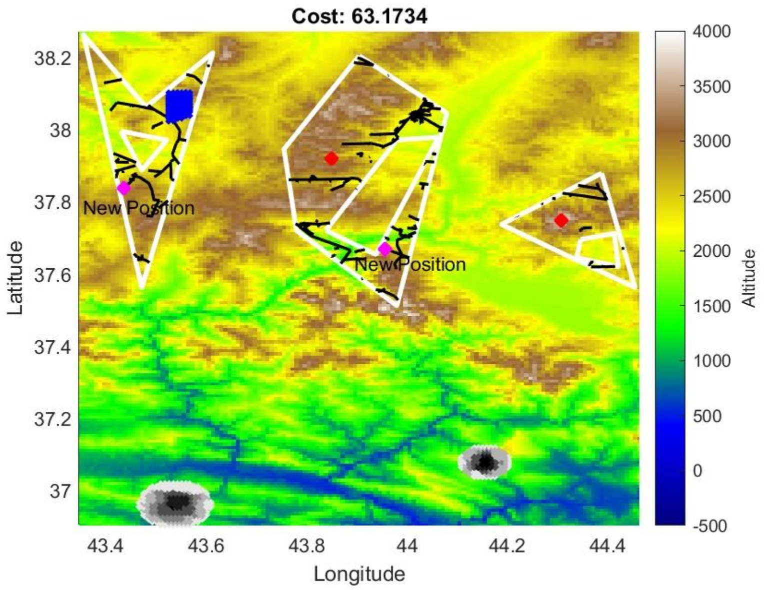

Figure 5.11. Scenario-5 Solution

5.4.6 Scenario-6

Table 5.11 Characteristics of Scenario-6

Characteristics	Explanations
Number of Total Jammers	5
Number of Detected Jammers	All (5)
Number of Target Areas	4
Difficulty Level of the Scenario	Low
Density of Road Networks	Normal

This scenario is taken from “Scenario-15” of the “Problem-1”. In this scenario, there are target areas inside of the feasible region and all of the jammers are detected by the enemy forces. Therefore, all the circle areas cannot be used by any of the jammers for effective jamming events due to the risk of enemy forces’ attacks. The cost function value of this scenario in “Problem-1” is around 41.

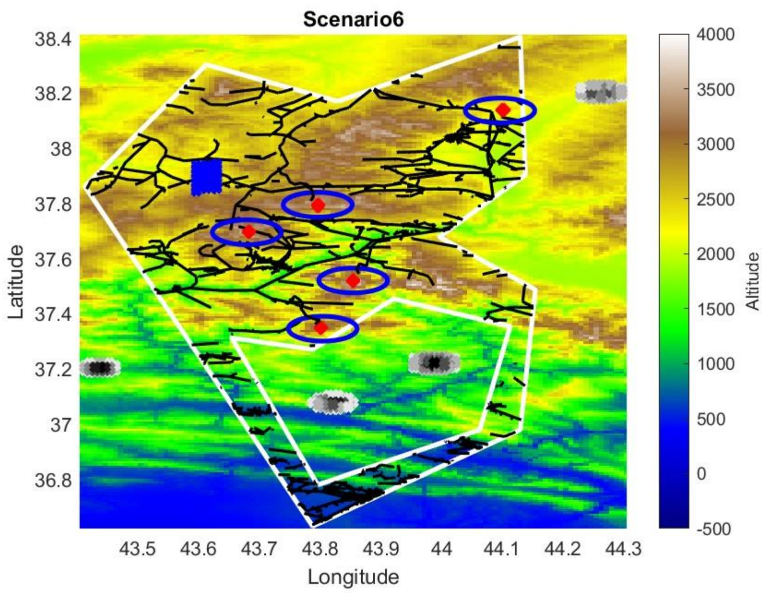

Figure 5.12. Scenario-6 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 5.12 Optimal Jammer Locations for Scenario-6

	Jammer 1	Jammer 2	Jammer 3
Latitude	38.049324	37.970924	37.495913
Longitude	44.004062	43.871378	43.988415
	Jammer 4	**Jammer 5**	**-**
Latitude	37.433655	37.608901	-
Longitude	43.795647	43.602880	-

The algorithm finds the new solution without any extra jammers. In this solution, two jammers are still mainly responsible for the target areas that are inside of the feasible region. On the other hand, the west side jammer covers the target area located on the west side of the map. Now, two jammers are responsible for the northeast side target area since the previous locations of the jammers were closer to this target area. The new cost function value increases around 55.

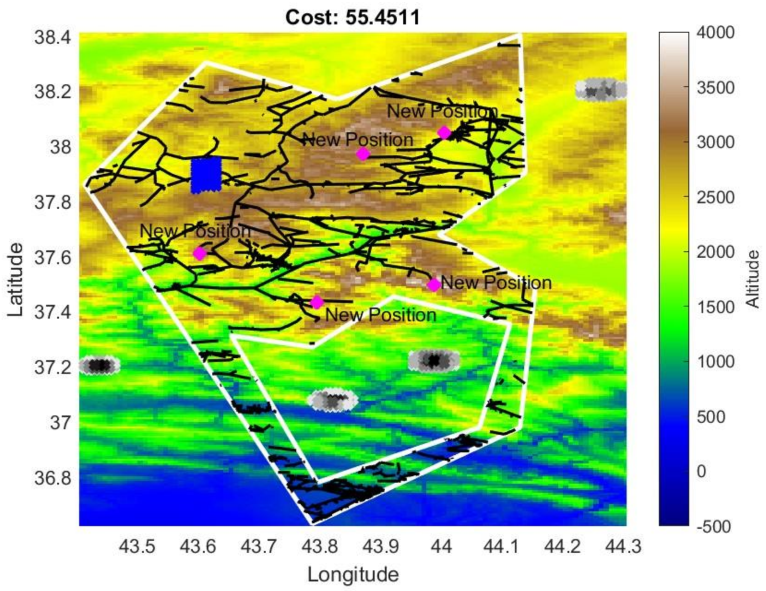

Figure 5.13. Scenario-6 Solution

5.4.7 Scenario-7

Table 5.13 Characteristics of Scenario-7

Characteristics	Explanations
Number of Total Jammers	5
Number of Detected Jammers	All (5)
Number of Target Areas	4
Difficulty Level of the Scenario	High
Density of Road Networks	Normal

This is the last scenario of the problem, and it is taken from "Scenario-13" of "Problem 1". In this scenario, all of the jammers are detected by enemy forces. The blue-circled areas cannot be used as the new positions of the jammers since these regions have a great risk of detection and attack by the enemy forces. Therefore, the rest of the area does not have greater altitude values at the closest regions to the target areas. This situation makes the problem harder with respect to the previous scenario. The cost function value before movement is around 43.

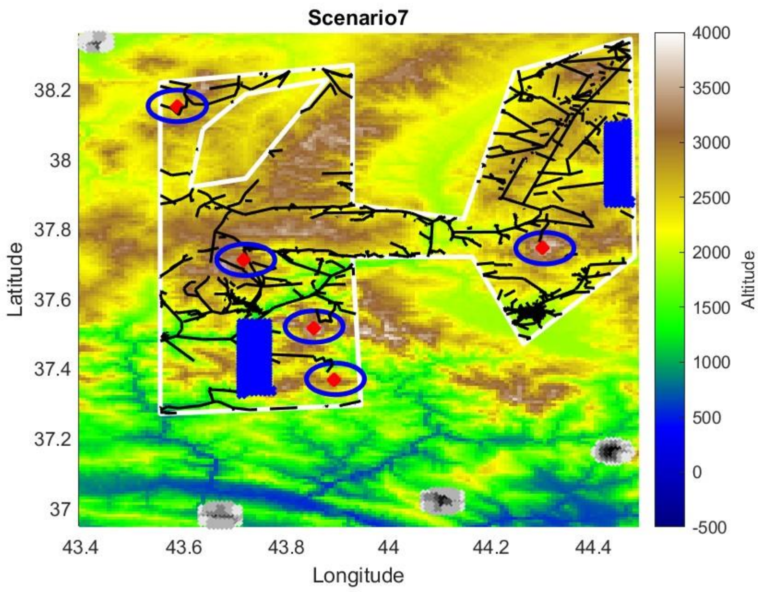

Figure 5.14. Scenario-7 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 5.14 Optimal Jammer Locations for Scenario-7

	Jammer 1	Jammer 2	Jammer 3
Latitude	38.210258	37.612231	37.437199
Longitude	43.646621	43.604256	43.797926
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.557534	37.796380	37.654166
Longitude	43.928805	44.397095	44.256381

The new solution requires an extra jammer addition to the particle. The jammer is added to the east side of the feasible region since the location of the jammer in this area goes north of the map and is farther from the target area. The new jammer increases the signal level at the southeast target area. On the other hand, the other jammers are located at the possible high grounds and satisfy the constraints of their new positions. The cost function increases around 59.

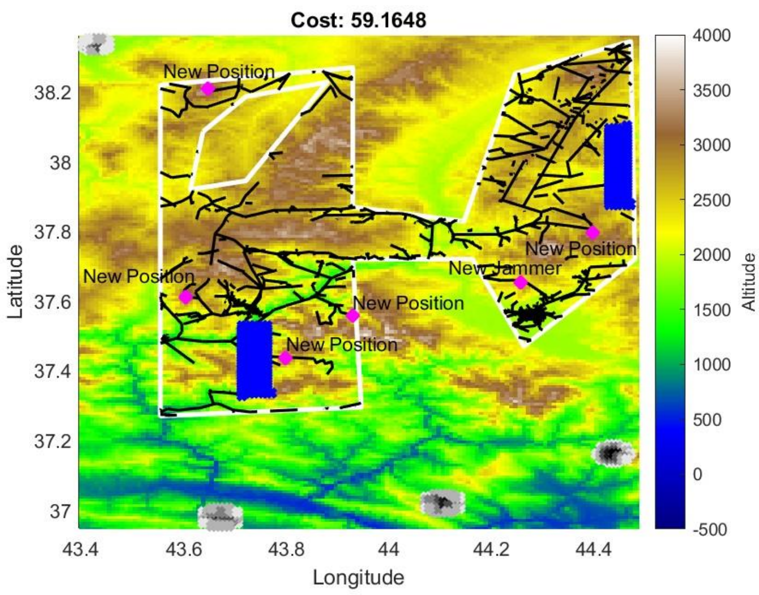

Figure 5.15. Scenario-7 Solution

CHAPTER 6

PROBLEM 3: STATIONARY JAMMERS AND MOBILE TARGETS

The concepts of stationary and mobile jammers are defined, formulated, and tested in the previous sections. In the previous sections, targets are stationary. However, the target can be mobile and this leads to the requirement of better coverage around target areas. Therefore, the ability to move the targets should be considered as a problem in this study.

6.1 Problem Definition

In this problem, the main aim is to find an optimal placement of stationary jammers so as to disrupt the operations of mobile targets effectively. As in the previous problem, “Problem 1”, the stationary jammers should be located within the feasible regions. On the other hand, the targets are mobile and follow specific or unpredictable paths [65]. The key challenge is to ensure that the stationary jammers supply continuous and effective jamming coverage for the movement of the targets. By doing so, various operational constraints such as terrain, signal propagation, and LOS should be considered.

Since the stationary jammers that are deployed in the feasible regions defined by polygons cannot relocated to another place, the optimization process should take care of maximizing signal coverage and minimizing the required LOS over the entire trajectory of the moving target. On the other hand, the trajectory of the enemy target may be unpredictable. Therefore, the optimum deployment of the jammers must satisfy sufficient coverage across all the potential target positions in terms of LOS and signal level. In addition, the optimization process should also consider the risk of detection and minimize the vulnerability of jammers to enemy attacks.

The objective function must balance several key factors:

- Maximizing jamming effectiveness over the specific or unpredictable target trajectories.
- Minimizing cost or resource usage, where deploying fewer jammers is preferred.
- Minimizing the risk of detection by enemy forces, which involves choosing locations that are more difficult to detect.
- Minimizing logistical challenges, by preferring locations that are near roads for easier transportation and deployment, unless more distant locations significantly improve operational effectiveness.

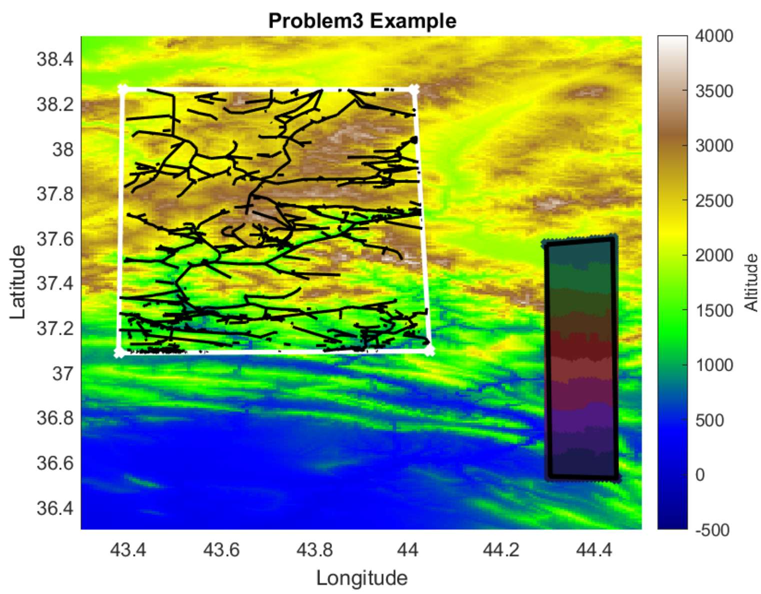

Figure 6.1. Problem 3 Visualization

In this visualization, the colored area is the mobile target area. The north side is the initial point of the mobile target. The mobile target is expected to move through the south of the area. The change of colors represents the movement of the mobile target according to the probability of the targets belonging to the area. Namely, as the color goes through purple, the probability of presenting the target in this area decreases.

Therefore, there is a priority for the jamming effectiveness throughout the trajectory, which is correlated with the mentioned probability.

6.2 Problem Formulation

The problem is mainly similar to the stationary jammers and stationary targets problem; therefore, the problem is assimilable to “Problem 1”. There are two unknowns for this problem.

The first unknown is the geolocational positions of the jammers in terms of latitude and longitude. In this problem, the geographic coordinates of the jammers are more important due to the ability of movement of the targets. Therefore, the jammers should cover extensive regions.

Throughout this section, the following notations are used to represent the geographical coordinates of the jammers;

$$P_j = (x_j, y_j), j = 1,2, \dots, J \tag{6.1}$$

x_j: Latitude of the j-th jammer.

y_j: Longitude of the j-th jammer.

J: Total number of jammers used in the solution.

The other unknown is the optimal number of jammers. Since the targets are not mobile in the previous sections, it is expected that a smaller number of jammers are required to cover the target areas in terms of electronic jamming. However, the mobility of targets leads to more number of jammers so as to maximize the effectiveness of jamming. Throughout this section, J is used to represent the total number of jammers where J is a positive integer.

6.2.1 Objective Function

The objective of the problem is to minimize the minimum required LOS between the jammers and target areas while maximizing the signal level at the target areas. On the other hand, the objective aims to keep the jammers separated from each other due to the detectability risks. Therefore, the objective function is constructed by considering these parameters.

$$F(P_i, J) = \left(\min_{\{P_i\,,J\}} (LOS_{Total} - SL_{Total})\right) \cdot K \tag{6.2}$$

Total LOS and signal level can be calculated as the following equations;

$$LOS_{Total} = \frac{1}{|T|} \cdot \frac{1}{J} \cdot \sum_{j=1}^{|T|} \left(\sum_{i=1}^{J} \left(\int_{T_j} \min\, (LOS(P_i, t) dt \right) \right) \tag{6.3}$$

$$SL_j = \int_{T_j} \left(\sum_{i=1}^{J} SL(P_i, t) \right) dt \tag{6.4}$$

$$SL = SignalSum\left(SL_j \circ SL_j\right) \text{ for } j = 1,2, \dots, |T| \tag{6.5}$$

$$SL_{Total} = \frac{1}{|T|} \cdot \sqrt{SL} \tag{6.6}$$

Where, $P_i \in A$.

$P_i = (x_i, y_i)$ is the coordinates of the i-th jammer in the deployment area $(A - A')$.

A is the continuous area in which jammers can be deployed.

T is the set of target areas.

T_j represents the continuous set of points within a target area, which is an element of the set T.

$|T|$ shows the number of elements in the set T.

J is the minimum number of jammers to satisfy the constraints.

K is the punishment coefficient according to the proximity of the jammers. K value is defined in the constraints as it is mostly dependent on constraints.

$A \circ B$ notation represents the elementwise multiplication.

6.2.2 Constraints

The problem has five constraints, as in the previous problems. The first constraint is the deployment locations, which are introduced as feasible regions in the previous parts. The jammers should be located in the feasible regions.

The other constraint is the signal level at the target areas. The signal level should be higher than the sensitivity level of the electronics at the target areas. This constraint is similar to the signal level constraint in “Problem 1”.

In addition, the LOS between the jammers and the target areas is a constraint in this problem. As in “Problem 1”, the minimum required LOS should be higher than 5 times the antenna height of the jammer. Similarly, the coefficient of 5 brings flexibility to this constraint. The flexibility means that the antenna can be located with a mast or on a building.

Moreover, the jammers should not be easily detected by the enemy forces. Therefore, the detectability constraint still continues in this problem. As in the previous parts, the detectability of the solution with J number of jammers and $J + 1$ number of jammers are compared.

The last constraint is about the distance between the jammers. The jammers should be separated from each other in order to prevent the risk of detectability. In addition, this constraint also provides the minimizing the detectability of many jammers at one time.

6.3 Solution Technique

In this section, the solution technique that is used to find the optimum jammer placements is explained. In this solution, since the jammers are not mobile, there is only one time to select the optimum deployment. Namely, this solution tries to deploy all the required jammers, unlike “Problem 2” and like “Problem 1”.

MPSO is used as an optimization algorithm. The optimization algorithm parameters are the same as the parameters that are used in “Problem 1”. The solution steps in “Problem 1” are also used similarly in this problem.

In this problem, since the target areas are bigger with respect to the stationary target cases and the scenarios are taken from “Problem 1”, the initial number of jammers are taken from the solutions of “Problem 1”. Namely, if a scenario is solved with J number of jammers in “Problem 1”; then, the initial number of jammers is chosen as J in the solution. If there is no optimal solution with J number of jammers, the algorithm tries to find more jammers in the solution.

6.4 Simulations and Results

In this section of the study, the scenarios for stationary jammers and mobile targets are simulated. The aim of the simulations is to test the robustness and flexibility of the optimization solution. All the scenarios are constructed by considering the concept of electronic warfare. Therefore, the enemy may move to another location on the map. Throughout the movement process, the enemy forces should be jammed continuously.

The simulation scenarios are divided into different parts by considering the number of mobile targets, the number of total targets, the altitude levels of the feasible regions, and the direction of mobile targets.

The scenarios are visualized by the figures. In these figures, some of the representations are similar to the previous parts. The areas surrounded by the white lines are feasible regions for jammer deployment. The black lines inside the feasible regions represent the roads. The white/gray shaded elliptic areas are the stationary target areas. In addition to these representations, there are mobility regions of the mobile targets. These regions are shown with a color palette that includes purple, red, pink, green, and blue tones. The colors individually represent the probability of the enemy target moving through this region. The purple region represents the highest probability, while the blue is the lowest. Namely, it can be considered as the mobile target should be in the colored regions surrounded by the black lines but it is in the purple area, probably. However, the optimization results should jam all of the mobile regions with different priorities, such as there is a higher priority for the purple region. On the other hand, the solution figures have a similar representation to the previous sections. The red points show the locations of the stationary jammers.

In this section, the number of feasible regions is taken equal for each scenario. The reason is that the effect of shapes and numbers is tested in “Problem 1”. In addition, the feasible regions are chosen for high-altitude scenarios in similar positions and low-altitude scenarios in similar positions.

6.4.1 Scenario-1

Table 6.1 Characteristics of Scenario-1

Characteristics	**Explanations**
Number of Mobile Targets	1
Number of Total Targets	1
Altitude Level of Feasible Regions Relative to the Target Area	High
Direction of Mobile Targets	Towards Feasible Regions
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

The first scenario is the most basic version of the stationary jammers and mobile targets problem. In this scenario, there is only one mobile target and there is no stationary target. Therefore, all of the jammers are responsible for the effective jamming of mobile targets. The altitude levels of the feasible regions are selected high so as to see the performance of the optimization algorithm under easy conditions. The direction of the target is chosen through the feasible regions. The directions are changed for many of the scenarios.

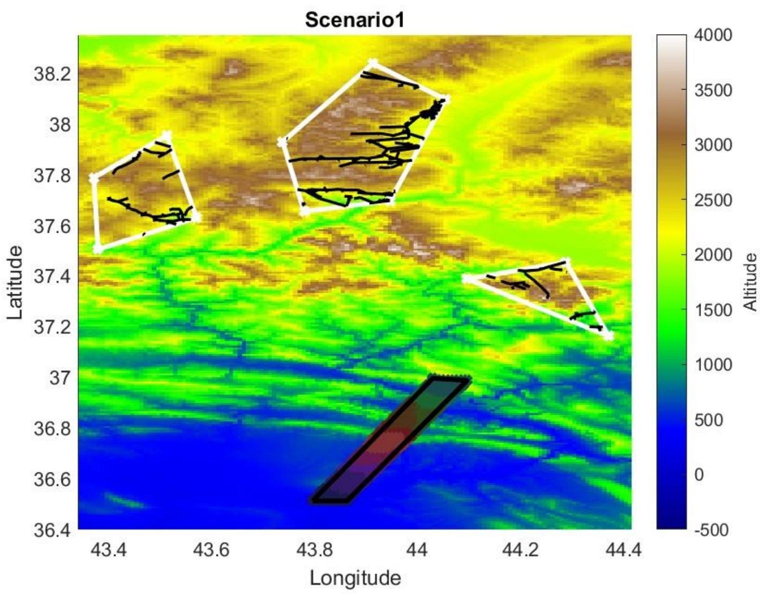

Figure 6.2. Scenario-1 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.2 Optimal Jammer Locations for Scenario-1

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.374344	37.309097	37.828557	37.818519
Longitude	44.167059	44.248150	43.850136	43.931226
	Jammer 5	**Jammer 6**	**Jammer 7**	**-**
Latitude	37.785896	37.660423	37.258908	-
Longitude	43.795827	43.454353	44.303202	-

The optimization algorithm finds the solution with 7 number of jammers. The jammers are mainly located in the highest areas of the feasible regions. Since the movement of mobile targets is through the triangular feasible region, three jammers are deployed in this region. On the other hand, the rest of the jammers help to increase the signal level and the clearance of the LOS at the mobile target region. The cost function value is around 90.

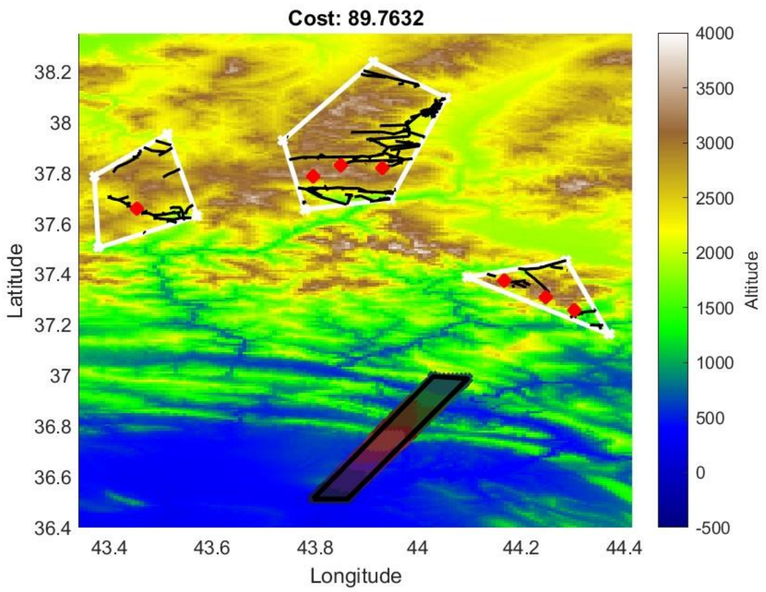

Figure 6.3. Scenario-1 Solution

6.4.2 Scenario-2

Table 6.3 Characteristics of Scenario-2

Characteristics	Explanations
Number of Mobile Targets	1
Number of Total Targets	1
Altitude Level of Feasible Regions Relative to the Target Area	High
Direction of Mobile Targets	Parallel to the Feasible Regions
Antenna Height (m)	15

Table 6.3 (continued)

Sensitivity Level (dBm)	-90

In this example, the number of mobile targets, total targets, and the altitude levels of the feasible regions are chosen the same as “Scenario-1”. The direction of the mobile target is changed parallel to the feasible regions. Since the problem is basic due to the number of targets and positions of the feasible regions, the effect of the direction can be observed in this scenario.

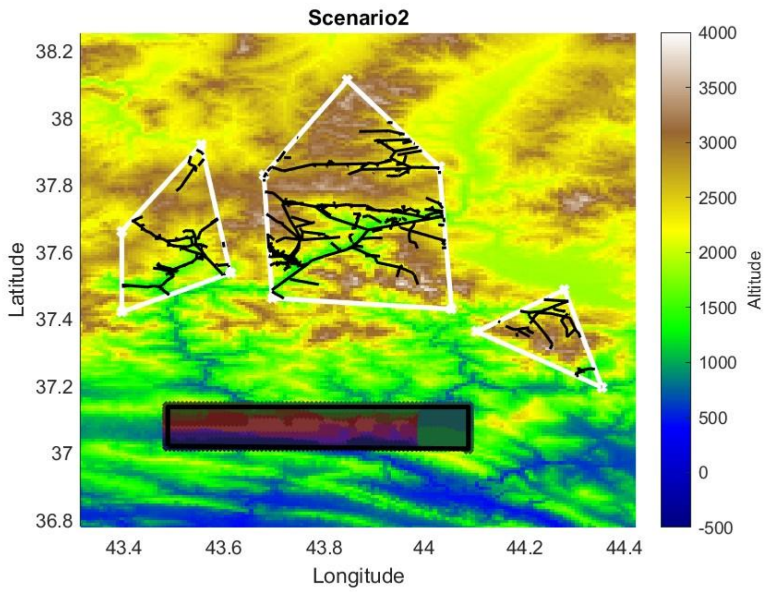

Figure 6.4. Scenario-2 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table in terms of latitude and longitude.

Table 6.4 Optimal Jammer Locations for Scenario-2

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.654050	37.739487	37.699616	37.794547
Longitude	43.445502	43.477735	43.698766	43.828468

Table 6.4 (continued)

	Jammer 5	Jammer 6	Jammer 7	-
Latitude	37.486972	37.317996	37.361664	-
Longitude	44.000381	44.242133	44.177665	-

The optimization algorithm finds the solution with 7 number of jammers. The jammers are mainly located in the highest areas of the feasible regions. The difference between this solution and the solution of the first scenario is the formation of the jammers. Since the mobile target area is parallel to the feasible regions, the jammers are deployed parallel to the mobile target area. There is no jammer between the target area and any other jammer. The cost function value is around 89.

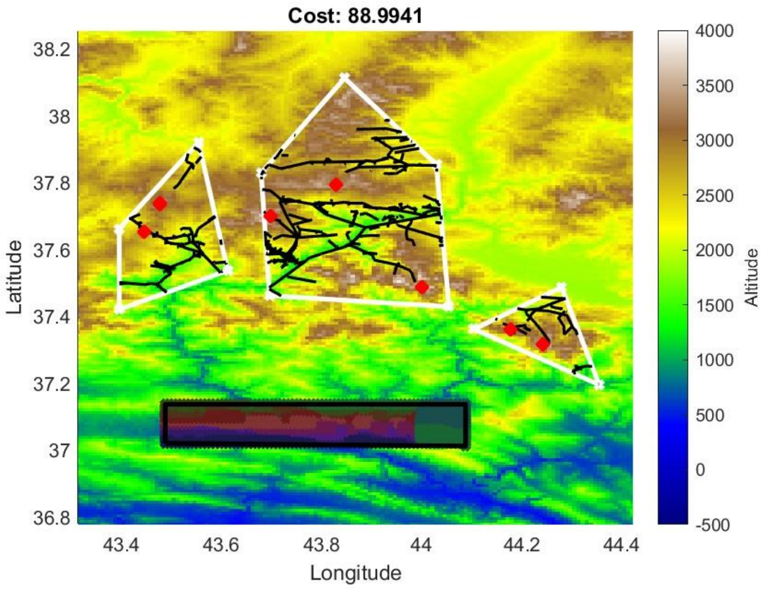

Figure 6.5. Scenario-2 Solution

6.4.3 Scenario-3

Table 6.5 Characteristics of Scenario-3

Characteristics	Explanations
Number of Mobile Targets	1
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	High
Direction of Mobile Targets	Towards Feasible Regions
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

In this scenario, the number of total targets is changed, and the other parameters are kept same. The scenario is similar to the first scenario; however, the stationary targets are distributed to the map. With the help of this scenario, the effect of the number of total targets can be observed.

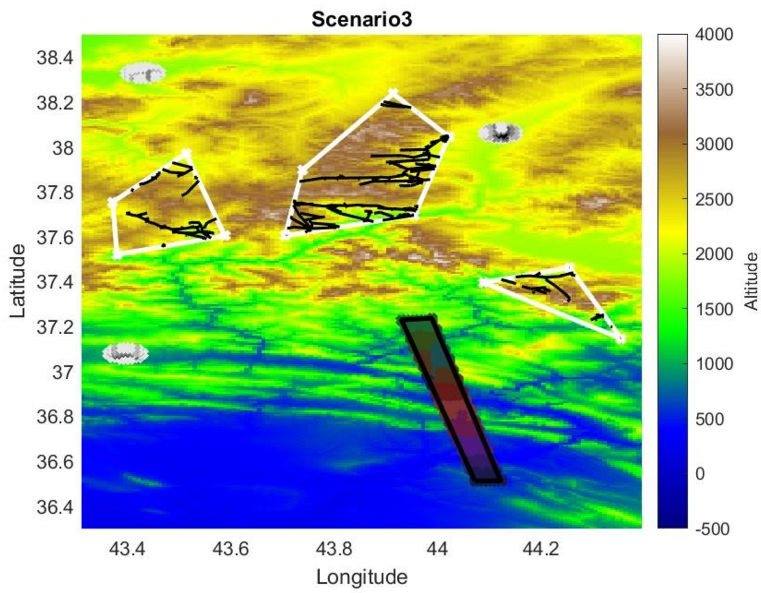

Figure 6.6. Scenario-3 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.6 Optimal Jammer Locations for Scenario-3

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	37.578378	37.892664	37.646332
Longitude	43.389960	43.504015	43.724623
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.810553	38.065379	38.048391
Longitude	43.870193	43.8521853	43.902459
	Jammer 7	**Jammer 8**	**Jammer 9**
Latitude	37.765250	37.374517	37.295238
Longitude	43.939977	44.159084	44.242374

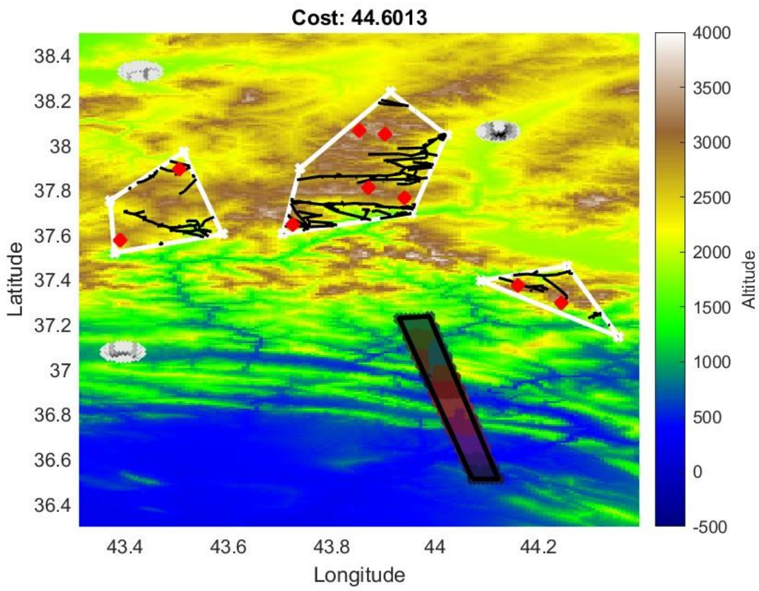

Figure 6.7. Scenario-3 Solution

The optimization algorithm finds the solution with 9 number of jammers. Since there are three extra stationary target areas, some of the jammers are deployed close to these areas. For the stationary targets located on the west side of the map, two of the jammers are used. Since the other stationary target area is not away from the mobile target area, the jammers are used jointly. The cost function value is around 45.

6.4.4 Scenario-4

Table 6.7 Characteristics of Scenario-4

Characteristics	Explanations
Number of Mobile Targets	1
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	High
Direction of Mobile Targets	Parallel to the Feasible Regions
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

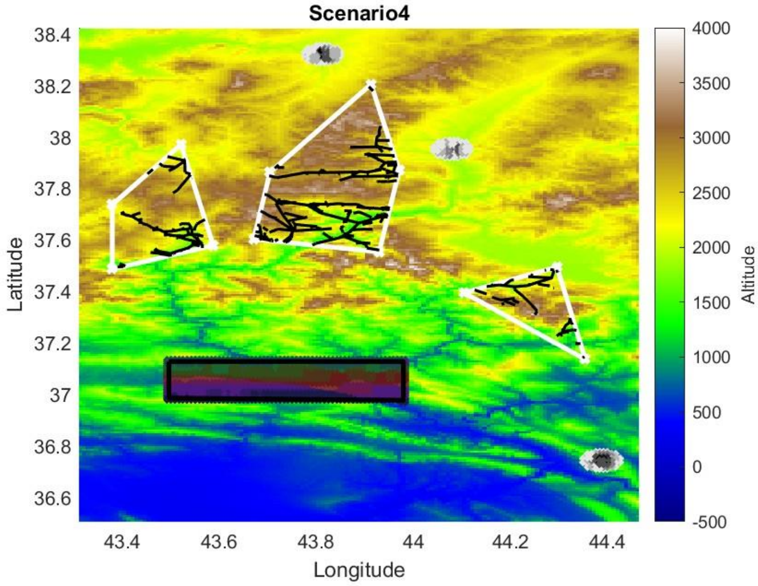

Figure 6.8. Scenario-4 Visualization

In this scenario, the effect of the addition of extra stationary targets is observed under the same conditions as the previous scenario, except for the parallel direction of the mobile target. Therefore, this scenario aims to see the behavior of the algorithm for the difference between directions. The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.8 Optimal Jammer Locations for Scenario-4

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.673234	37.690454	37.796231	38.069284
Longitude	43.472702	43.694972	43.764532	43.854879
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	38.052064	37.269804	37.316543	37.781471
Longitude	43.913245	44.297821	44.235457	43.902052

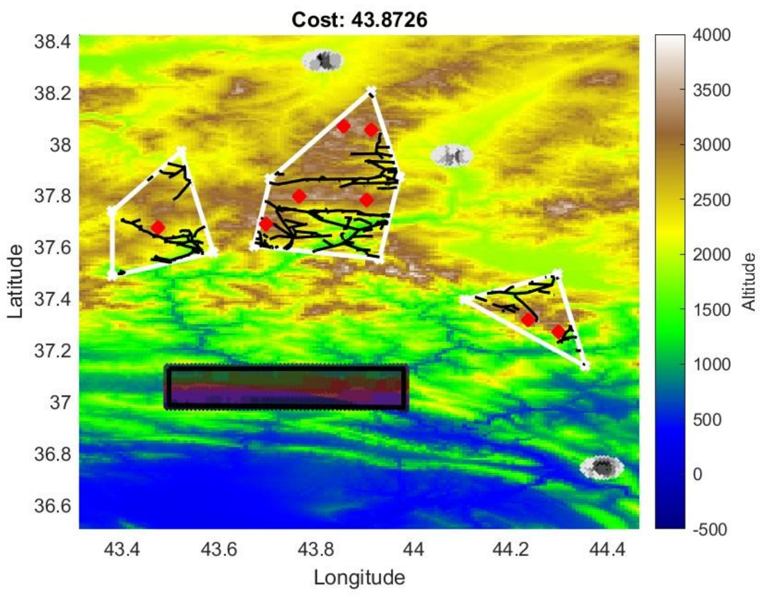

Figure 6.9. Scenario-4 Solution

The optimization algorithm finds the solution with 8 number of jammers. The jammer inside the quadrangle area is responsible with the cover the west side of the mobile target area. The jammers located in the triangle regions are responsible for jamming the southeast stationary target area and east of the mobile target area. The jammers at the north of the pentagon region are also responsible for the stationary areas and mobile target areas. The cost function value is around 44.

6.4.5 Scenario-5

Table 6.9 Characteristics of Scenario-5

Characteristics	Explanations
Number of Mobile Targets	1
Number of Total Targets	1
Altitude Level of Feasible Regions Relative to the Target Area	Low
Direction of Mobile Targets	Towards Feasible Regions
Antenna Height (m)	35
Sensitivity Level (dBm)	-90

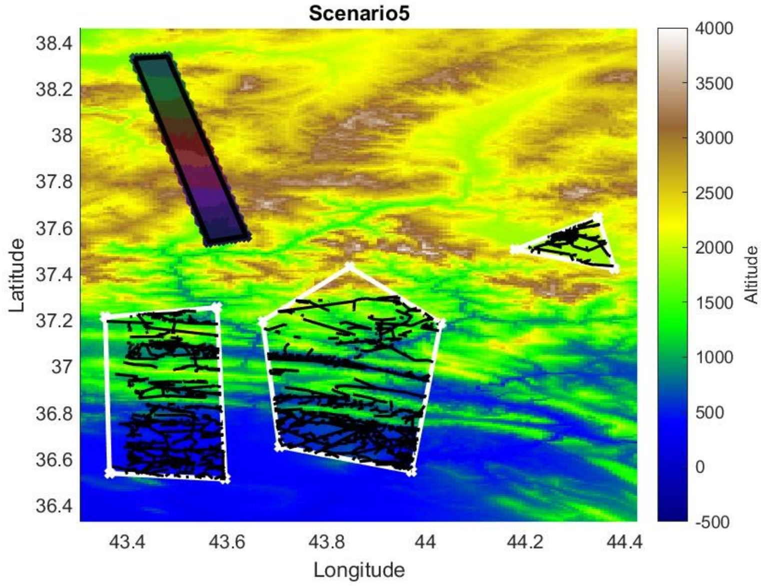

Figure 6.10. Scenario-5 Visualization

This scenario is designed to test the algorithm and jamming performance of the system under hard altitude conditions. In this scenario, the altitude levels of the feasible regions are changed to low while the other parameters are kept the same. On the other hand, the mobile target area has both low and high altitude values.. The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.10 Optimal Jammer Locations for Scenario-5

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	37.135969	37.152413	37.352477
Longitude	43.412105	43.531612	43.819515
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.377142	37.089379	36.974274
Longitude	43.864524	43.734929	43.531612
	Jammer 7	**Jammer 8**	**Jammer 9**
Latitude	36.987977	37.264777	37.253815
Longitude	43.443922	43.759761	43.859868

The optimization algorithm finds the solution with 9 number of jammers. The jammers are located inside the quadrangle and pentagon regions since the triangular region is far away from the mobile target area. The jammers are placed in the highest areas of the regions so as to satisfy the LOS constraint. Moreover, the locations are close to the mobile target area since the signal level at the mobile target area should be higher than the sensitivity threshold. The cost function value is around 203.

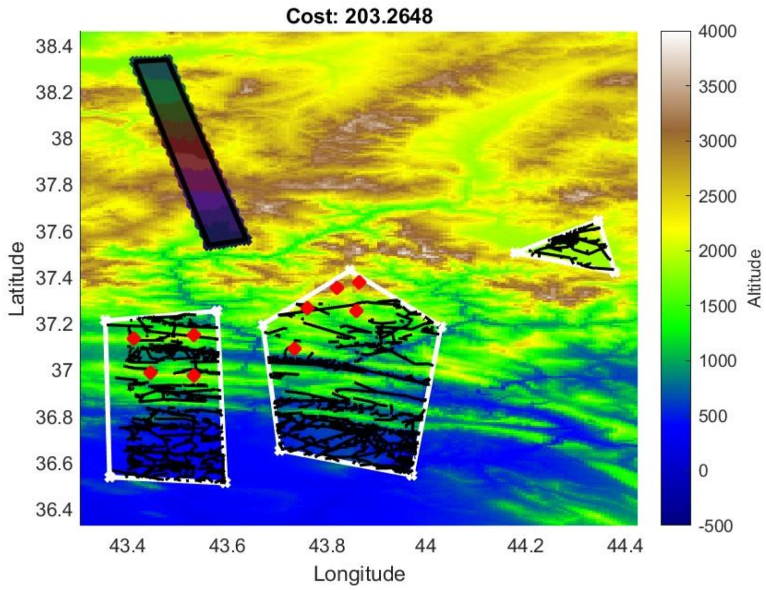

Figure 6.11. Scenario-5 Solution

6.4.6 Scenario-6

Table 6.11 Characteristics of Scenario-6

Characteristics	Explanations
Number of Mobile Targets	1
Number of Total Targets	1
Altitude Level of Feasible Regions Relative to the Target Area	Low
Direction of Mobile Targets	Parallel to the Feasible Regions
Antenna Height (m)	35
Sensitivity Level (dBm)	-90

In this scenario, the direction of the mobile target is changed to parallel to the feasible regions. The other parameters are kept the same. Therefore, the effect of feasible regions with low altitude values can be observed for different directions of mobile targets.

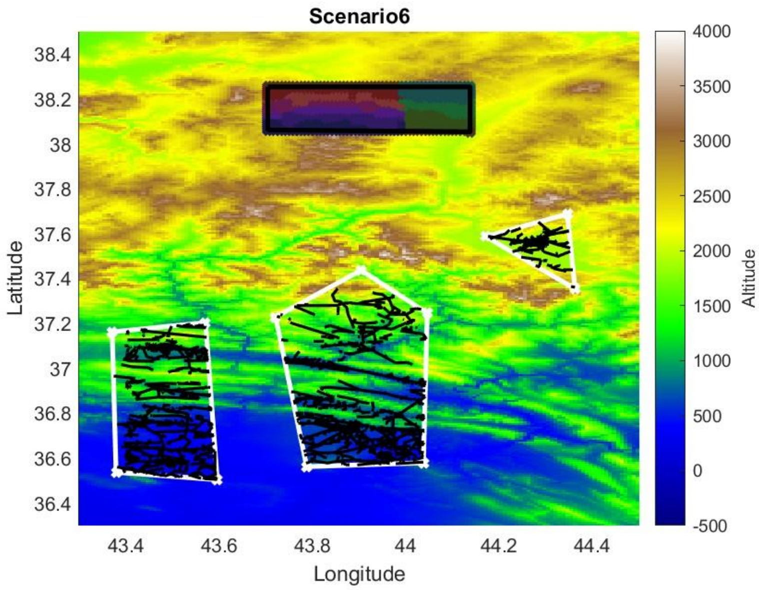

Figure 6.12. Scenario-6 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.12 Optimal Jammer Locations for Scenario-6

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.645031	37.599985	37.364153	37.348254
Longitude	44.322019	44.254285	43.865387	43.915616
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.215764	37.205165	37.160119	37.297908
Longitude	44.009987	43.768733	43.531284	43.832661

The optimization algorithm finds the solution with 8 number of jammers. The jammers are placed in the highest areas of the feasible regions to satisfy the LOS constraint. In addition, the jammers are as close as possible to the parallel mobile target area to increase the signal level in this area. The cost function for this scenario is found to be around 192.

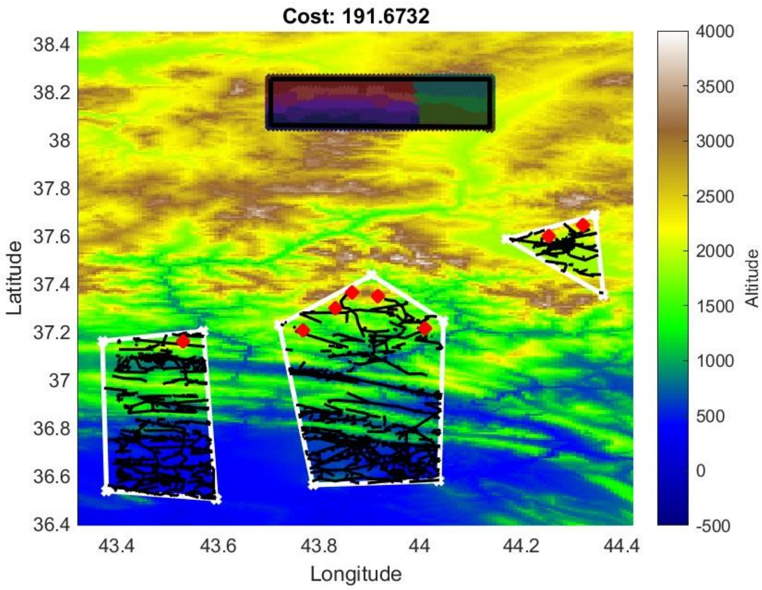

Figure 6.13. Scenario-6 Solution

6.4.7 Scenario-7

Table 6.13 Characteristics of Scenario-7

Characteristics	Explanations
Number of Mobile Targets	1
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	Low
Direction of Mobile Targets	Towards Feasible Regions
Antenna Height (m)	35
Sensitivity Level (dBm)	-90

In this scenario, the number of total targets is increased. On the other hand, the other parameters are kept same. The aim of the scenario is to test the effect of feasible regions with low altitude values for both mobile and stationary target cases. Two of the stationary targets have high altitude values, and one of them has low altitude values.

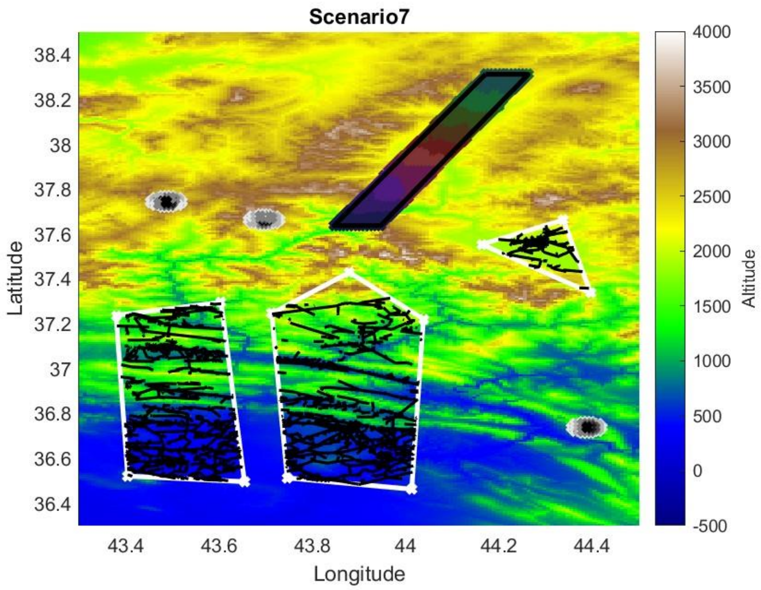

Figure 6.14. Scenario-7 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.14 Optimal Jammer Locations for Scenario-7

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.388674	37.6236808	37.3745173	37.334877
Longitude	44.374012	44.3282744	43.8958419	43.828482
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.139510	37.1508365	37.2301158	37.431145
Longitude	43.415176	43.5474012	44.0014553	44.330769
	Jammer 9	**Jammer 10**	**Jammer 11**	**-**
Latitude	37.249935	37.2952380	37.5953667	-
Longitude	43.771933	43.9349272	44.2733887	-

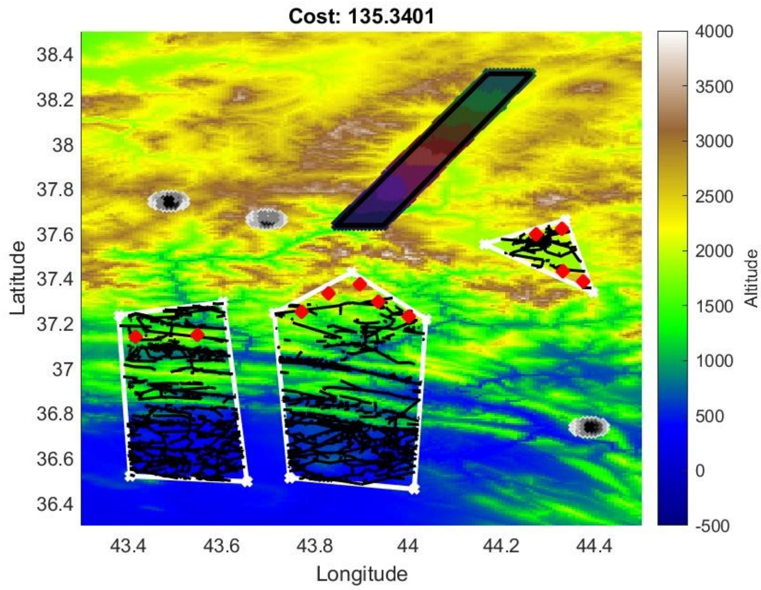

Figure 6.15. Scenario-7 Solution

The optimization algorithm finds the solution with 11 number of jammers. Like in the “Scenario-6”, the 8 of the jammers are placed into the similar areas. There is an additional one jammer inside the quadrangle area that is responsible for the stationary target areas on the west side of the map. In addition, there are two extra jammers inside the triangle area, which helps to jam both the stationary target and mobile target. The cost function for this scenario is found to be around 135.

6.4.8 Scenario-8

Table 6.15 Characteristics of Scenario-8

Characteristics	Explanations
Number of Mobile Targets	1
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	Low
Direction of Mobile Targets	Parallel to the Feasible Regions

Table 6.15 (continued)

Antenna Height (m)	35
Sensitivity Level (dBm)	-90

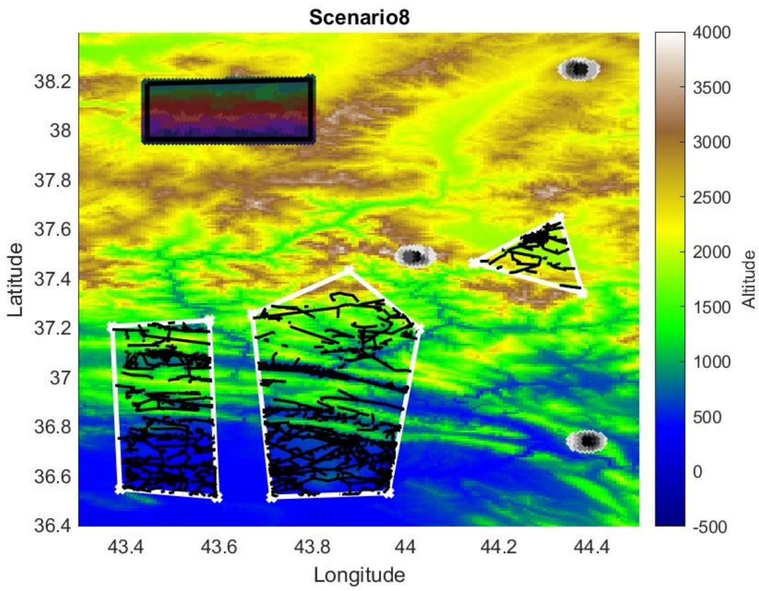

Figure 6.16. Scenario-8 Visualization

This scenario is similar to the previous scenario. The number of mobile targets, the number of total targets, and the altitude levels of feasible regions are not changed. The direction of the mobile target is changed parallel to the feasible regions. This scenario aims to observe the effect of direction change on the jammer deployment.

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.16 Optimal Jammer Locations for Scenario-8

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.375557	37.586748	37.414190	37.344651
Longitude	44.352390	44.324116	44.302494	43.901663
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.372981	37.311169	37.159215	36.981505

Table 6.17 (continued)

Longitude	43.851767	43.778586	43.531600	43.548232
	Jammer 9	**Jammer 10**	**-**	**-**
Latitude	37.141186	37.205574	-	-
Longitude	43.440956	43.738669	-	-

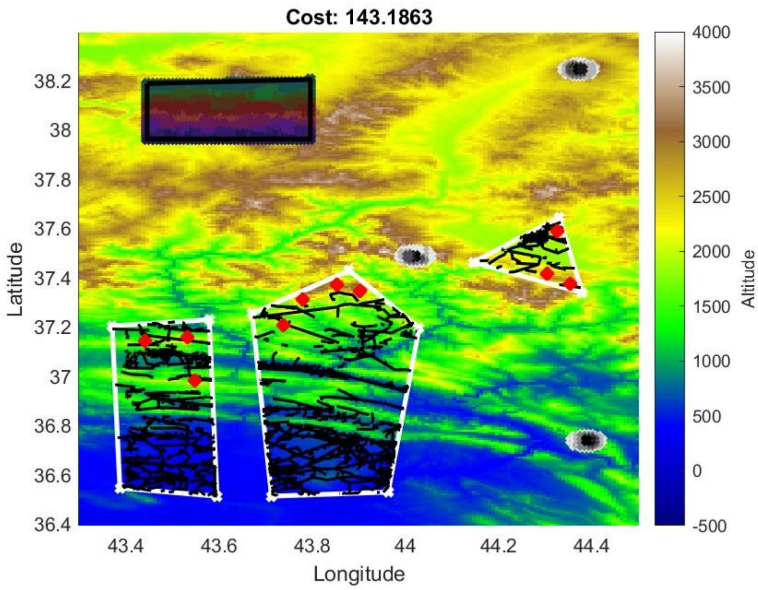

Figure 6.17. Scenario-8 Solution

The optimization algorithm finds the solution with 10 number of jammers. The triangular feasible region has three jammers. These jammers are mainly responsible for the stationary targets since the triangular area is far away from the mobile region. On the other hand, the rest of the jammers aim to jam the mobile target area. The jammers that are located at the east side of the pentagon region also help to jam the stationary area that is close to these jammers. The cost function for this scenario is found around 143.

6.4.9 Scenario-9

Table 6.17 Characteristics of Scenario-9

Characteristics	Explanations
Number of Mobile Targets	2
Number of Total Targets	2
Altitude Level of Feasible Regions Relative to the Target Area	High
Direction of Mobile Targets	Mixed
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

This scenario is designed so as to observe the effect of multiple mobile targets. There are two mobile targets, and one of them is vertical to the feasible regions, and the other is parallel. Since the aim is to see the behavior of the algorithm against multiple mobile targets, the feasible regions are placed on the high ground, which provides flexibility in terms of LOS constraint.

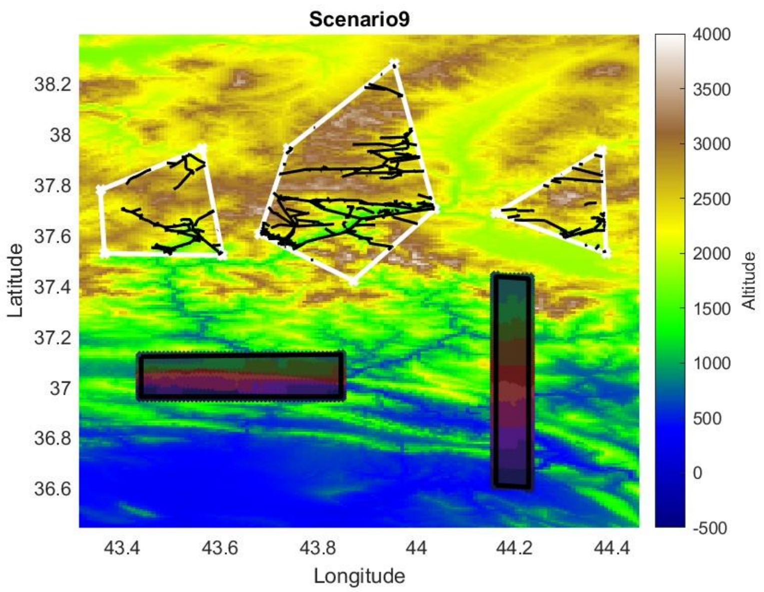

Figure 6.18. Scenario-9 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.18 Optimal Jammer Locations for Scenario-9

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.740453	37.592395	37.529658	37.532167
Longitude	43.473783	43.394471	43.807686	43.908413
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.725396	37.614980	37.788133	38.039079
Longitude	44.293076	43.968690	43.753754	43.887792

The optimization algorithm finds the solution with 8 number of jammers. A small part of the vertical mobile target area is on the high ground. Therefore, the jammers that are close to this target are placed in regions with high altitude values. There are more jammers in the middle feasible region since this region covers both of the target areas. The cost function for this scenario is found around 62.

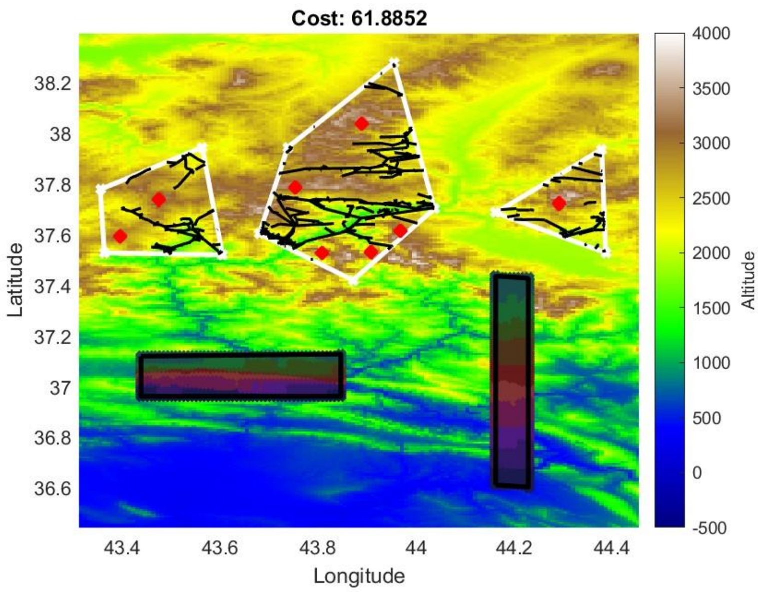

Figure 6.19. Scenario-9 Solution

6.4.10 Scenario-10

Table 6.19 Characteristics of Scenario-10

Characteristics	Explanations
Number of Mobile Targets	2
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	High
Direction of Mobile Targets	Mixed
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

In this scenario, there are two additional stationary target areas. The aim of the scenario is to observe the effect of the extra stationary target areas under the conditions of multiple mobile target areas. To see the effect clearly, the feasible regions are placed on the high ground.

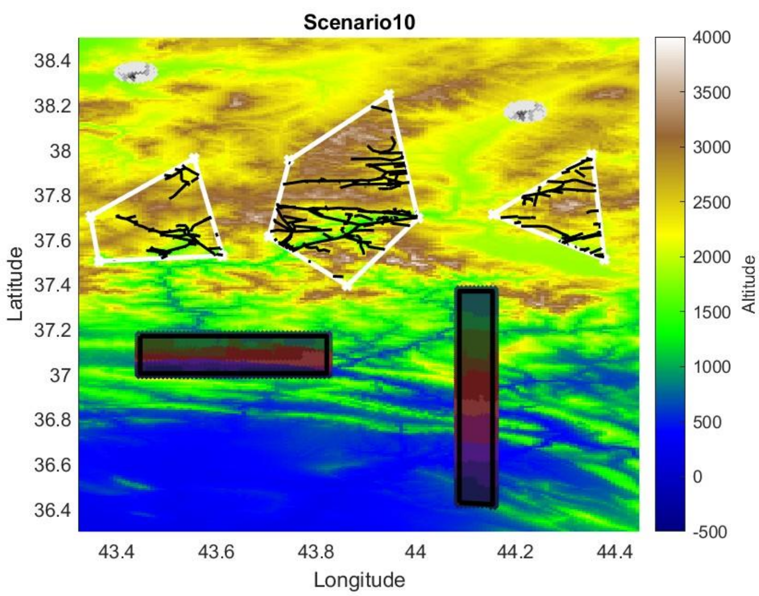

Figure 6.20. Scenario-10 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.20 Optimal Jammer Locations for Scenario-10

	Jammer 1	Jammer 2	Jammer 3
Latitude	38.085199	37.748262	37.521750
Longitude	43.942299	44.305916	43.904845
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.524581	37.773745	37.756756
Longitude	43.817452	43.434328	43.501433
	Jammer 7	**Jammer 8**	**Jammer 9**
Latitude	37.988931	37.799227	37.731274
Longitude	43.819793	43.748786	44.230227

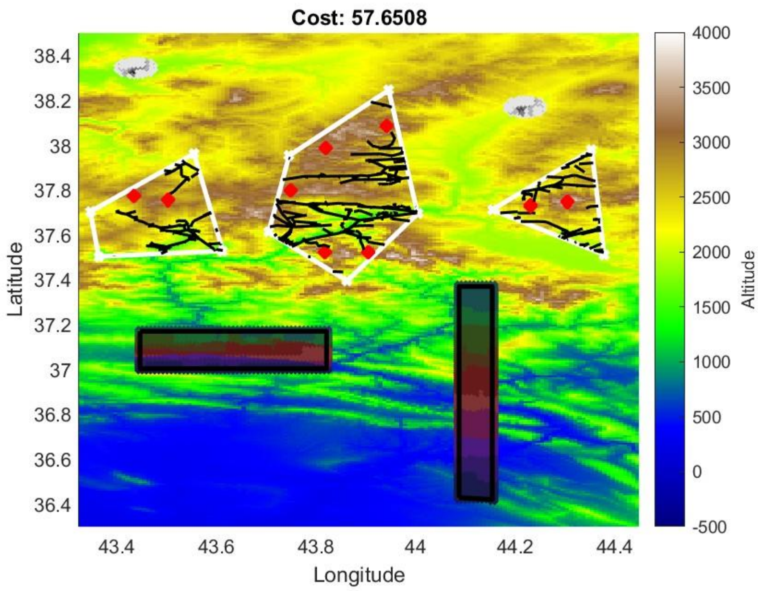

Figure 6.21. Scenario-10 Solution

The optimization algorithm finds a solution with 9 number of jammers. According to the previous scenario, one of the jammers inside the quadrangle area is placed to the north of this area. The reason behind this is that it increases the signal level and the coverage on the stationary target that is close to this area. In addition, one of the jammers inside the pentagon region is placed northeast of this area to focus also on the stationary target. Moreover, there is an additional jammer inside the triangle area that aims to increase signal level and LOS coverage both on mobile and stationary targets. The cost function for this scenario is found around 58.

6.4.11 Scenario-11

Table 6.21 Characteristics of Scenario-11

Characteristics	Explanations
Number of Mobile Targets	4
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	High
Direction of Mobile Targets	Mixed
Antenna Height (m)	15
Sensitivity Level (dBm)	-90

The last scenario aims to see more than two mobile targets, and all of the targets are mobile cases. To better observe the effect of the four mobile targets, the feasible regions are placed on high grounds. In addition, the mobile targets go both directions, which are through the feasible regions and parallel to the feasible regions.

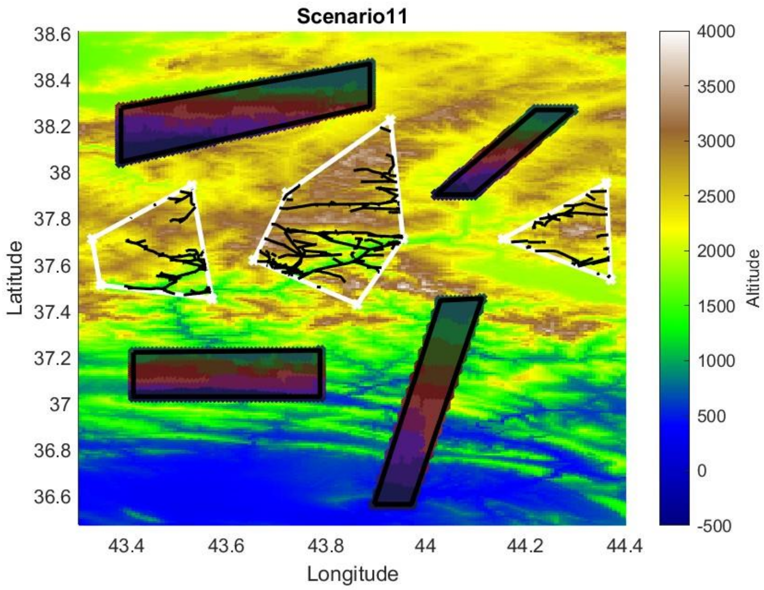

Figure 6.22. Scenario-11 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 6.22 Optimal Jammer Locations for Scenario-11

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.798885	37.669510	37.735574	38.093421
Longitude	44.334485	44.300110	44.234890	43.913888
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	38.032862	37.697037	37.507103	37.774111
Longitude	43.838808	43.692480	43.844937	43.475669
	Jammer 9	**Jammer 10**	-	-
Latitude	37.595188	37.793380	-	-
Longitude	43.380671	43.782116	-	-

The optimization algorithm finds the solution with 10 number of jammers. According to the previous scenarios, the number of jammers used is increased so as to satisfy the signal level and LOS constraints over the mobile target areas. The jammers are mainly deployed to the closest regions of the feasible regions to the target areas. The cost function for this scenario is found around 92.

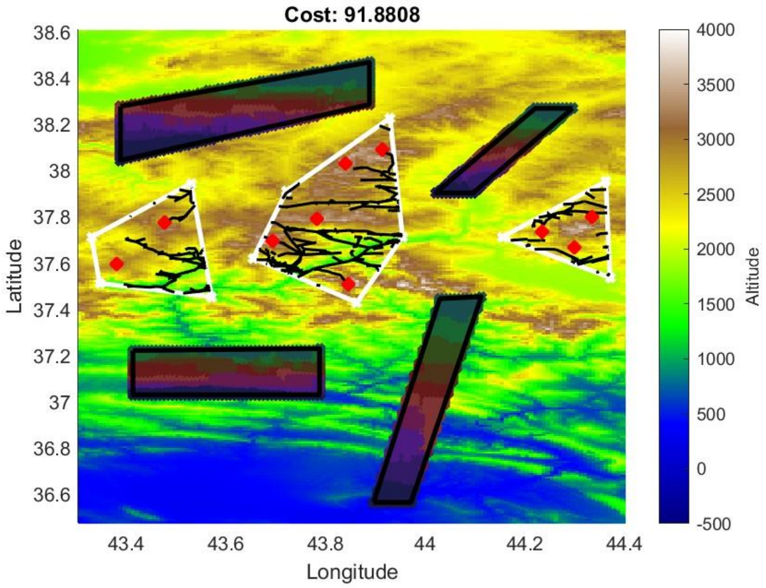

Figure 6.23. Scenario-11 Solution

CHAPTER 7

PROBLEM 4: MOBILE JAMMERS AND MOBILE TARGETS

The concepts of stationary jammers and stationary targets, mobile jammers and stationary targets, and stationary jammers and mobile targets are defined, formulated, and tested in the previous sections. In this section, the concept of mobile jammers and mobile targets is studied since the enemy forces may detect the locations of the jammers and attack the jammers [64]. In the case of detection by enemy forces, the jammers should move to another place in the feasible region and continue to jam the enemy forces effectively. Therefore, the concept of mobile jammers against the mobile targets is important.

7.1 Problem Definition

The optimum jammer deployment problem involving mobile jammers and mobile targets provides a dynamic optimization scenario for the jammers in feasible deployment regions and the targets in motion with specific or unpredictable trajectories. The aim is to find an optimal jammer deployment so that the mobile targets are jammed in their trajectories, and the jammers that are detected by the enemy forces can change their positions. In this problem, the LOS, signal level at the target trajectories, and the risk of detection should be considered for the solution.

This problem is the most complex one among the problems, and it requires the jammers to adapt, changing their positions due to the risk of detectability and finding effective coverage due to the mobile targets [65]. Therefore, this problem can be considered as a mix of "Problem 2" and "Problem 3". Therefore, the constraints in these problems should be satisfied for mobile jammers and mobile target cases.

The objective function must balance several key factors:

- Maximizing jamming effectiveness over the specific or unpredictable target trajectories.
- Minimizing cost or resource usage, where deploying fewer jammers is preferred.
- Minimizing the risk of detection by enemy forces, which involves choosing locations that are more difficult to detect. Find new locations if the jammers are detected by the enemy forces.
- Minimizing movement time by using roads for efficient travel between positions.

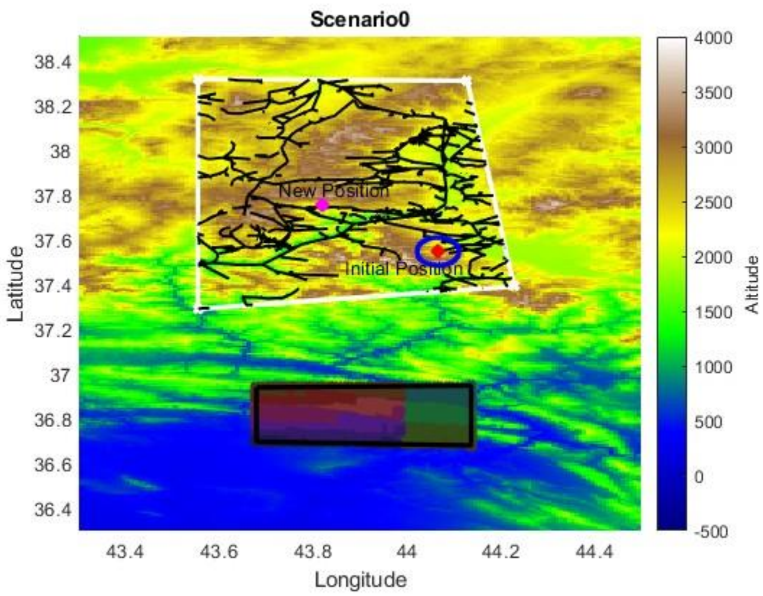

Figure 7.1. Problem 4 Visualization

In this visualization, the red dot demonstrates the jammer deployment point. If the jammer is deployed at its initial location, the risk of detectability increases, and the jammers have to change their positions through a new location. The blue circle area defines the potential detected area. On the other hand, the purple, red, blue, and green area is the prediction of the target trajectory.

7.2 Problem Formulation

The problem can be considered as the combination of "Problem 3" and "Problem 4". There are two unknowns for the problem.

The first unknown is the new positions of the mobile jammers. This unknown is represented in latitude and longitude. As the friend jammers are detected by the enemy forces, this unknown should be updated, and new positions should be found. When new positions are found by the optimization, the minimum required LOS, signal level at the mobile target areas, and terrain features should be considered.

Throughout this section, the following notations are used to represent the geographical coordinates of the jammers;

$$P_j = \left(x_j, y_j\right), j = 1,2, \dots, J \tag{7.1}$$

x_j: Latitude of the j-th jammer.

y_j: Longitude of the j-th jammer.

J: Total number of jammers used in the solution.

In addition to the geolocation of the jammers, the total number of jammers is unknown for the problem. Since the initial solutions satisfy the constraints with the minimum cost function value, the change in the locations of the jammers may cause dissatisfaction with the constraints. Therefore, the number of jammers may increase with the addition of new jammers to the solutions to ensure the constraints, and this is unknown for the problem. Throughout this section, the total number of jammers is represented by J, where J is a positive integer. In the solution, a minimum number of jammers should be used so as to keep the consumption to a minimum.

7.2.1 Objective Function

The objective of this study is to minimize the total minimum required LOS between the jammers and the mobile target areas while maximizing the jamming signal level at these target areas as they move. The approach must satisfy all constraints, ensuring effective jamming coverage and operational feasibility as the targets dynamically change positions. Furthermore, the locations of the jammers should be strategically distanced from one another to reduce the likelihood of detection by enemy forces. This spacing minimizes mutual interference between jammers and decreases detectability, enhancing the operational security of the jamming units in an adaptive battlefield environment. Therefore, the objective function is constructed by considering the mentioned parameters.

$$F(P_i, J) = \left(\min_{\{P_i\,,J\}} (LOS_{Total} - SL_{Total})\right) \cdot K \tag{7.2}$$

Total LOS and signal level can be calculated as the following equations;

$$LOS_{Total} = \frac{1}{|T|} \cdot \frac{1}{J} \cdot \sum_{j=1}^{|T|} \left(\sum_{i=1}^{J} \left(\int_{T_j} \min\,(LOS(P_i, t)dt \right) \right) \tag{7.3}$$

$$SL_j = \int_{T_j} \left(\sum_{i=1}^{J} SL(P_i, t) \right) dt \tag{7.4}$$

$$SL = SignalSum\big(SL_j \circ SL_j\big) \text{ for } j = 1,2, \dots, |T| \tag{7.5}$$

$$SL_{Total} = \frac{1}{|T|} \cdot \sqrt{SL} \tag{7.6}$$

Where, $P_i \in A - A'$.

$P_i = (x_i, y_i)$ is the coordinates of the i-th jammer in the deployment area $(A - A')$.

A is the continuous area in which jammers can be deployed. On the other hand, A' is the continuous area in which jammers cannot be deployed due to the detectability risks. Therefore, $(A - A')$ refers to the set of geolocation that is inside the area A and outside the area A'.

T is the set of target areas.

T_j represents the continuous set of points within a target area, which is an element of the set T.

$|T|$ shows the number of elements in the set T.

J is the minimum number of jammers to satisfy the constraints.

K is the punishment coefficient according to the proximity of the jammers. K value is defined in the constraints as it is mostly dependent on constraints.

$A \circ B$ notation represents the elementwise multiplication.

7.2.2 Constraints

The problem includes five constraints. The first constraint addresses the feasible deployment area for mobile jammers. Specifically, the locations of the mobile jammers must remain within the feasible region A at all times as they move while avoiding the restricted detected area A'. This constraint ensures that the jammers operate within designated operational zones and remain undetected by staying outside of high-risk zones.

$$P_i \in (A - A') \text{ for all } i = 1,2, \dots, J$$

For mobile jammers, even as they relocate from their initial optimal positions to evade detection, the jamming signal level at the target areas must consistently remain above the sensitivity threshold of the enemy electronics. This ensures that the effectiveness of the jamming operation is maintained despite the jammers' movement. The mobility of the jammers should not compromise the jamming signal level; rather, their repositioning must be managed in such a way that target areas continue to experience sufficient jamming interference.

Additionally, LOS remains a critical factor in this problem. Consequently, as mobile jammers relocate to new positions, each new location must continue to satisfy the LOS constraint, ensuring clear and unobstructed signal paths to the target areas. The movement of the jammers should be planned to maintain effective LOS coverage, guaranteeing that the jamming signal reaches the target areas without interruption or degradation due to obstacles. This constraint ensures that the repositioning of jammers does not compromise their operational effectiveness in maintaining strong jamming signals at the target areas.

As detected mobile jammers relocate to new positions, their danger level initially decreases due to the movement away from known locations. However, once these jammers are set up at their new positions, the danger level gradually begins to increase as the enemy potentially detects their presence over time. Therefore, selecting new positions with the lowest possible initial danger level is essential. The objective is to ensure that each relocation minimizes the initial risk of detection, keeping the jammers' danger level at a minimum from the moment they reach their new setup points. This strategy helps maintain operational security by reducing the likelihood of detection at each new deployment location.

The final constraint addresses the proximity of mobile jammers to one another. Upon reaching their new locations, the mobile jammers must maintain a sufficient distance from each other. If they are positioned too close together, the risk of detection by enemy forces increases significantly. Therefore, the deployment of jammers should be carefully managed to ensure adequate spacing, minimizing the likelihood of simultaneous detection and enhancing overall operational security. This constraint ensures that the jammers' spatial distribution reduces detectability and maintains the effectiveness of the jamming operation.

7.3 Solution Technique

This section explains the solution technique used to determine the optimal placements for mobile jammers in scenarios involving mobile targets. In this approach, if a jammer remains undetected by enemy forces, its location remains unchanged. Therefore, the problem specifically focuses on the repositioning of jammers that have been detected by the enemy, ensuring that these jammers adjust their positions to maintain effective jamming against dynamically moving targets. This strategy enables continuous adaptation of jammer placements in response to both the detection status of jammers and the mobility of target areas, ensuring persistent and effective electronic warfare coverage.

In this study, MPSO is utilized as the optimization algorithm to determine optimal jammer placements in a dynamic scenario with mobile jammers and mobile targets. The parameters of the optimization algorithm are kept consistent with those used in the solution technique for the previous sections, ensuring stability and comparability across evaluations. The evaluation of populations generated during the optimization process is conducted in a manner similar to the previous sections, assessing each potential solution based on predefined constraints and cost functions. Similarly, the velocity updates for jammers in each iteration follow the approach used in the previous sections, guiding their movements toward optimal positions relative to the mobile targets. At the end of the optimization process, a fine-tuning phase, which is identical to that used in the previous sections, is applied to refine the solution, enhancing the accuracy of jammer placements. Consequently, parameter selection, constraint evaluations, cost function assessments, and velocity updates are not reiterated in detail in this section, as they remain consistent with the methods established in the previous problems.

On the other hand, the population initialization and handling of the non-convergence problem are not similar to all of the previous parts. In the section “Problem 2”, the creation of the initial population and techniques for the non-convergence problem are defined. To initialize the population, the undetected jammers stay in their positions, and the detected jammers are reinitialized similarly. In addition, a similar technique is used to prevent non-convergence. If the J A number of jammers cannot solve the problem after they are moved out of their initial best positions, so a new jammer is added to the solution. The new jammers are added until the solution converges.

7.4 Simulations and Results

In this section, scenarios involving mobile jammers and mobile targets are simulated. The simulations aim to evaluate the robustness and adaptability of the optimization algorithm in dynamic environments. These scenarios are designed with the complexities of electronic warfare in mind, where both jammers and targets can move. As a result, there is an ongoing risk that the enemy may detect the jamming signal transmitter, allowing them to counter the jammer's effectiveness or even launch an attack on its location. This dynamic interaction between mobile jammers and targets adds complexity to the scenarios, testing the algorithm's ability to maintain optimal jamming effectiveness while adapting to changing conditions.

The scenarios for mobile jammers and mobile targets are selected based on the scenarios developed for "Stationary Jammers and Mobile Targets". This approach allows the feasible solutions obtained in the stationary setup to serve as the initial conditions for the mobile jammers. By leveraging these established solutions, the algorithm has a solid starting point for optimizing jammer movements in response to mobile targets. Consequently, six scenarios from the previous section are adapted to this setting.

The information in the figures is similar to that in the previous parts. It should be noted that the blue circles in this section represent the detected area by the enemy forces. In addition, the purple region represents the highest probability while the blue is the lowest. Namely, it can be considered that the mobile target should be in the colored regions surrounded by the black lines.

7.4.1 Scenario-1

Table 7.1 Characteristics of Scenario-1

Characteristics	Explanations
Number of Detected Jammers	2

Table 7.1 (continued)

Number of Total Jammers	7
Number of Mobile Targets	1
Number of Total Targets	1
Altitude Level of Feasible Regions Relative to the Target Area	High

The first scenario is a basic scenario for mobile jammers and mobile targets. In this scenario, two jammers, which are close to the target area, out of seven jammers, are detected by the enemy forces. This scenario is taken from “Scenario-2” in the previous section. The initial cost value is around 89 for the initial situation of the scenario. The scenario aims to investigate the behavior of the algorithm under easy conditions, such as no extra stationary targets and high altitudes.

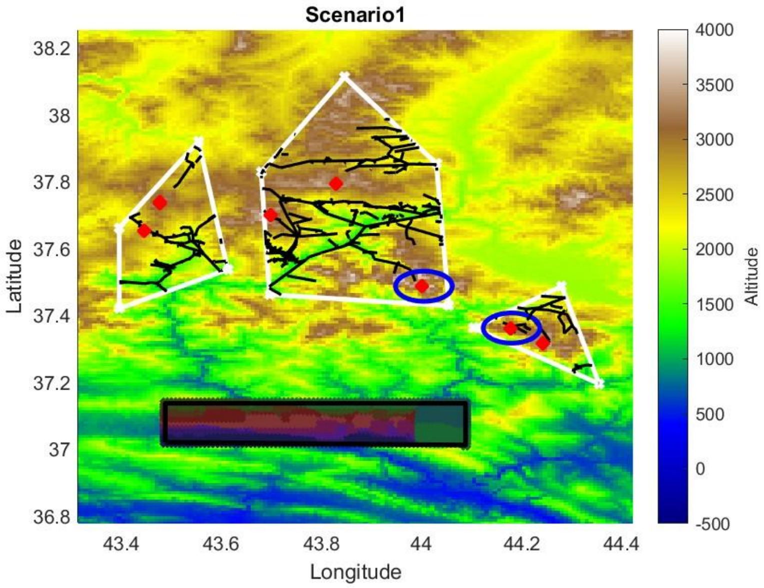

Figure 7.2. Scenario-1 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 7.2 Optimal Jammer Locations for Scenario-1

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.654050	37.7394876	37.6996169	37.794547
Longitude	43.445502	43.4777359	43.6987664	43.828468
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.317996	37.5211477	37.3123008	37.629368
Longitude	44.242133	43.9428210	44.3142751	43.960472

The optimization algorithm finds a new position for the detected jammers. The new position has a greater altitude value for the detected jammer inside pentagon region. In addition, the detected jammer inside the triangle feasible region uses the connected road to find a new location. On the other hand, since the jammers are away from the target area with their new positions, a new jammer is added to the swarm so as to satisfy the constraints. The final cost value is found around 97.

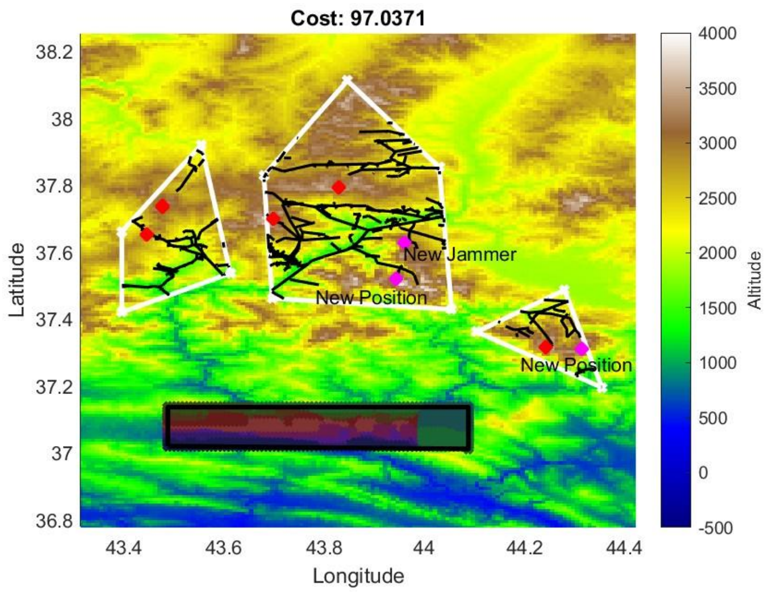

Figure 7.3. Scenario-1 Solution

7.4.2 Scenario-2

Table 7.3 Characteristics of Scenario-2

Characteristics	Explanations
Number of Detected Jammers	3
Number of Total Jammers	8
Number of Mobile Targets	1
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	High

This scenario is taken from “Scenario-4” of the stationary jammers and mobile targets problem. In this scenario, three jammers out of eight jammers are detected. Since there are stationary targets, one of the jammers is detected by a stationary target. This scenario investigates the situation of detection by both stationary and mobile targets when the feasible region has greater altitude values with respect to the target areas. The cost function value before the movements is around 44.

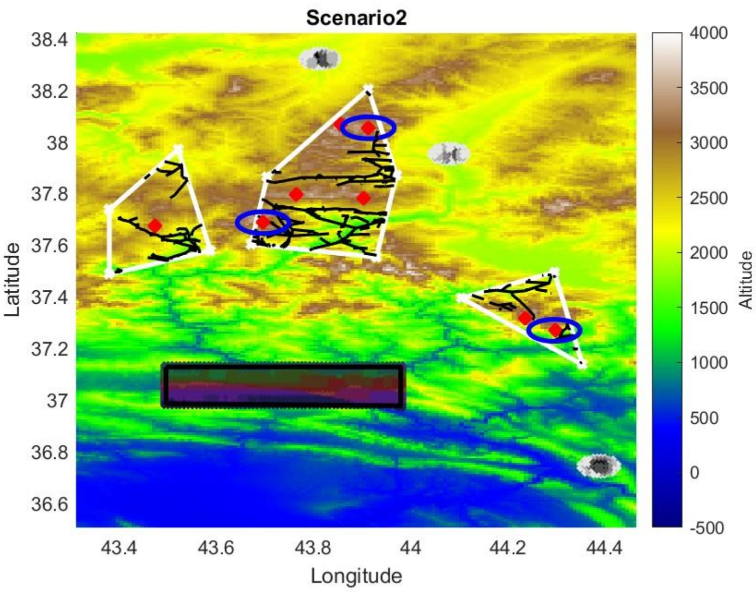

Figure 7.4. Scenario-2 Visualization

The optimization algorithm for this scenario provides the following results.

Table 7.4 Optimal Jammer Locations for Scenario-2

	Jammer 1	Jammer 2	Jammer 3
Latitude	37.673234	37.796231	38.069284
Longitude	43.472702	43.764532	43.854879
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	37.316543	37.781471	37.631415
Longitude	44.235457	43.902052	43.747742
	Jammer 7	**Jammer 8**	**Jammer 9**
Latitude	37.970886	37.331303	37.365742
Longitude	43.878865	44.317010	44.162700

The optimization algorithm finds a new solution by adding an extra jammer. Since three of the jammers from the set are detected, they are relocated into the feasible regions. In addition, a new jammer is deployed in the pentagon in a feasible region to satisfy the constraints. The final cost value is increased to 49.

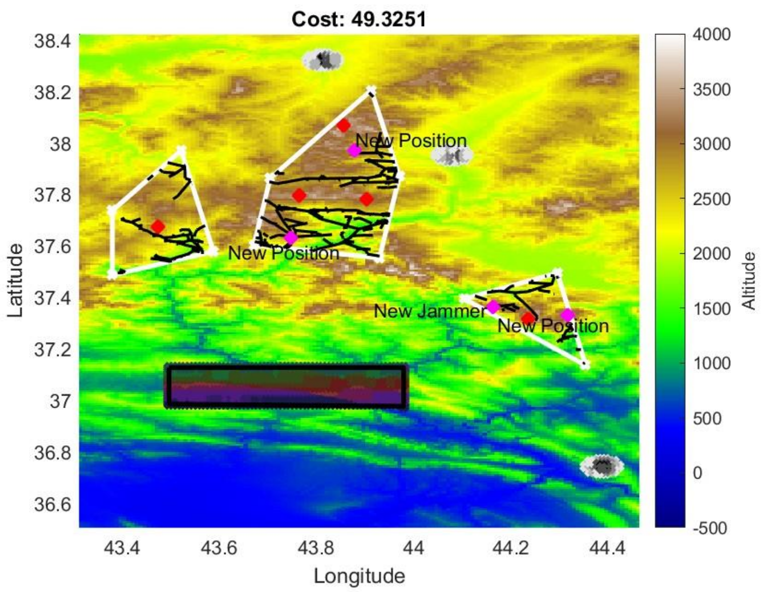

Figure 7.5. Scenario-2 Solution

7.4.3 Scenario-3

Table 7.5 Characteristics of Scenario-3

Characteristics	Explanations
Number of Detected Jammers	3
Number of Total Jammers	8
Number of Mobile Targets	1
Number of Total Targets	1
Altitude Level of Feasible Regions Relative to the Target Area	Low

This scenario is taken from the "Scenario-6" of the previous section. In this scenario, three jammers are detected by the mobile enemy target. The difference in this scenario is the altitude levels of the feasible regions, which are low. Therefore, the scenario aims to investigate the effect of altitude levels on the mobile jammers and mobile targets problem. The initial cost function is around 192 before the movements of the jammers.

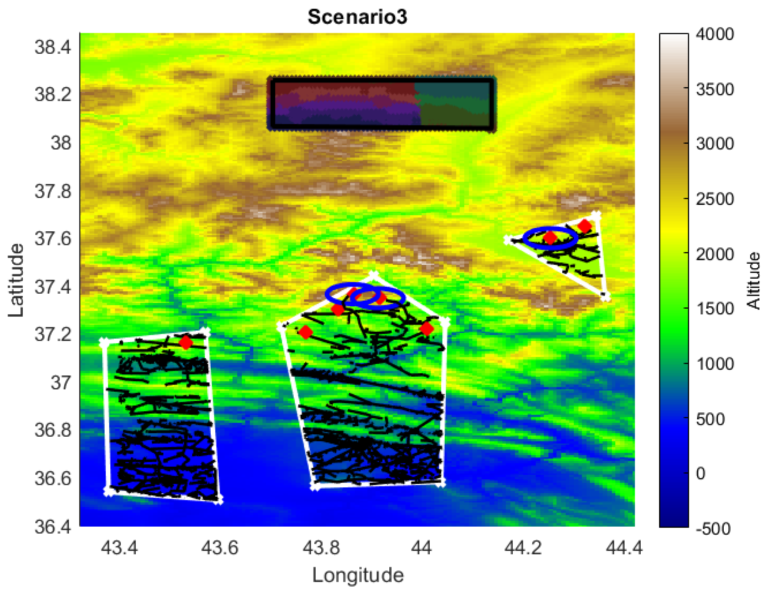

Figure 7.6. Scenario-3 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 7.6 Optimal Jammer Locations for Scenario-3

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.645031	37.215764	37.205165	37.160119
Longitude	44.322019	44.009987	43.768733	43.531284
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.297908	37.226364	37.287309	37.578786
Longitude	43.832661	43.892023	43.956713	44.195684
	Jammer 9	**Jammer 10**	**-**	**-**
Latitude	37.038228	37.141570	-	-
Longitude	44.015314	43.844838	-	-

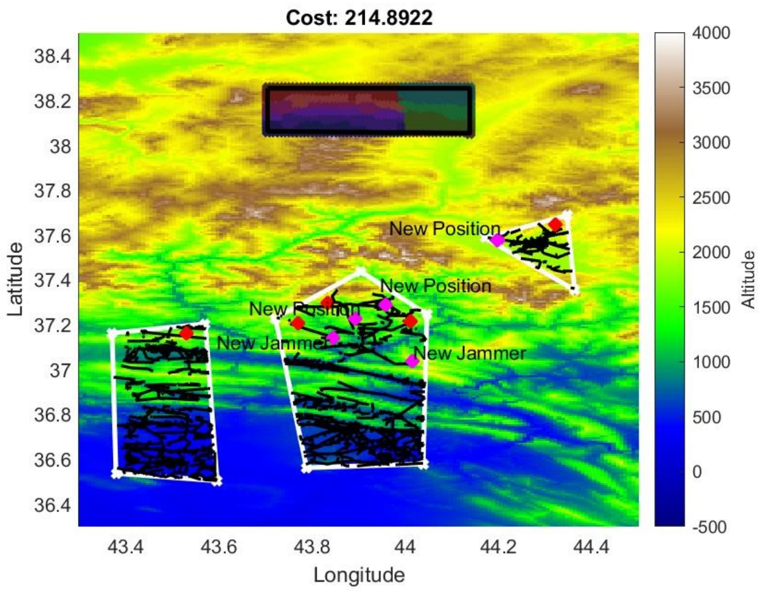

Figure 7.7. Scenario-3 Solution

In this scenario, the total number of jammers is increased to 10 from 8. The detected jammers are deployed to the feasible regions, and they are used on the connected roads. In addition, the feasible regions have lower altitude values with respect to the mobile target area. Therefore, the change in the locations of the jammers leads to unsatisfied constraints. In order to ensure the constraints, two extra jammers are used. For the final locations of the jammers, the cost value is around 215.

7.4.4 Scenario-4

Table 7.7 Characteristics of Scenario-4

Characteristics	Explanations
Number of Detected Jammers	5
Number of Total Jammers	10
Number of Mobile Targets	1
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	Low

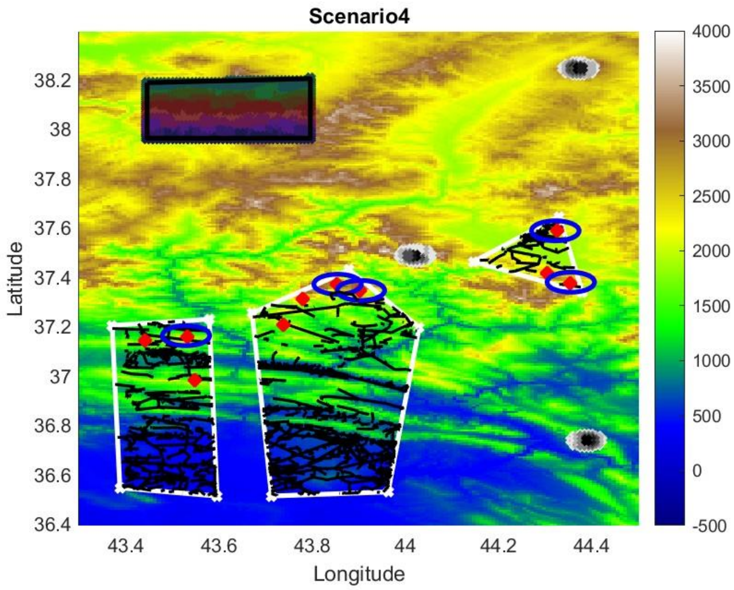

Figure 7.8. Scenario-4 Visualization

The scenario is similar to the “Scenario-8” from the stationary jammers and mobile targets section. In this scenario, five jammers are detected due to the low altitude values of feasible regions and the distance between the jammers and target areas. The aim of the scenario is to observe the effect of the stationary targets when the altitude levels of the feasible regions are low. The starting cost value is around 143.

Table 7.8 Optimal Jammer Locations for Scenario-4

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.414190	37.3111698	36.9815054	37.141186
Longitude	44.302494	43.7785862	43.5482328	43.440956
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.205574	37.5609937	37.4373695	37.282839
Longitude	43.738669	44.2659043	44.3540540	43.948232
	Jammer 9	**Jammer 10**	**Jammer 11**	**Jammer 12**
Latitude	37.295716	37.1025541	36.9815054	37.264810
Longitude	43.838461	43.4975051	43.4866943	43.894178

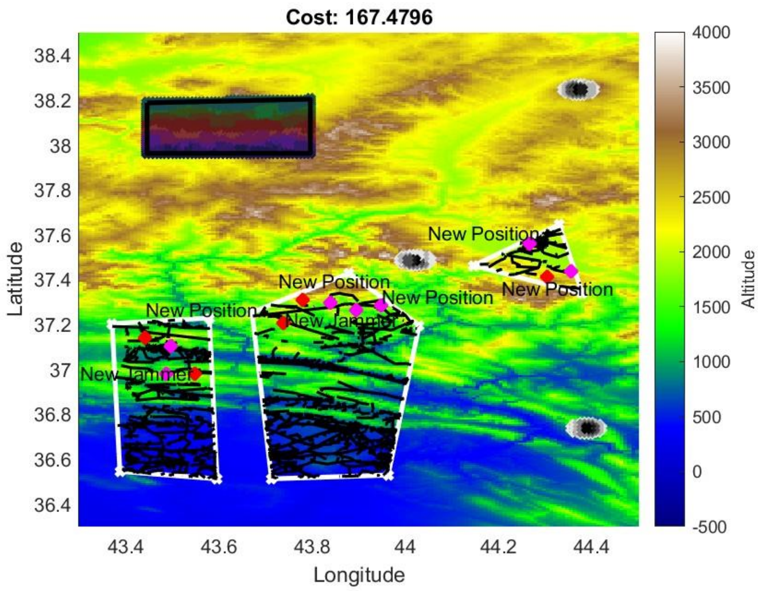

Figure 7.9. Scenario-4 Solution

The optimization algorithm finds a new solution with 12 number of jammers. Namely, the algorithm requires two extra jammers. In this solution, the positions of jammers are close to the target areas as the altitude values of the feasible regions are relatively low. In the final deployment, the cost function value is increased 167.

7.4.5 Scenario-5

Table 7.9 Characteristics of Scenario-5

Characteristics	Explanations
Number of Detected Jammers	4
Number of Total Jammers	9
Number of Mobile Targets	2
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	High

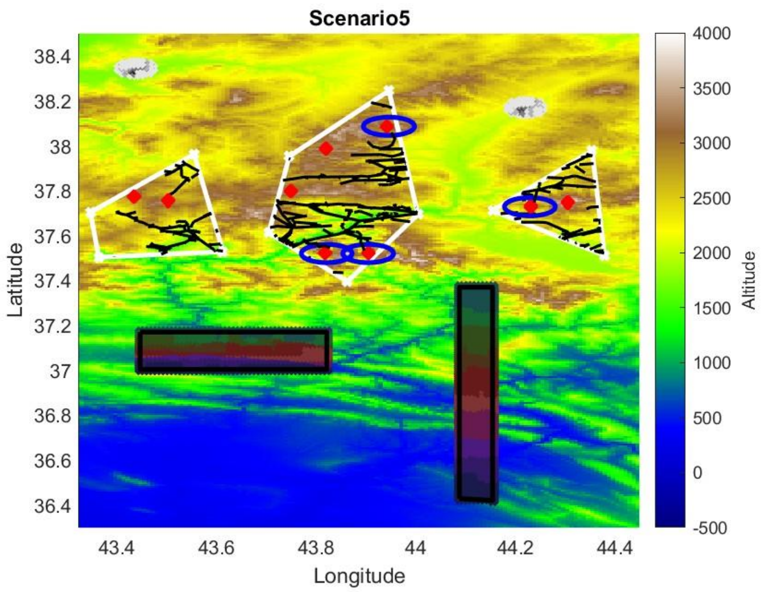

Figure 7.10. Scenario-5 Visualization

The scenario is taken from the “Scenari-10” of the previous section. In this scenario, the altitude levels of the feasible regions are high again. However, there are two mobile and two stationary targets. Therefore, the scenario aims to observe the effect of multiple target areas on the algorithm when there are stationary target areas. The cost function of the scenario is around 58 at the initial stage. The optimization algorithm for this scenario provides the following results.

Table 7.10 Optimal Jammer Locations for Scenario-5

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.748262	37.773745	37.756756	37.988931
Longitude	44.305916	43.434328	43.501433	43.819793
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.799227	37.592535	37.649163	38.039897
Longitude	43.748786	43.825255	43.957124	43.902504
	Jammer 9	**Jammer 10**	**-**	**-**
Latitude	37.867181	37.646332	-	-
Longitude	44.325423	44.275484	-	-

The initial solution was completed with nine jammers. However, the detected jammers are close to the mobile target areas. Therefore, the extensive change in locations of these jammers may lead to a decrease in signal levels in the mobile target areas. In order to prevent this decrease, the optimization algorithm finds the new positions of the jammers close to the mobile target areas. In addition, there is an extra jammer to ensure the constraints. Therefore, the final cost value has a small change and increases to 63.

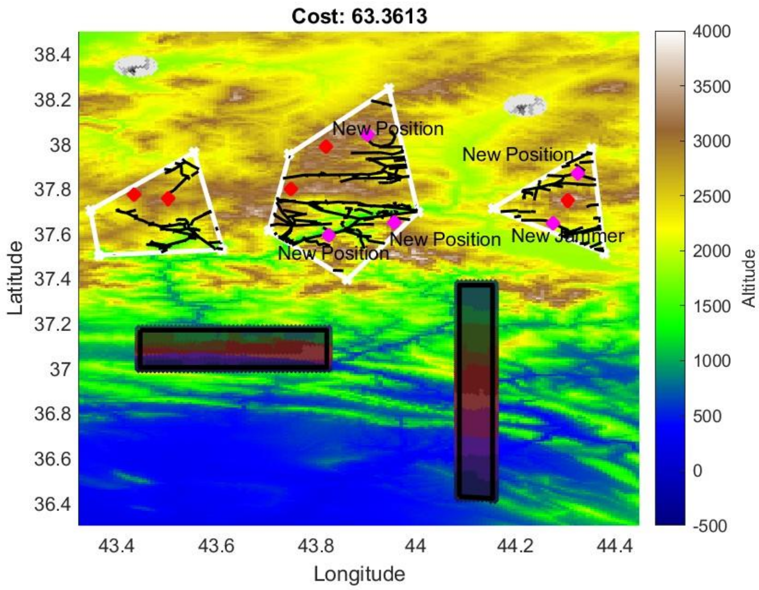

Figure 7.11. Scenario-5 Solution

7.4.6 Scenario-6

Table 7.11 Characteristics of Scenario-6

Characteristics	Explanations
Number of Detected Jammers	6
Number of Total Jammers	10
Number of Mobile Targets	4
Number of Total Targets	4
Altitude Level of Feasible Regions Relative to the Target Area	High

The last scenario is similar to the “Scenario-11” of the previous problem. In this scenario, there are six jammers detected by the enemy forces and four mobile targets. The scenario investigates the effect of many mobile target areas on the problem. The starting cost function value is around 92 in this scenario.

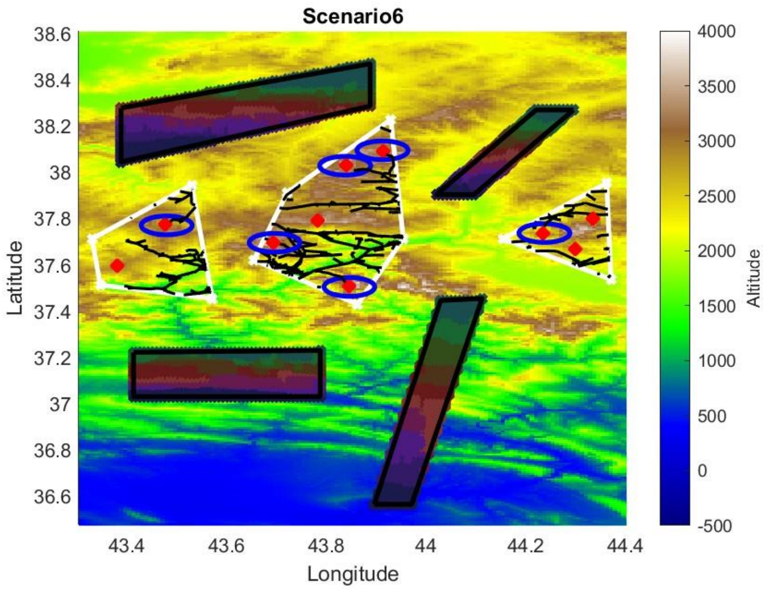

Figure 7.12. Scenario-6 Visualization

The optimization algorithm for this scenario provides the following results. The numerical results for the optimal jammer locations are given in the table.

Table 7.12 Optimal Jammer Locations for Scenario-6

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.798885	37.669510	37.595188	37.793380
Longitude	44.334485	44.301017	43.380671	43.782116
	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	38.038367	37.966798	37.630973	37.578672
Longitude	43.922315	43.857961	43.730786	43.823486
	Jammer 9	**Jammer 10**	**Jammer 11**	**Jammer 12**
Latitude	37.859444	37.796133	37.818154	37.669510
Longitude	43.494056	44.270898	43.871751	43.477201
	Jammer 13	**-**	**-**	**-**
Latitude	37.661252	-	-	-
Longitude	43.915420	-	-	-

In this scenario, six of the ten jammers are detected by the enemy forces. Therefore, these jammer locations are changed by the algorithm. On the other hand, this change leads to unsatisfied constraints with the same number of jammers. Hence, there are three extra jammers. The jammers are distributed to the relatively high grounds in order to jam all of the mobile target areas. The new solution results in a cost value of 106.

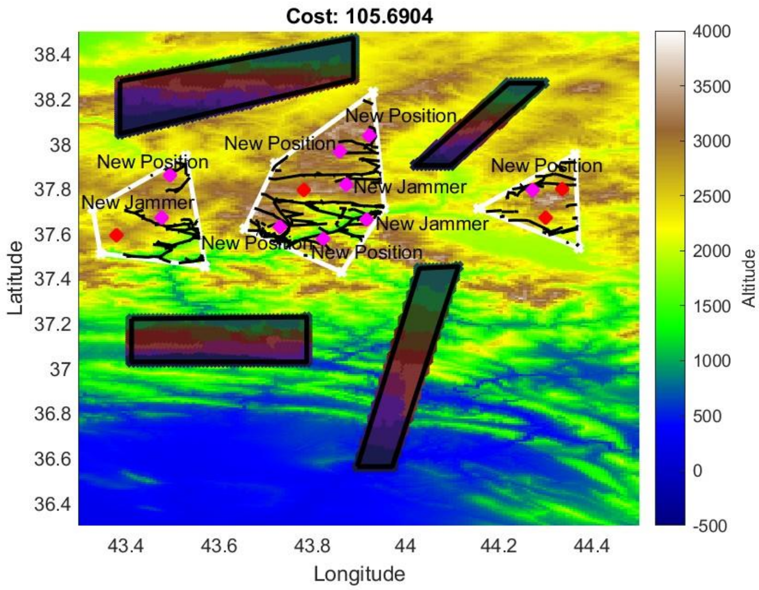

Figure 7.13. Scenario-6 Solution

CHAPTER 8

PROBLEM 5: POWER ALLOCATION FOR JAMMERS

In the context of electronic warfare, the power allocation for the jammers is also an important topic [66]. This chapter focuses on power allocation optimization. This chapter aims to improve effective jamming by using power allocation. In this problem, power allocation is included in the previous problem as a new constraint. Therefore, the optimization process still takes into account various factors such as LOS, signal strength at the target areas, and the risk of detection by enemy forces.

8.1 Problem Definition

The problem of optimal power allocation for jammers in electronic warfare focuses on distributing the available power among multiple jammers in the best way possible. The main goal is to make jamming more effective, disrupting enemy communication networks while still considering important factors like LOS, the strength of the jamming signal at target areas, and the risk of being detected by enemy forces.

In this problem, it should be decided how much power each jammer should use to make sure the jamming works well at target areas. The power allocation strategy needs to use limited energy efficiently to minimize the waste of power and keep the risk of detection low. It also has to be adjusted for different environmental conditions, like changes in terrain or how signals travel, which can affect how well the jamming works.

The optimization process must carefully balance these different factors. For example, using more power can make the jamming signal stronger, but it can also increase the chance of being discovered by the enemy. At the same time, having a clear LOS for the jamming signals might require adjusting power levels to be most effective. The goal is to create a power allocation plan that ensures strong jamming while staying within the limits of the system and reducing the risk of getting detected.

8.2 Problem Formulation

The problem considers the number of jammers, the optimal locations of jammers, and the transmitting power for each jammer. Therefore, there are three unknowns to the problem.

The first unknown is the positions of the jammers. This unknown is represented in terms of latitude and longitude, as in the previous problems. In addition, the positions of the jammers affect the LOS, signal strength at the target areas and the detectability risk of the jammers by the enemy forces. On the other hand, terrain features such as hills and feasible regions affect this variable.

Throughout this section, the following notations are used to represent the geographical coordinates of the jammers;

$$P_j = \left(x_j, y_j\right), j = 1,2, \dots, J \qquad (8.1)$$

x_j: Latitude of the j-th jammer.

y_j: Longitude of the j-th jammer.

J: Total number of jammers used in the solution.

In addition to the positions of the jammers, the total number of jammers is another unknown for this problem, like the previous problems. The aim of the problem is to minimize the number of jammers while maximizing the jamming efficiency. Throughout this section, the total number of jammers is represented by J, where J is a positive integer. In the solution, a minimum number of jammers should be used so as to keep the consumption at a minimum.

The last and new unknown for the problem is the transmitting power for the jammers. In this problem, the aim is also to keep the power consumption minimum while maximizing the jamming efficiency. Therefore, each jammer should have the upper limit for transmitting power and may not use the full capability of their transmitting power. Throughout this section, G_j is used to represent the transmitting power of the jammers. G_j variable uses the Watt (W) to represent the amount of transmit power for each jammer and $j = \{1,2, \dots, J\}$. In the solution, the minimum average transmitting power should be considered in order to keep consumption and detectability risks by the enemy forces at a minimum.

8.2.1 Objective Function

The objective of this problem is to maximize the jamming efficiency at the target communication networks. In addition, the problem aims to minimize the total consumption in terms of the number of jammers and the transmit power of the jammers. Also, the minimization of these variables leads to the minimization of the detectability risk of the jammers by the enemy forces. Therefore, the objective function should consider the minimum required LOS and signal level at the target areas so as to maximize the jamming efficiency. Moreover, the function should also take into account the transmit power to minimize it. In addition, the proximity coefficient is similar to the previous problems. Therefore, the objective function is constructed by considering the mentioned variables.

$$F(P_i, J, G_i) = \left(\min_{\{P_i\ , J\}} (LOS_{Total} - SL_{Total}) \right) \cdot K \cdot G_{Total} \tag{8.2}$$

The total LOS, signal level, and transmit power can be calculated as the following equations;

$$LOS_{Total} = \frac{1}{|T|} \cdot \frac{1}{J} \cdot \sum_{j=1}^{|T|} \left(\sum_{i=1}^{J} \left(\int_{T_j} \min\ (LOS(P_i, t) dt \right) \right) \tag{8.3}$$

$$SL_j = \int_{T_j} \left(\sum_{i=1}^{J} SL(P_i, t) \right) dt \tag{8.4}$$

$$SL = SignalSum\left(SL_j \circ SL_j\right) \text{ for } j = 1,2, \dots, |T| \tag{8.5}$$

$$SL_{Total} = \frac{1}{|T|} \cdot \sqrt{SL} \tag{8.6}$$

$$G_{Total} = \frac{1}{J} \cdot \frac{\sum_{i=1}^{J} G_i}{1000} \tag{8.7}$$

Where, $P_i \in A$.

$P_i = (x_i, y_i)$ is the coordinates of the i-th jammer in the deployment area A.

A is the continuous area in which jammers can be deployed.

T is the set of target areas.

T_j represents the continuous set of points within a target area which is an element of the set T.

$|T|$ shows the number of elements in the set T.

J is the minimum number of jammers to satisfy the constraints.

K is the punishment coefficient according to the proximity of the jammers. K value is defined in the constraints as it is mostly dependent on constraints.

$A \circ B$ notation represents the elementwise multiplication.

G_i is the transmit power in terms of W for the i-th jammer. The upper bound for the transmit power is chosen as 1000 W for the problem. Therefore, the coefficient G_{total} refers to the average transmit power ratio to the allowable available transmit power of the jammers.

8.2.2 Constraints

The problem involves six key constraints, and the first five constraints are consistent with those in the previous problems. The first constraint refers to the deployment locations, which are defined as feasible regions. Similar to the earlier sections, the jammers must be positioned within these predefined feasible regions to ensure practical applicability.

The second constraint addresses the signal level at the target areas. The signal level must exceed the sensitivity threshold of the electronics at the target areas. This requirement aligns with the signal level constraint introduced in “Problem 1,” ensuring effective jamming performance.

Additionally, the LOS between the jammers and the target areas remains a critical constraint. As in “Problem 1,” the minimum required LOS must exceed five times the antenna height of the jammer. The coefficient of 5 introduces flexibility into this constraint, allowing the antenna to be mounted on a mast or a building to meet the requirement.

Furthermore, the detectability of the jammers by enemy forces is a significant consideration. The detectability constraint continues to play a vital role in this problem. As in the previous parts, the detectability of solutions is evaluated by comparing configurations with J jammers to those with $J + 1$ jammers, ensuring the jammers remain as inconspicuous as possible. A new part is also added to this detectability constraint. In the scenarios of this problem, the scenarios and results published in “Problem 1” are used. Therefore, an optimal solution is known when there is no transmit power constraint. The detectability level of the solution in this problem should be strictly less than the detectability value of the scenario of “Problem 1”. Therefore, the following constraint is introduced.

$$DL\left(\widehat{P_{opt}}, \widehat{J_{opt}}\right) > DL\left(P_{opt}, J_{opt}\right) \tag{8.8}$$

$\widehat{P_{opt}}$ represents the optimal jammer locations and $\widehat{J_{opt}}$ denotes the optimal jammer number for the solution of “Problem 1” with the same scenario. On the other hand, P_{opt} is the optimal jammer locations and J_{opt} is the optimal number of jammers for the solution of this problem.

In addition, the problem includes a constraint on the minimum distance between the jammers. This constraint ensures that jammers are adequately separated to reduce the risk of simultaneous detection by enemy forces. Additionally, maintaining sufficient separation minimizes the likelihood of multiple jammers being detected at the same time, thereby enhancing the operational effectiveness and survivability of the deployment.

The last and new constraint is introduced to this problem. This constraint is about the transmit power of the jammers. It refers to the upper bound for the transmit power of the jammers. So as to bound the transmit power, 1000 W is chosen in this problem. Therefore, the following constraint should be satisfied for each jammer used in the solution.

$$G_i \leq 1000 \text{ W}, \text{for all } i = 1,2,\dots,J \tag{8.9}$$

8.3 Solution Technique

In this section, the solution technique that is used to find the optimum jammer placements is explained. Like in the previous problems, MPSO is used as the optimization algorithm. MPSO has crucial steps such as the selection of parameters, population initialization, evaluation of the initial population, and velocity updates. In addition, the algorithm should consider handling the non-convergence problem and fine-tuning the final result. These steps are defined in “Problem 1” and some of these steps are similar to the definitions done before. Therefore, the differences between the algorithm steps for this problem and “Problem 1” are shared in this section.

The first step is to determine the parameters of the algorithm. The population size was selected as 5% of the feasible regions, namely, the possible location points. In this problem, the number of unknowns is changed to 3. Using the same ratio leads to more convergence time since the number of unknowns is increased. Therefore, the population size decreased to 3% of the feasible regions. In addition, the maximum number of iterations is kept the same; namely, $\#\text{ of Iterations} = 20$. The aim using these initial population size and maximum number of iterations parameters is to balance between the exploration and computational efficiency.

$$\text{Population Size} = (\text{Total Possible Location Points}) \times 0.03 \qquad (8.10)$$

The cognitive parameter and social parameters are kept the same with the solution technique of “Problem 1”. $(c_1 = c_2 = 2)$

Due to the same reasons mentioned in “Problem 1”, another parameter that is kept same is the constriction factor, K.

In addition, there are also minimum inertia weight (W_0) and current inertia weights for the i-th iteration (W_i). They are kept the same as “Problem 1”.

The population initialization step is done in a similar way to the previous solutions. It considers the altitude levels of the jammer placement locations and the distance between the target areas and possible jammer placement locations. In addition, the jammers are initialized with the normal distribution between the limits of transmit power. Furthermore, the velocity is updated in the same way in the solution of “Problem 1”.

If the algorithm does not converge to optimal jammer locations set with the transmit power constraint. The number of jammers has increased by one. However, it still may not lead to a convergence inside the determined feasible region. Since the scenarios are taken from the simulations and results part of “Problem 1”, the number of jammers of an optimal solution is known without transmit power constraint for a scenario. Therefore, if the number of jammers is greater than the number of jammers in the optimal solution of the scenario in “Problem 1”, the feasible region is expanded 2 kilometers from each side.

When the algorithm finds an optimal solution, the fine-tuning process starts in the same way as “Problem 1” so that it can improve the solution near the jammer locations and in terms of used transmit power.

8.4 Simulations and Results

In this section, the performance of the algorithm and the effects of the transmit power variable are investigated. So as to investigate these, seven scenarios are taken from the simulations and results section of “Problem 1”. The taken scenarios are 1, 4, 5, 7, 9, 13, and 15. For “Problem 1”, all the jammers are considered to use the same transmit power, and it is assumed to be 750 W. In this section, the upper bound for the transmit power is selected as 1000 W. Therefore, some of the jammers have greater than 750 W, and some of them have less than 750 W.

In the figures of the scenarios, the red dots represent the optimal jammer locations and J_i texts denote the i^{th} jammer. In addition, the optimal transmit power levels are given in the paragraphs.

8.4.1 Scenario-1

This scenario is also the first scenario of “Problem 1”. In “Problem 1”, the optimal solution was found by 4 number of jammers. When the transmit power variable is introduced to this scenario, the optimal number of jammers is increased to 5. In order to decrease the detectability constraint, some of the jammers find themselves in new positions that are away from the target area.

The numerical results for the optimal jammer locations are given in the table.

Table 8.1 Optimal Jammer Locations for Scenario-1

	Jammer 1	**Jammer 2**	**Jammer 3**
Latitude	37.841468	37.832373	37.768709
Longitude	43.450482	43.789197	43.888735
	Jammer 4	**Jammer 5**	**-**
Latitude	38.014269	37.750520	-
Longitude	43.929553	44.362794	-

For the solution, the transmit power values for the jammers are 697 W, 758 W, 753 W, 738 W, and 726 W, respectively. Therefore, the detectability of enemy forces parameter decreases to 114 from 108. The change in the locations and transmit power levels leads to increasing the cost function value from 90 to 94.

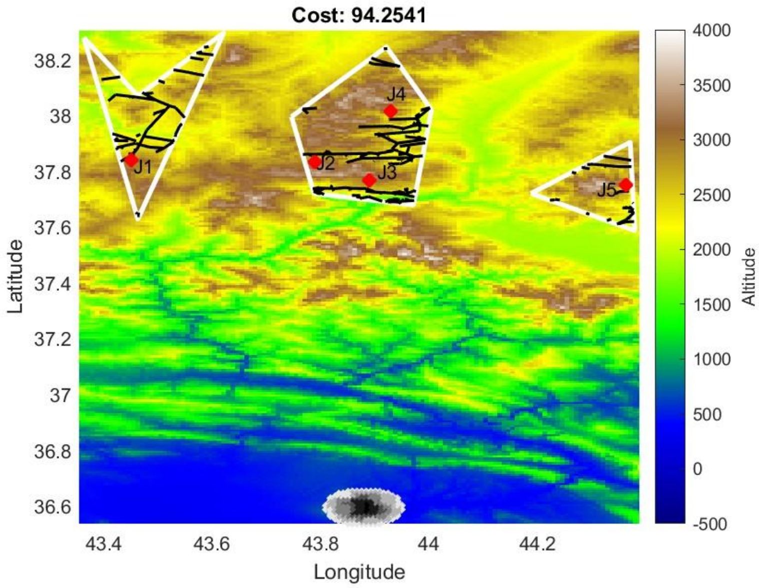

Figure 8.1. Scenario-1 Solution

8.4.2 Scenario-2

This scenario is the “Scenario-4” of “Problem 1”. In “Problem 1”, the optimal solution is found by six jammers. When the transmit power variable is introduced to this scenario, the optimal number of jammers is increased to 8. In this scenario, the algorithm takes some of the jammers back and adds two new jammers to the swarm.

The numerical results for the optimal jammer locations are given in the table.

Table 8.2 Optimal Jammer Locations for Scenario-2

	Jammer 1	Jammer 2	Jammer 3	Jammer 4
Latitude	37.520881	37.324963	37.667820	37.111552
Longitude	43.413359	43.608548	44.375558	44.213359

Table 8.2 (continued)

	Jammer 5	**Jammer 6**	**Jammer 7**	**Jammer 8**
Latitude	37.066071	37.258491	37.122048	37.052077
Longitude	44.130884	43.454596	43.523324	44.053908

For the solution, the transmit power values for the jammers are 811 W, 724 W, 634 W, 767 W, 736 W, 745 W, and 731 W, respectively. Therefore, the detectability of enemy forces parameter decreases to 1691 from 1383. The change in the locations and transmit power levels lead to an increase in the cost function value from 121 to 138.

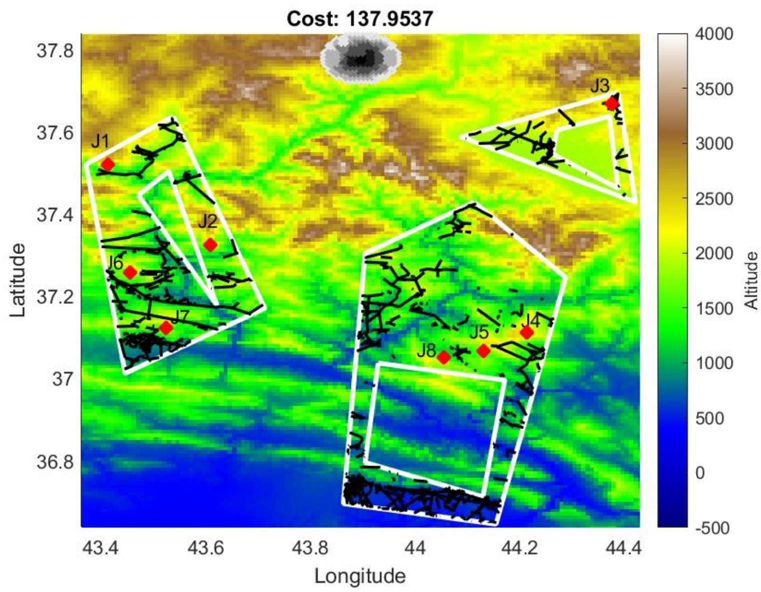

Figure 8.2. Scenario-2 Solution

8.4.3 Scenario-3

This scenario is the "Scenario-5" of "Problem 1". In "Problem 1", the optimal solution found by 3 number of jammers. When the transmit power variable is introduced to this scenario, the optimal number of jammers is increased to 5. In this scenario, the algorithm generally takes the jammers away from the target areas. In addition, there are two new jammers to ensure the other constraints are met.

The numerical results for the optimal jammer locations are given in the table.

Table 8.3 Optimal Jammer Locations for Scenario-3

	Jammer 1	Jammer 2	Jammer 3
Latitude	37.843901	38.022206	37.791715
Longitude	43.835389	43.927163	44.281512
	Jammer 4	**Jammer 5**	-
Latitude	37.852599	37.756924	-
Longitude	43.465745	43.973050	-

For the solution, the transmit power values for the jammers are 769 W, 724 W, 791 W, 783 W, and 716 W, respectively. Therefore, the detectability of enemy forces parameter decreases to 132 from 103. The change in the locations and transmit power levels leads to increasing the cost function value from 60 to 66.

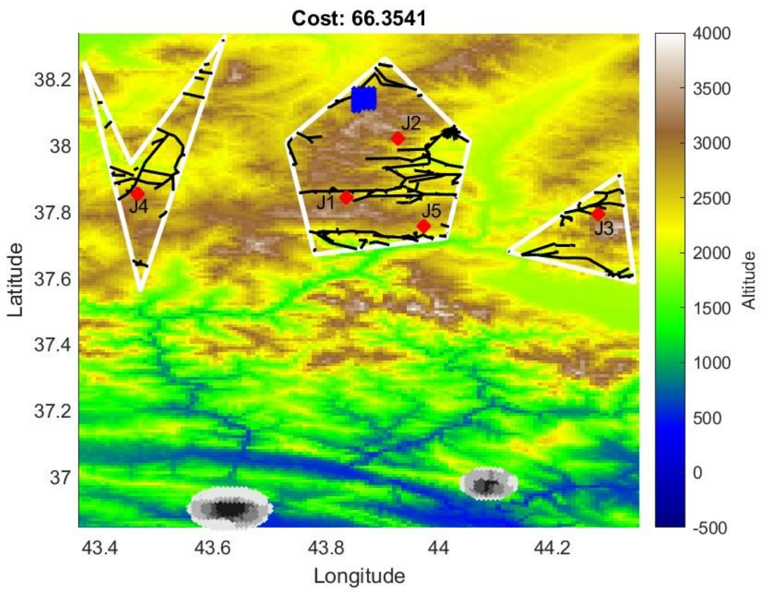

Figure 8.3. Scenario-3 Solution

8.4.4 Scenario-4

This scenario is the "Scenario-7" of "Problem 1". In "Problem 1", the optimal solution is found by six jammers. When the transmit power variable is introduced to this scenario, the optimal number of jammers is increased to 7. In this scenario, the algorithm cancels one of the jammers that are inside the triangular feasible region. This leads to the decrease in the detectability level. On the other hand, the transmit power of the another jammer inside the triangular region increased in order to continue to satisfy the other constraints. In addition, the addition of the new jammer helps to ensure the constraints.

The numerical results for the optimal jammer locations are given in the table.

Table 8.4 Optimal Jammer Locations for Scenario-4

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.013532	36.963313	37.048299	37.558211
Longitude	43.504959	43.589449	44.054145	44.352345
	Jammer 5	**Jammer 6**	**Jammer 7**	**-**
Latitude	37.237585	37.005806	37.214407	-
Longitude	44.029295	43.994505	43.870254	-

For the solution, the transmit power values for the jammers are 781 W, 774 W, 812 W, 819 W, 657 W, 829 W, and 613 W, respectively. Therefore, the detectability of enemy forces parameter decreases to 1716 from 1267. The change in the locations and transmit power levels led to an increase in the cost function value from 175 to 192.

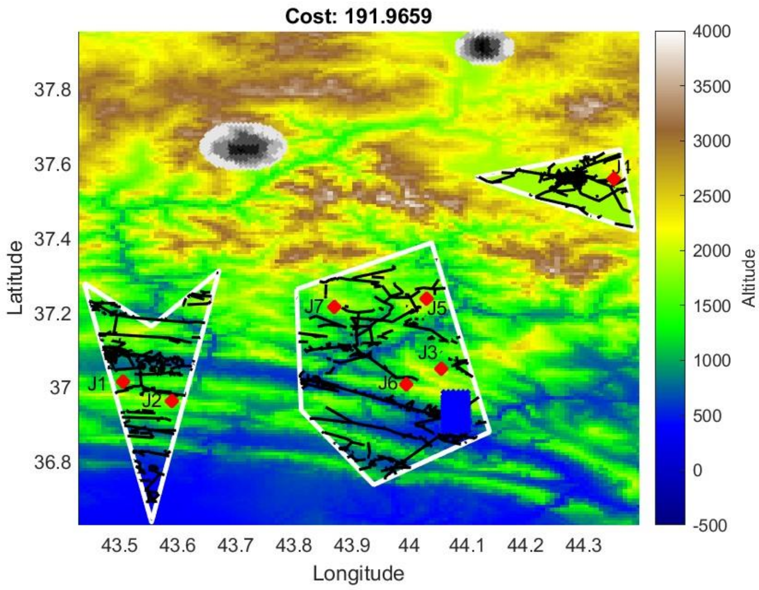

Figure 8.4. Scenario-4 Solution

8.4.5 Scenario-5

This scenario is the “Scenario-9” of “Problem 1”. In “Problem 1”, the optimal solution was found by 4 number of jammers. When the transmit power variable is introduced to this scenario, the optimal number of jammers is not changed. In the solution, the jammer numbers 1 and 3 are taken to the closer locations to the target areas. The detectability parameter is dependent on both the distance inversely and transmit power directly. Since the distance decreases, the algorithm also decreases the transmit power levels of these jammers so as to keep the constraints satisfied in the solution.

The numerical results for the optimal jammer locations are given in the table.

Table 8.5 Optimal Jammer Locations for Scenario-5

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.679142	37.766800	37.583515	37.750862
Longitude	43.470704	43.800824	43.970190	44.329016

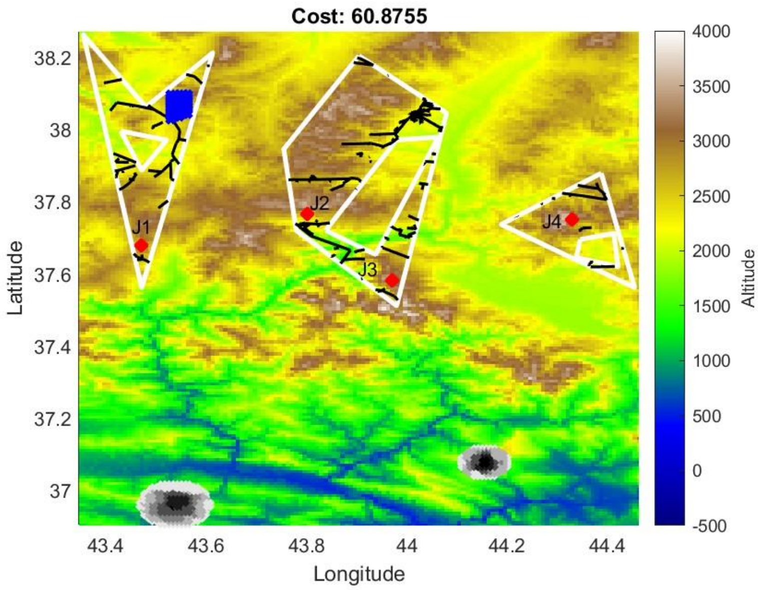

Figure 8.5. Scenario-5 Solution

For the solution, the transmit power values for the jammers are 598 W, 609 W, 754 W, and 746 W, respectively. Therefore, the detectability of enemy forces parameter decreases to 93 from 89. The change in the locations and transmit power levels does not affect the final cost function. The change in the cost function value is decreased by less than 1.

8.4.6 Scenario-6

This scenario is the "Scenario-13" of "Problem 1". In "Problem 1", the optimal solution was found by 5 number of jammers. When the transmit power variable is introduced to this scenario, the optimal number of jammers is increased to 6. In the solution, some of the jammers are taken away from the target areas. This change leads to an increase in the transmit power values. On the other hand, one of the jammers is closer to the target area. This change in the location results in a decrease in the transmit power. In addition, on the east side of the map, a new jammer is introduced. Since there are two jammers mainly responsible for the target area on the east side, the transmit power levels of these jammers are decreased.

The numerical results for the optimal jammer locations are given in the table.

Table 8.6 Optimal Jammer Locations for Scenario-6

	Jammer 1	Jammer 2	Jammer 3
Latitude	37.745031	37.778073	37.476567
Longitude	44.435582	44.253170	43.857476
	Jammer 4	**Jammer 5**	**Jammer 6**
Latitude	38.195225	37.534390	37.641775
Longitude	43.672257	43.635775	43.891152

For the solution, the transmit power values for the jammers are 641 W, 618 W, 757 W, 803 W, 725 W, and 754 W, respectively. Therefore, the detectability of enemy forces parameter decreases to 136 from 122. The change in the locations and transmit power levels leads to an increase in the cost function value from 43 to 49.

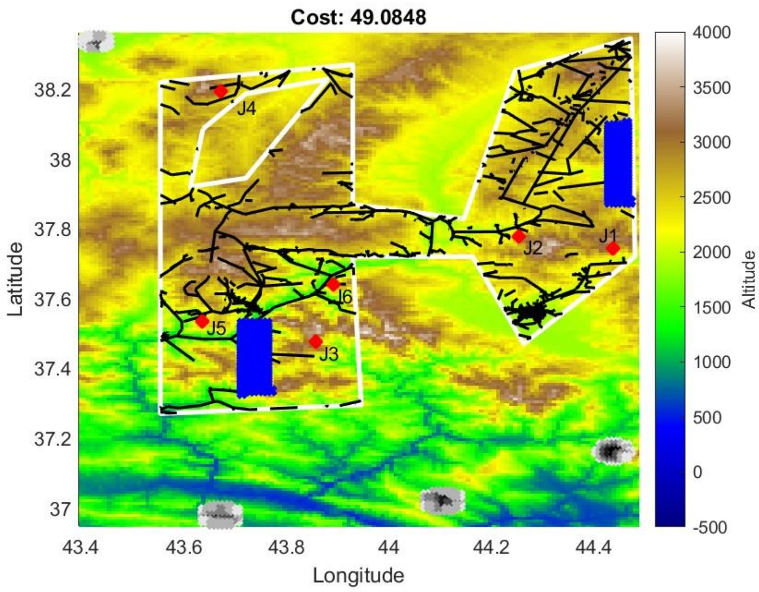

Figure 8.6. Scenario-6 Solution

8.4.7 Scenario-7

This scenario is the “Scenario-15” of “Problem 1”. In “Problem 1”, the optimal solution was found by 5 number of jammers. When the transmit power variable is introduced to this scenario, the optimal number of jammers is increased to 7. In the solution, some of the jammers are placed in locations with greater minimum required LOS values, which decreases the detectability level and may result in not satisfying constraints. Therefore, two new jammers are introduced to the swarm, and the transmit power level of the jammers is arranged to keep the constraints ensured.

The numerical results for the optimal jammer locations are given in the table.

Table 8.7 Optimal Jammer Locations for Scenario-7

	Jammer 1	**Jammer 2**	**Jammer 3**	**Jammer 4**
Latitude	37.845748	38.007677	37.485325	37.453984
Longitude	43.514298	43.926403	44.087456	43.656403
	Jammer 5	**Jammer 6**	**Jammer 7**	**-**
Latitude	37.736054	37.647254	37.558454	-
Longitude	43.677719	43.933508	43.796140	-

For the solution, the transmit power values for the jammers are 610 W, 734 W, 756 W, 722 W, 758 W, 747 W, and 763 W, respectively. Therefore, the detectability of enemy forces parameter decreases to 146 from 134. The change in the locations and transmit power levels lead to a decrease in the cost function value from 41 to 38.

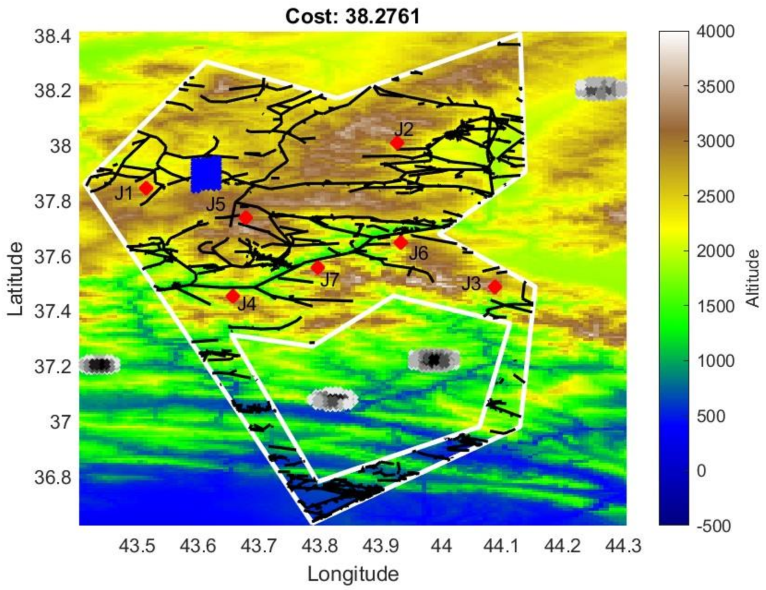

Figure 8.7. Scenario-7 Solution

CHAPTER 9

PROBLEM 6: STATIONARY JAMMERS IN LOCALIZATION SYSTEMS

The last problem of the study focuses on the concept of localization. In this section, the self-localization of the enemy communication electronics is selected as the target. The aim of the problem is to jam the enemy so that they can not localize themselves when there is no access to GNSS (Global Navigation Satellite Systems) such as GPS (Global Positioning System).

9.1 Problem Definition

In the concept of electronic warfare, jamming GNSS signals is highly important so that the enemy can not able to localize their positions [67]. As a result of this jamming concept, countermeasures have been developed. One of these developments is using anchor nodes [68]. In the concept of self-localization via anchor nodes, the anchor nodes are located at the known locations. By using many measurements, such as time-of-arrival (TOA) or received signal strength (RSS), the systems that do not have access to GNSS signals can localize themselves [69]. In these self-localization systems and algorithms, the aim is to increase the localization accuracy and the accuracy can be defined in terms of the mean squared position error [70]

On the other hand, these systems, which need to localize themselves, can also be affected by jamming. Therefore, jamming the self-localization systems can be optimized in terms of the location of the jammers. In this problem of the thesis, the aim is to minimize the performance of the self-localization systems in three-dimensional cases. The target systems work non-cooperatively in this problem. Therefore, the target systems receive signals from the anchor nodes and do not receive signals from any other target systems. In addition, constant jamming attacks are considered to be part of this problem. In the literature, there are studies of similar problems with two-dimensional cases [30].

In order to maximize the effect of the jamming, a system model is constructed in the study. This model is based on the Cramer-Rao Lower Bound (CRLB) for localization of the self-localization systems, namely, targets. CRLB for localization systems can be defined as the minimum achievable localization position error [71]. Therefore, CRLB can be used as the optimization parameter in this problem. In addition to the CRLB, the distance between the jammer location and targets is also considered as a constraint in the problem. This thesis problem is defined and solved in the three-dimensional environment.

9.2 Problem Formulation

In the problem definition part, the CRLB of the self-localization systems and three-dimensional problem cases are mentioned. Therefore, a three-dimensional system model is constructed using CRLB.

9.2.1 3D System Model

In the literature, there are system models that are constructed for two-dimensional problems [30]. However, a three-dimensional system model is constructed for this thesis problem.

In the system model, there are anchor nodes and target nodes. The number of anchor nodes and target nodes are represented with N_A and N_T, respectively. The location of the anchor nodes is represented with $x_i \in \mathbb{R}^3$, where $i = 1,2, \ldots N_A$. In addition, the location of the target nodes is demonstrated with $y_i \in \mathbb{R}^3$, where $i = 1,2, \ldots N_T$. x_i and y_i variables are represented in the cartesian coordinates, where $\tilde{x}$ is the x-coordinate, $\tilde{y}$ is the y-coordinate, and $\tilde{z}$ is the z-coordinate of the cartesian.

$$x_i = [\tilde{x}_{x_i}, \tilde{y}_{x_i}, \tilde{z}_{x_i}] \tag{9.1}$$

$$y_i = [\tilde{x}_{y_i}, \tilde{y}_{y_i}, \tilde{z}_{y_i}] \tag{9.2}$$

On the other hand, the optimization parameter; namely, the location of the jammer node is represented with $z \in \mathbb{R}^3$. The location of the jammer node is also demonstrated in cartesian coordinates.

$$z = [\tilde{x}_z, \tilde{y}_z, \tilde{z}_z] \tag{9.3}$$

In addition, the received signal model is used for the problem [72].

$$r_{ij}(t) = \sum_{k=1}^{L_{ij}} \alpha_{ij}^k s_j\left(t - \tau_{ij}^k\right) + \gamma_{ij}\sqrt{P_j}v_{ij}(t) + n_{ij}(t) \tag{9.4}$$

t represents the time and $t \in [0, T_{obs}]$. T_{obs} demonstrates the observation time.

r_{ij} is the received signal from the anchor node j to the target node i. Therefore, $i \in \{1,2, \ldots N_T\}$ and $j \in \mathrm{A}_i$. A_i sets are defined as the connectivity sets; $\mathrm{A}_i \triangleq \{j \in \{1,2, \ldots N_A\} \mid \text{anchor node } j \text{ is connected to the target node } i\}$.

α_{ij}^k is the amplitude of the k^{th} multipath component between j^{th} anchor node and i^{th} target node.

τ_{ij}^k is the delay of the k^{th} multipath component between j^{th} anchor node and i^{th} target node.

L_{ij} represents the number of paths between j^{th} anchor node and i^{th} target node. P_j is the transmit power of the jammer.

γ_{ij} demonstrates the channel coefficient between the jammer and i^{th} target node for the signal transmission between j^{th} anchor node and i^{th} target node.

s_j is a known transmit signal from the jammer.

The noise is represented with $n_{ij}(t)$. The spectral density level of the noise is $N_0/2$ and assumed zero-mean white Gaussian random process, which is independent of the jammer noise ($\sqrt{P_j}v_{ij}(t)$). In addition, jammer noise is also assumed to be a zero-mean Gaussian random process. In this study, $v_{ij}(t) = 1$ is assumed.

In addition, the time delay is expressed in terms of the distance, range bias, and speed of propagation [30].

$$\tau_{ij}^{k} = \frac{\left\| x_i - y_j \right\| + b_{ij}^{k}}{c} \tag{9.5}$$

$\left\| x_i - y_j \right\|$ represents the distance between j^{th} target node and i^{th} anchor node; namely, the norm function.

b_{ij}^{k} is the range bias.

c is the propagation speed.

Furthermore, A_i is represented as follows [30];

$$\mathrm{A}_i \triangleq \mathrm{A}_i^{L} \cup \mathrm{A}_i^{NL} \tag{9.6}$$

A_i^{L} are the sets of anchor nodes to the i^{th} target node with LOS and A_i^{NL} are the sets of anchor nodes to the i^{th} target node with NLOS.

9.2.2 CRLB For 3D Localization of Targets

In the problem, CRLB is used as the objective function parameter. Therefore, three-dimensional CRLB should be calculated. For the previous problems, the effect of LOS is considered as the minimum required altitude distance so that there is a clear LOS between targets and jammers. However, in this problem, the LOS is not considered in the same way. There is a LOS and NLOS situations in this problem. Therefore, the bias terms can be defined as in the following form for LOS and NLOS situations [30], [73].

$$b_{ij} = \begin{cases} \left[b_{ij}^{2}, \dots, b_{ij}^{L_{ij}}\right]^{T}, & j \in \mathrm{A}_i^{L} \\ \left[b_{ij}^{1}, \dots, b_{ij}^{L_{ij}}\right]^{T}, & j \in \mathrm{A}_i^{NL} \end{cases} \tag{9.7}$$

Thus, the unknown parameters for the i^{th} target node is the following [30];

$$\mu_i \triangleq \left[x_i^{T}\, b_{i\mathrm{A}_i(1)}^{T} \dots b_{i\mathrm{A}_i(|\mathrm{A}_i|)}^{T} \alpha_{i\mathrm{A}_i(1)}^{T} \dots \alpha_{i\mathrm{A}_i(|\mathrm{A}_i|)}^{T}\right]^{T} \tag{9.8}$$

$\mathrm{A}_i(j)$ demonstrates the j^{th} element of A_i and $|\mathrm{A}_i|$ is the number of elements of the set. In addition, $\alpha_{ij} = \left[\alpha_{ij}^1 \dots \alpha_{ij}^{L_i}\right]$.

Therefore, the CRLB for the self-location estimation system in a three-dimensional environment is defined as the following [74];

$$\mathbb{E}\{\|\hat{x}_i - x_i\|^2\} \geq \mathrm{tr}\{[F_i^{-1}]_{3x3}\} \tag{9.9}$$

In the CRLB formulation, $\hat{x}_i$ is defined as the unbiased estimate of the i^{th} target node and the matrix F_i is the Fisher Information Matrix (FIM) for the unknowns μ_i. In addition, 'tr' represents the trace of the matrix. Since FIM includes the unknown parameters, it should be defined as the following [74];

$$[F_i^{-1}]_{3x3} = \mathcal{J}_i(x_i, P_j)^{-1} \tag{9.10}$$

$\mathcal{J}_i(x_i, P_j)$ represents the equivalent of FIM for the situations when there is no prior information for the location of the target nodes. According to the derivations in [74], $\mathcal{J}_i(x_i, P_j)$ can be stated as the following;

$$\mathcal{J}_i(x_i, P_j) = \sum_{j \in \mathrm{A}_i^L} \frac{\lambda_{ij}}{\frac{N_0}{2} + P_j|\gamma_{ij}|^2} \phi_{ij}\phi_{ij}^T \tag{9.11}$$

Where λ_{ij} is defined as in the following form [30], [74];

$$\lambda_{ij} \triangleq \frac{4\pi^2\beta_j^2|\alpha_{ij}^1|^2 \int_{-\infty}^{\infty}|S_j(f)|^2 df}{c^2}(1 - \xi_{ij}) \tag{9.12}$$

In the equation, $S_j(f)$ is the Fourier transform of the signal $s_j(t)$. β_j represents the effective bandwidth. ξ_{ij} is the coefficient of path-overlap and $0 \leq \xi_{ij} \leq 1$.

In addition, ϕ_{ij} is defined as follows [74];

$$\phi_{ij} \triangleq [\cos\varphi_{ij}\cos\theta_{ij} \;\; \sin\varphi_{ij}\cos\theta_{ij} \;\; \sin\theta_{ij}] \tag{9.13}$$

In the equation, φ_{ij} is the azimuth angle and θ_{ij} is the elevation angle between the i^{th} target node and j^{th} anchor node. Therefore, the three-dimensional CRLB for i^{th} target node is in the following form;

$$CRLB_i = \mathrm{tr}\left\{\mathcal{J}_i\left(x_i, P_j\right)^{-1}\right\} \quad (9.14)$$

9.2.3 Objective Function and Constraints

In this section, the objective function and the constraints of the problem are formulated. Since the objective parameter includes the CRLB, the mathematical formulations in the previous part are used. In the optimization problem, the CRLB of all the targets should be increased. Therefore, the minimum of the CRLB values are used in the objective function and the aim is to maximize the minimum of these CRLBs. Therefore, the following objective function is used [30].

$$\text{maximize} \min_{i \in \{1,2,\ldots,N_T\}} CRLB_i \quad (9.15)$$

Since the CRLB is defined as $\mathcal{J}_i\left(x_i, P_j\right)^{-1}$ in the previous part. The objective function is the following.

$$\text{maximize} \min_{i \in \{1,2,\ldots,N_T\}} \mathrm{tr}\left(\mathcal{J}_i\left(x_i, P_j\right)^{-1}\right) \quad (9.16)$$

In the problem, there is a constraint for the distance between the jammer placement and the target nodes. Therefore, the constraint is defined as the following [30].

$$\|z - x_i\| \geq \varepsilon \text{ for } i = 1,2,\ldots,N_T \text{ and } \varepsilon > 0 \quad (9.17)$$

ε is the minimum available distance between the jammer placement and the target nodes.

In the previous part, $\mathcal{J}_i\left(x_i, P_j\right)^{-1}$ is defined for $CRLB_i$. However, this function includes many parameters. Therefore, these parameters should be manipulated and the final version of the objective function should be derived. Therefore, the channel gain is identified as the following [30].

$$\left|\gamma_{ij}\right|^2 = \widetilde{K}_i \left(\frac{d_0}{\|z - x_i\|}\right)^v \quad (9.18)$$

$$\|z - x_i\| > d_0 \quad (9.19)$$

In the equations, d_0 represents the reference distance and v denotes the path-loss exponent. On the other hand, $\widetilde{K}_i$ is used for the other parameters such as antenna characteristics and channel attenuation. In the optimization problem, $\widetilde{K}_i$ values, d_0, and ε are assumed as known parameters. Therefore, by using the channel gain formulation, the CRLB function can be updated as follows [30].

$$\mathrm{tr}\left(\mathcal{J}_i\left(x_i, P_j\right)^{-1}\right) = \mathrm{tr}\left\{\left[\sum_{j\in \mathrm{A}_i^L} \lambda_{ij}\phi_{ij}\phi_{ij}^T\right]^{-1}\right\}\left(\widetilde{K}_i P_j \left(\frac{d_0}{\|z - x_i\|}\right)^v + \frac{N_0}{2}\right) \quad (9.20)$$

In order to simplify the equation, the following variables are defined.

$$R_i \triangleq \mathrm{tr}\left\{\left[\sum_{j\in \mathrm{A}_i^L} \lambda_{ij}\phi_{ij}\phi_{ij}^T\right]^{-1}\right\} \quad (9.21)$$

$$K_i \triangleq \widetilde{K}_i {d_0}^v \quad (9.22)$$

If these definitions are put into the $\mathrm{tr}\left(\mathcal{J}_i\left(x_i, P_j\right)^{-1}\right)$ formulation. The following results are gathered.

$$\mathrm{tr}\left(\mathcal{J}_i\left(x_i, P_j\right)^{-1}\right) = R_i\left(\frac{K_i P_j}{\|z - x_i\|^v} + \frac{N_0}{2}\right) \quad (9.23)$$

Therefore, the optimization problem formulation with objective function and the constraint is as follows:

$$\begin{gathered}\text{maximize } \min_{i\in\{1,2,\dots,N_T\}} R_i\left(\frac{K_i P_j}{\|z - x_i\|^v} + \frac{N_0}{2}\right) \\ \text{subject to } \|z - x_i\| \geq \varepsilon \text{ for } i = 1,2,\dots,N_T \text{ and } \varepsilon > 0\end{gathered} \quad (9.24)$$

9.3 Solution Technique

In this section, the solution technique that is used to find the optimal jammer location is investigated. The solution includes different propositions for three-dimensional problems.

According to the problem formulation, the optimization problem is non-convex. Therefore, the problem cannot be solved by using convex optimization techniques. On the other hand, there are theoretical results in [30] for the similar problem with two dimensions. In this problem of the study, these theoretical results are extended into three-dimensional cases since the thesis problem is a three-dimensional problem. The propositions aim to reduce the search space for the optimal jammer location.

9.3.1 Proposition 1

The first proposition is investigated in the literature [30]. It focuses on the existence of a target node l, and this target node ensures the following inequality.

$$R_l\left(\frac{K_l P_j}{\varepsilon^v}+\frac{N_0}{2}\right) \leq \min_{\substack{i\in\{1,2,\dots,N_T\}\\ i\neq l}} R_i\left(\frac{K_i P_j}{(\|x_i - x_l\| + \varepsilon)^v}+\frac{N_0}{2}\right) \tag{9.25}$$

This inequality assumes that there exist at least one optimal location for the jammer placement that satisfies the following statements.

$$\|z - x_l\| = \varepsilon \text{ and } \|z - x_i\| \geq \varepsilon \text{ for all } i = 1, \dots, l-1, l+1, \dots, N_T \tag{9.26}$$

The inequality uses the triangle inequality. Namely, it considers a triangle that is constructed by z, x_i, and x_l. According to the triangle inequality,

$$\|x_i - x_l\| + \|z - x_l\| = \|x_i - x_l\| + \varepsilon > \|z - x_i\| \tag{9.27}$$

Therefore,

$$\frac{1}{(\|x_i - x_l\| + \varepsilon)^v} < \frac{1}{\|z - x_i\|^v} \tag{9.28}$$

$$\min_{\substack{i\in\{1,\dots,N_T\}\\ i\neq l}} R_i\left(\frac{K_i P_j}{(\|x_i - x_l\| + \varepsilon)^v}+\frac{N_0}{2}\right) < \min_{\substack{i\in\{1,\dots,N_T\}\\ i\neq l}} R_i\left(\frac{K_i P_j}{\|z - x_i\|^v}+\frac{N_0}{2}\right) \tag{9.29}$$

Therefore, if the given inequality is satisfied by any target node l, the optimum location for the jammer can be found as is z^{opt}. In addition, z^{opt} should deployed to a point that has a distance of ε from the target node l.

9.3.2 Proposition 2

The second proposition considers the two target nodes from set of target nodes scenarios. The meaning of two target nodes is that the other target nodes have larger CRLB values; therefore, these two target nodes are considered in the problem. This problem and proposition are investigated in the literature [30]. Since this proposition focuses on two target nodes scenario, the problem turns into the following form.

$$\begin{gathered} \text{maximize} \min_{i \in \{l_1, l_2\}} R_i \left(\frac{K_i P_j}{\|z - x_i\|^v} + \frac{N_0}{2} \right) \\ \text{subject to } \|z - x_i\| \geq \varepsilon \text{ for } i = l_1, l_2 \text{ and } \varepsilon > 0 \end{gathered} \tag{9.30}$$

In this version of the problem, the target nodes are represented by l_1 and l_2, where the target nodes $l_1 \neq l_2$. In addition, the target nodes are chosen from the set of target nodes, namely, $l_1, l_2 \in \{1,2, \dots, N_T\}$.

For this section, the optimum solution for the jammer location is defined with z_{l_1,l_2}^{opt}; therefore, the CRLB for these target nodes is represented by $CRLB_{l_1,l_2}$. Therefore, this proposition defines the minimum of CRLB values for l_1 and l_2 as the following.

$$CRLB_{k,i} \triangleq \min_{i \in \{l_1, l_2\}} R_i \left(\frac{K_i P_j}{\|z - x_i\|^v} + \frac{N_0}{2} \right) \tag{9.31}$$

This proposition assumes that the following statement is satisfied by at least one jammer location.

$$\|z - x_m\| \geq \varepsilon \; for \; m \in \big\{\{1,2, \dots, N_T\} - \{k, i\}\big\} \tag{9.32}$$

If there exists a jammer location that satisfies the above condition, then this location is named by $z_{k,i}^{opt}$. Therefore, the following condition should also be satisfied by the optimum location $z_{k,i}^{opt}$.

$$R_m \left(\frac{K_m P_j}{\left\| z_{k,i}^{opt} - x_m \right\|^v} + \frac{N_0}{2} \right) \geq CRLB_{k,i} \tag{9.33}$$

Namely, this inequality focuses on all of the CRLB values except $CRLB_{k,i}$ have larger values.

9.3.3 Proposition 3

If the conditions of "Proposition 1" and "Proposition 2" are not satisfied, the third proposition is constructed. This proposition is claimed in the literature [30]. In this proposition, two different target nodes should exist. Namely, N_T should be equal to 2. In order to use this proposition, one of the following two conditions should be satisfied. The first condition is based on constructing triangles if the distance between two target nodes is less than two times of the distance constraint ε.

$$\|x_1 - x_2\| < 2\varepsilon \Longrightarrow \|z^{opt} - x_1\| = \|z^{opt} - x_2\| = \varepsilon \tag{9.34}$$

When there are exactly two target nodes and the distance condition, which is defined above, is not satisfied, the next conditions should be checked to use the proposition properly. The first condition checks whether the ε distance between the first target node and jammer location solves the problem.

$$\begin{gathered} R_1\left(\frac{K_1 P_j}{\varepsilon^v} + \frac{N_0}{2}\right) \leq R_2\left(\frac{K_2 P_j}{(\|x_1 - x_2\| - \varepsilon)^v} + \frac{N_0}{2}\right) \Longrightarrow \\ \|z^{opt} - x_1\| = \varepsilon, \|z^{opt} - x_2\| = \|x_1 - x_2\| - \varepsilon \end{gathered} \tag{9.35}$$

The second condition examines that whether the ε distance between the second target node and jammer location solves the problem.

$$\begin{gathered} R_2\left(\frac{K_2 P_j}{\varepsilon^v} + \frac{N_0}{2}\right) \leq R_1\left(\frac{K_1 P_j}{(\|x_1 - x_2\| - \varepsilon)^v} + \frac{N_0}{2}\right) \Longrightarrow \\ \|z^{opt} - x_1\| = \|x_1 - x_2\| - \varepsilon, \|z^{opt} - x_2\| = \varepsilon \end{gathered} \tag{9.36}$$

On the other hand, the two conditions given above may not be satisfied for all cases of $N_T = 2$. In this case, there is no existing minimum CRLB for the target nodes. Therefore, CRLB values for all of the target nodes should be maximized so that they are equal when the jammer node is deployed. In this condition, the following condition should be satisfied by the variable d^*; namely, the jammer node should be deployed at a distance of d^* from the first target node. The solution d^* is defined as $\|z^{opt} - x_1\| = d^*$ and $\|z^{opt} - x_2\| = \|x_1 - x_2\| - d^*$. In addition, d^* is the solution of the following equation.

$$R_1\left(\frac{K_1P_j}{d^v}+\frac{N_0}{2}\right)\leq R_2\left(\frac{K_2P_j}{(\|x_1-x_2\|-d)^v}+\frac{N_0}{2}\right) \tag{9.37}$$

The proof of this proposition is given in [30] in detail.

9.3.4 Proposition 4

In the fourth proposition, $N_T \geq 3$ cases are investigated. In this investigation, it is assumed that the distance constraint does not appear in the problem. In the literature, this proposition is examined in a two-dimensional environment. Therefore, the proposition in the literature shows that the optimal jammer location cannot be outside of the convex hull, which is formed by the target node locations [30]. However, the problem is three-dimensional in this study. Therefore, a convex hull is not a surface in the thesis problem. The convex hull denotes a three-dimensional construction. This three-dimensional construction is formed by many pyramids.

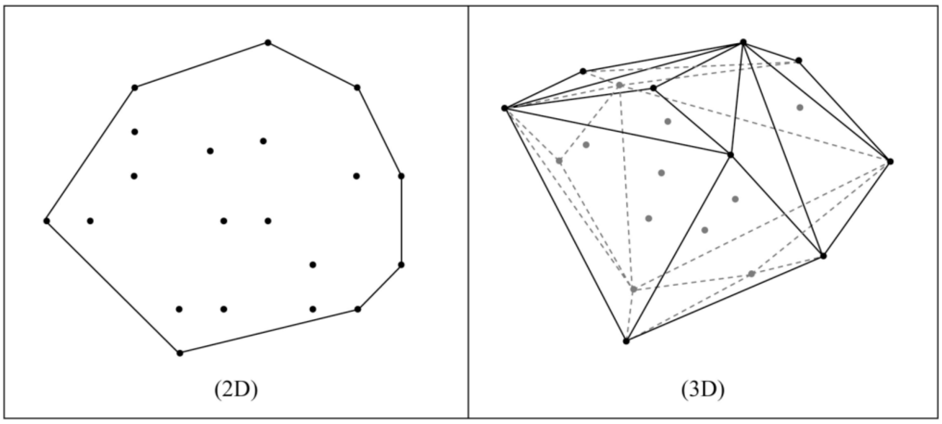

Figure 9.1. 2D and 3D Convex Hull Example

The proof of the two-dimensional version of the proposition is investigated in the literature [30]. In this proof, the only variable metric is distance. The proof shows that any possible jammer location outside the convex hull is farther away from all the target nodes than the projection of this jammer location onto the convex hull. Since the proof is only dependent on the distance metric and the projection theorem, it is valid for a three-dimensional environment.

The proposition states that for every jammer location outside of the convex hull, the projection of these jammer locations onto the convex hull is closer to all of the target nodes. As a result, the optimal jammer location must be on the convex hull, which is constructed by the target nodes.

9.3.5 Proposition 5

$N_T = 3$ case represents a two-dimensional surface inside the space. It is examined in the literature [30], and it is going to solve the problem for three-dimensional cases. Therefore, this proposition is demonstrated in this section of the thesis.

For the case of $N_T = 3$, the target nodes l_1, l_2, and l_3 are used. The maximum-minimum of the CRLB function turns into the following form when the distance constraint does not appear in the problem.

$$CRLB_{l_1,l_2,l_3} \triangleq \max_{z} \min_{i\in\{l_1,l_2,l_3\}} R_m\left(\frac{K_m P_j}{\|z - x_m\|^v} + \frac{N_0}{2}\right) \tag{9.38}$$

In the section "Proposition 4", it is shown that the jammer location should be inside (or boundaries) of the convex hull that is constructed by the target nodes l_1, l_2, and l_3. By using this proposition, "Proposition 5" states that if $N_T = 3$ and the optimal jammer location is inside of the convex hull, the CRLB values for these three target nodes should be equal. The proof of this proposition is investigated in the literature [30].

9.3.6 Proposition 5 (3D Extension)

In the section "Proposition 5", a two-dimensional solution for the case of $N_T = 3$ is investigated. Since $N_T = 3$ is always represents a surface in the space, "Proposition 5" can be used for $N_T = 3$ scenarios. However, $N_T = 4$ may not always represent a surface. Therefore, $N_T = 4$ case should be investigated in three-dimensional space.

The target nodes are l_1, l_2, l_3, and l_4 for $N_T = 4$. The convex hull that is constructed by l_1, l_2, l_3, and l_4 represents a three-dimensional volume, namely, a pyramid. According to the 3D extension of "Proposition 5", if the optimal jammer location is inside the interior of the pyramid convex hull, the CRLB values for each target node should be equal.

9.3.6.1 Proof

Let $z_{l_1,l_2,l_3,l_4}^{opt}$ is the optimum jammer location for the network that consists of target nodes l_1, l_2, l_3, and l_4. In addition, $\mathcal{H}$ is the pyramid convex hull constructed by the target nodes, where the target nodes are at the vertices of the pyramid. According to the proposition, the optimum jammer location, $z_{l_1,l_2,l_3,l_4}^{opt}$ should be inside of the $\mathcal{H}$.

Firstly, the CRLB value for one of the target nodes is the minimum of the set of CRLB values. In addition, the other CRLB values from the set are strictly larger for the optimal location of the jammer, $z_{l_1,l_2,l_3,l_4}^{opt}$. Without loss of generality, the following conditions can be assumed.

$$\begin{aligned} CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) &< CRLB_{l_1}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \\ CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) &< CRLB_{l_2}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \\ CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) &< CRLB_{l_3}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \end{aligned} \tag{9.39}$$

According to these conditions, the following statement can be concluded.

$$CRLB_{l_1,l_2,l_3,l_4} = CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \tag{9.40}$$

Now, the projection of $z_{l_1,l_2,l_3,l_4}^{opt}$ onto the triangular surface that includes l_2, l_3, and l_4 can be considered. This projection is represented with z_0. $z_{l_1,l_2,l_3,l_4}^{opt}$ is inside of the convex hull $\mathcal{H}$; therefore, there exists $\Delta > 0$ such that $z_\delta \triangleq z_{l_1,l_2,l_3,l_4}^{opt} + \frac{\delta\left(z_0 - z_{l_1,l_2,l_3,l_4}^{opt}\right)}{\left\|z_0 - z_{l_1,l_2,l_3,l_4}^{opt}\right\|}$ is also inside of the convex hull $\mathcal{H}$ for $\delta \in (0, \Delta)$. Namely, if $z_{l_1,l_2,l_3,l_4}^{opt}$ is deviated at a distance between $(0, \Delta)$, then the new z point is still inside of $\mathcal{H}$. z_δ

can be also considered as the projection of $z^{opt}_{l_1,l_2,l_3,l_4}$ onto the pyramid whose vertices are z_δ, l_2, l_3, and l_4. Therefore, z_δ is closer to the target nodes l_2, l_3, and l_4.

$$\begin{gathered}\|z_\delta - x_{l_2}\| < \|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_2}\| \\ \|z_\delta - x_{l_3}\| < \|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_3}\| \\ \|z_\delta - x_{l_4}\| < \|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_4}\|\end{gathered} \tag{9.41}$$

A lemma that mentions the distance between an insider point from a pyramid and the vertices of a pyramid is used at this step of the proof. Consider the pyramid in a three-dimensional space with the vertices of x_{l_1}, x_{l_2}, x_{l_3}, and x_{l_4} and a point inside of this pyramid z_δ. The distance between z_δ and the vertex points are the following;

$$\begin{gathered}\|z_\delta - x_{l_1}\| = d_{x_{l_1},z_\delta},\ \|z_\delta - x_{l_2}\| = d_{x_{l_2},z_\delta} \\ \|z_\delta - x_{l_3}\| = d_{x_{l_3},z_\delta},\ \|z_\delta - x_{l_4}\| = d_{x_{l_4},z_\delta}\end{gathered} \tag{9.42}$$

Then, consider another point inside a pyramid $z^{opt}_{l_1,l_2,l_3,l_4}$. The distance between $z^{opt}_{l_1,l_2,l_3,l_4}$ and vertex points are the followings;

$$\begin{gathered}\|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_1}\| = d_{x_{l_1},z^{opt}_{l_1,l_2,l_3,l_4}},\ \|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_2}\| = d_{x_{l_2},z^{opt}_{l_1,l_2,l_3,l_4}} \\ \|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_3}\| = d_{x_{l_3},z^{opt}_{l_1,l_2,l_3,l_4}},\ \|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_4}\| = d_{x_{l_4},z^{opt}_{l_1,l_2,l_3,l_4}}\end{gathered} \tag{9.43}$$

Therefore, if the following conditions are satisfied;

$$\begin{gathered}\left(d_{x_{l_2},z^{opt}_{l_1,l_2,l_3,l_4}} \geq d_{x_{l_2},z_\delta}\right), \left(d_{x_{l_3},z^{opt}_{l_1,l_2,l_3,l_4}} \geq d_{x_{l_3},z_\delta}\right), \\ \left(d_{x_{l_4},z^{opt}_{l_1,l_2,l_3,l_4}} \geq d_{x_{l_4},z_\delta}\right)\end{gathered} \tag{9.44}$$

Then, the following statement holds;

$$d_{x_{l_1},z^{opt}_{l_1,l_2,l_3,l_4}} \leq d_{x_{l_1},z_\delta} \tag{9.45}$$

According to this lemma,

$$\|z_\delta - x_{l_1}\| > \|z^{opt}_{l_1,l_2,l_3,l_4} - x_{l_1}\| \tag{9.46}$$

Hence, it can be concluded that,

$$
\begin{aligned}
&CRLB_{l_1}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \geq CRLB_{l_1}(z_\delta) \\
&CRLB_{l_2}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) < CRLB_{l_2}(z_\delta) \\
&CRLB_{l_3}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) < CRLB_{l_3}(z_\delta) \\
&CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) < CRLB_{l_4}(z_\delta)
\end{aligned} \tag{9.47}
$$

Since $CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) < CRLB_{l_1}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right)$ and CRLB is a continuous function; there exists $\delta \in (0, \Delta)$ such that $CRLB_{l_1}(z_\delta) > CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) = CRLB_{l_1,l_2,l_3,l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right)$.

Therefore, the following results can be gathered.

$$
\exists \delta \in (0, \Delta), CRLB_{l_1,l_2,l_3,l_4}(z_\delta) > CRLB_{l_1,l_2,l_3,l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \tag{9.48}
$$

However, $z_{l_1,l_2,l_3,l_4}^{opt}$ is assumed to be the optimal location and this inequality leads to a contradiction. Therefore, it is not possible that the CRLB for one of the target nodes is the minimum and the other target nodes are strictly larger for $z_{l_1,l_2,l_3,l_4}^{opt}$.

Secondly, without loss of generality, the following conditions can be assumed.

$$
\begin{aligned}
&CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) < CRLB_{l_1}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \\
&CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) < CRLB_{l_2}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \\
&CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) = CRLB_{l_3}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right)
\end{aligned} \tag{9.49}
$$

According to these conditions, the following statement can be concluded.

$$
CRLB_{l_1,l_2,l_3,l_4} = CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) = CRLB_{l_3}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \tag{9.50}
$$

By using the same arguments that are mentioned in the first case, it can be proven that there exists a jammer location z_δ that satisfies the conditions. Similarly, $CRLB_{l_1,l_2,l_3,l_4}(z_\delta) > CRLB_{l_1,l_2,l_3,l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right)$ can be gathered. This situation results with a contradiction and $z_{l_1,l_2,l_3,l_4}^{opt}$ cannot be an optimal location for jammer placement. Therefore, there cannot be a feasible location that makes two of the CRLB values are equal to each other and makes them less than the other CRLB values of the target nodes.

Lastly, three of the CRLB values are equal to each other and strictly less than the other CRLB value should be examined. Without loss of generality, the following conditions can be assumed.

$$\begin{aligned} CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) &< CRLB_{l_1}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \\ CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) &= CRLB_{l_2}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \\ CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) &= CRLB_{l_3}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \end{aligned} \tag{9.51}$$

According to these conditions, the following statement can be concluded.

$$\begin{aligned} CRLB_{l_1,l_2,l_3,l_4} &= CRLB_{l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \\ = CRLB_{l_3}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) &= CRLB_{l_2}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right) \end{aligned} \tag{9.52}$$

Similar to the first case, $CRLB_{l_1,l_2,l_3,l_4}(z_\delta) > CRLB_{l_1,l_2,l_3,l_4}\left(z_{l_1,l_2,l_3,l_4}^{opt}\right)$ can be gathered by using the given expressions. This situation results with a contradiction and $z_{l_1,l_2,l_3,l_4}^{opt}$ cannot be an optimal location for jammer placement. Therefore, there cannot be a feasible location that makes three of the CRLB values are equal to each other and makes them less than the other CRLB value of the last target node.

9.3.7 Proposition 6

In Proposition 5, the optimal jammer location inside the convex hull case is investigated. However, it may be on the boundaries of the convex hull that is constructed by l_1, l_2, and l_3 [30]. For this case, the maximum-minimum of the CRLB function turns into the following form.

$$CRLB_{m,n} \triangleq \max_{z} min \left\{R_m\left(\frac{K_m P_j}{\|z - x_m\|^v} + \frac{N_0}{2}\right), R_n\left(\frac{K_n P_j}{\|z - x_n\|^v} + \frac{N_0}{2}\right)\right\} \tag{9.53}$$

In “Proposition 3”, the equalization of the CRLB values scenario is similar to this problem. Therefore, the CRLB values given in the equation should be equalized according to “Proposition 3,” and the optimal jammer location should be on the line that connects target nodes m and n. Proposition 6 is mainly based on the previous propositions and investigates the $N_T = 3$ and the optimal jammer location is on the boundaries of the convex hull.

Since this proposition focuses on the boundaries, the CRLB values of the network with target nodes l_1, l_2, and l_3 are defined as the following set.

$$\{CRLB_{l_1,l_2}, CRLB_{l_1,l_3}, CRLB_{l_2,l_3}\}$$

It is supposed that $CRLB_{l_1,l_2}$ is the minimum of the defined CRLB set. Therefore, the optimal jammer location can be represented with z_{l_1,l_2}^{opt}. The optimum location for the jammer should satisfy the following condition so that the optimal location is on the boundary of the convex hull.

$$CRLB_{l_3} \geq CRLB_{l_1,l_2} \tag{9.54}$$

$$R_{l_3}\left(\frac{K_{l_3}P_j}{\left\|z_{l_1,l_2}^{opt} - x_{l_3}\right\|^v} + \frac{N_0}{2}\right) \geq CRLB_{l_1,l_2} \tag{9.55}$$

$$\sqrt[v]{K_{l_3}P_j\left(\frac{CRLB_{l_1,l_2}}{R_{l_3}} - \frac{N_0}{2}\right)} \geq \left\|z_{l_1,l_2}^{opt} - x_3\right\| \tag{9.56}$$

According to this condition, the CRLB values for the target nodes l_1 and l_2 must be equal to each other.

$$CRLB_{l_1}\left(z_{l_1,l_2}^{opt}\right) = CRLB_{l_2}\left(z_{l_1,l_2}^{opt}\right) \tag{9.57}$$

The proof of this two-dimensional problem is investigated in [30].

9.3.8 Proposition 6 (3D Extension)

In the section "Proposition 6", a two-dimensional solution for the case of $N_T = 3$ is investigated. Since $N_T = 3$ is always represents a surface in the space, "Proposition 5" can be used for $N_T = 3$ scenarios. However, $N_T = 4$ may not always represent a surface. Therefore, $N_T = 4$ case should be investigated in three-dimensional space.

The target nodes are l_1, l_2, l_3, and l_4 for $N_T = 4$ are used. The convex hull that is constructed by l_1, l_2, l_3, and l_4 represents a three-dimensional volume, namely, a pyramid instead of a triangular surface like in the section "Proposition 6". According to the 3D extension of "Proposition 6", the optimal jammer location may be on the boundaries of the pyramid convex hull.

Since this proposition focuses on the boundaries, the CRLB values of the network with target nodes l_1, l_2, l_3, and l_4 are defined as the following set.

$$\{CRLB_{l_1,l_2,l_3}, CRLB_{l_1,l_2,l_4}, CRLB_{l_1,l_3,l_4}, CRLB_{l_2,l_3,l_4}\}$$

It is supposed that $CRLB_{l_1,l_2,l_3}$ is the minimum of the defined CRLB set. Therefore, the optimal jammer location can be represented with z_{l_1,l_2,l_3}^{opt}. The optimum location for the jammer should satisfy the following condition so that the optimal location is on the boundary of the convex hull.

$$CRLB_{l_4} \geq CRLB_{l_1,l_2,l_3} \tag{9.58}$$

According to this condition, the CRLB values for the target nodes l_1, l_2, and l_3 should be examined. Since the boundary of the pyramid convex hull represents a triangular surface, the optimal jammer placement location may belong to the interior or the boundary of the triangular surface.

In order to determine the position of the optimal jammer location if it is proven that it is on the boundary of the pyramid, the triangular surface should be examined with "Proposition 5" and "Proposition 6".

9.3.8.1 Proof

It should be considered a network with the target nodes e_1, e_2, e_3, and e_4. This network includes the following set of CRLB values.

$$\{CRLB_{e_1,e_2,e_3}, CRLB_{e_1,e_2,e_4}, CRLB_{e_1,e_3,e_4}, CRLB_{e_2,e_3,e_4}\}$$

The minimum value of this set is assumed to be $CRLB_{l_1,l_2,l_3}$. Assume that the optimal jammer location z^* is located on the boundary, namely, the surface of the pyramid. This surface is constructed by the triangle of e_1, e_2, and e_3. Therefore, the following can be said without the loss of generality;

$$\begin{aligned} CRLB_{e_1,e_2,e_3,e_4} = CRLB_{e_1,e_2,e_3} < CRLB_{e_1,e_2,e_4} \\ < CRLB_{e_1,e_3,e_4} < CRLB_{e_2,e_3,e_4} \end{aligned} \tag{9.59}$$

The proof is done in steps.

1. Exhaust all the triangles by choosing any triangle formed by l_1, l_2, and l_3; where, $l_1, l_2, l_3 \in \{e_1, e_2, e_3, e_4\}$ and e_1, e_2, e_3, e_4 are the vertices of the pyramid.
2. Now, say the optimal jammer location for this triangle is $z^* = z^{opt}_{l_1,l_2,l_3}$. By definition, it can be said that
$$CRLB_{l_1,l_2,l_3}(z^*) = CRLB_{l_1,l_2,l_3} \geq CRLB_{l_1,l_2,l_3,l_4} \tag{9.60}$$
3. Exhaust all the edges l_1, l_2, l_3 by doing the following steps.
    a. Define and choose an edge $g_1 \in \{l_1, l_2, l_3\}$.
    b. Choose a point $\hat{z}$ that is closer to the edge g_1 than z^*. By the definition of CRLB, the following can be said;
    $$CRLB_{g_1}(\hat{z}) > CRLB_{g_1}(z^*) \tag{9.61}$$
    c. Now, choose another point $\hat{z}_\delta$ that is on the line connection $\hat{z}$ and its projection onto the triangle formed by the set of points $\{e_1, e_2, e_3, e_4\} - g_1$.
    d. The choice will be performed in such a manner that $CRLB_{g_1}(\hat{z}_\delta) > CRLB_{g_1}(z^*)$. This is achievable as CRLB is a continuous function.
    e. Recall that the optimal jammer location for a triangle satisfies either
        i. $CRLB_{l_1,l_2,l_3} = CRLB_{l_1,l_2,l_3}(z^*) = CRLB_{l_1}(z^*) = CRLB_{l_2}(z^*) = CRLB_{l_3}(z^*)$ if z^* is interior by the "Proposition 5".

ii. $CRLB_{l_1,l_2,l_3} = CRLB_{l_1,l_2,l_3}(z^*) = CRLB_{l_1}(z^*) = CRLB_{l_2}(z^*) \leq CRLB_{l_3}(z^*)$ if z^* is on the line (l_1, l_2) by the "Proposition 6".

iii. $CRLB_{l_1,l_2,l_3} = CRLB_{l_1,l_2,l_3}(z^*) = CRLB_{l_1}(z^*) = CRLB_{l_3}(z^*) \leq CRLB_{l_2}(z^*)$ if z^* is on the line (l_1, l_3) by the "Proposition 6".

iv. $CRLB_{l_1,l_2,l_3} = CRLB_{l_1,l_2,l_3}(z^*) = CRLB_{l_2}(z^*) = CRLB_{l_3}(z^*) \leq CRLB_{l_1}(z^*)$ if z^* is on the line (l_2, l_3) by the "Proposition 6".

f. It is shown that

$$\begin{gathered} CRLB_{g_1}(\hat{z}) > CRLB_{g_1}(z^*) \\ CRLB_{g_1}(\hat{z}_\delta) > CRLB_{g_1}(z^*) \end{gathered} \tag{9.62}$$

Now using facts in "Step 3-e", it can be seen that any CRLB for a single edge is either equal or greater than the CRLB for that triangle. Then,

$$\begin{gathered} CRLB_{g_1}(\hat{z}) > CRLB_{g_1}(z^*) \geq CRLB_{l_1,l_2,l_3} \\ CRLB_{g_1}(\hat{z}_\delta) > CRLB_{g_1}(z^*) \geq CRLB_{l_1,l_2,l_3} \end{gathered} \tag{9.63}$$

Using the fact in "Step 2", the following can be obtained;

$$\begin{gathered} CRLB_{g_1}(\hat{z}) > CRLB_{g_1}(z^*) \\ \geq CRLB_{l_1,l_2,l_3} \geq CRLB_{e_1,e_2,e_3,e_4} \\ CRLB_{g_1}(\hat{z}_\delta) > CRLB_{g_1}(z^*) \\ \geq CRLB_{l_1,l_2,l_3} \geq CRLB_{e_1,e_2,e_3,e_4} \end{gathered} \tag{9.64}$$

g. The definition of $CRLB_{e_1,e_2,e_3,e_4}$ states the following;

$$C = \left\{CRLB_{e_1}(z), CRLB_{e_2}(z), CRLB_{e_3}(z), CRLB_{e_4}(z)\right\} \tag{9.65}$$

$$CRLB_{e_1,e_2,e_3,e_4} = \max_z \min C \tag{9.66}$$

Then, it can be said that for any location z, $\min\{CRLB_{e_1}(z), CRLB_{e_2}(z), CRLB_{e_3}(z), CRLB_{e_4}(z)\}$ is upper bounded by $CRLB_{e_1,e_2,e_3,e_4}$. Therefore, the following relation holds;

$$\hat{C} = \{CRLB_{e_1}(\hat{z}), CRLB_{e_2}(\hat{z}), CRLB_{e_3}(\hat{z}), CRLB_{e_4}(\hat{z})\} \quad (9.67)$$

$$\begin{aligned} CRLB_{g_1}(\hat{z}) > CRLB_{e_1,e_2,e_3,e_4} &\geq \min\{\hat{C}\} \\ &= CRLB_{e_1,e_2,e_3,e_4}(\hat{z}) \end{aligned} \quad (9.68)$$

$$\check{C} = \{CRLB_{e_1}(\hat{z}_\delta), CRLB_{e_2}(\hat{z}_\delta), CRLB_{e_3}(\hat{z}_\delta), CRLB_{e_4}(\hat{z}_\delta)\} \quad (9.69)$$

$$\begin{aligned} CRLB_{g_1}(\hat{z}_\delta) > CRLB_{e_1,e_2,e_3,e_4} &\geq \min\{\check{C}\} \\ &= CRLB_{e_1,e_2,e_3,e_4}(\hat{z}_\delta) \end{aligned} \quad (9.70)$$

h. Now, by the definition of $\hat{z}_\delta$ and projection theorem, it is known that for the edges of the triangle $q_1, q_2, q_3 \in \{e_1, e_2, e_3, e_4\} - g_1$.

$$\begin{aligned} \|x_{q_1} - \hat{z}_\delta\| &< \|x_{q_1} - \hat{z}\| \\ \|x_{q_2} - \hat{z}_\delta\| &< \|x_{q_2} - \hat{z}\| \\ \|x_{q_3} - \hat{z}_\delta\| &< \|x_{q_3} - \hat{z}\| \end{aligned} \quad (9.71)$$

By the definition of CRLB, the relations given above lead to the following;

$$\begin{aligned} C_{q_1}(\hat{z}_\delta) &> C_{q_1}(\hat{z}) \\ C_{q_2}(\hat{z}_\delta) &> C_{q_2}(\hat{z}) \\ C_{q_3}(\hat{z}_\delta) &> C_{q_3}(\hat{z}) \end{aligned} \quad (9.72)$$

i. In the “Step 3-g”, it is shown that the CRLB for g_1 is not the minimum of the CRLB set $\{g_1, q_1, q_2, q_3\}$ or the equivalent set $\{e_1, e_2, e_3, e_4\}$ for both $\hat{z}$ and $\hat{z}_\delta$. In addition, in the “Step 3-h”, it is shown that for the remaining edges in the pyramid $\{q_1, q_2, q_3\}$ the CRLB for $\hat{z}_\delta$ is greater than CRLB for $\hat{z}$. Combining these two facts, the following can be deduced;

$$\begin{aligned} &\min\{CRLB_{e_1}(\hat{z}_\delta), CRLB_{e_2}(\hat{z}_\delta), CRLB_{e_3}(\hat{z}_\delta), CRLB_{e_4}(\hat{z}_\delta)\} \\ &> \min\{CRLB_{e_1}(\hat{z}), CRLB_{e_2}(\hat{z}), CRLB_{e_3}(\hat{z}), CRLB_{e_4}(\hat{z})\} \end{aligned} \quad (9.73)$$

j. In addition, by the definition;

$$\min\{CRLB_{e_1}(\hat{z}), CRLB_{e_2}(\hat{z}), CRLB_{e_3}(\hat{z}), CRLB_{e_4}(\hat{z})\} \\ = CRLB_{e_1,e_2,e_3,e_4}(\hat{z}) \tag{9.74}$$

$$\min\{CRLB_{e_1}(\hat{z}_\delta), CRLB_{e_2}(\hat{z}_\delta), CRLB_{e_3}(\hat{z}_\delta), CRLB_{e_4}(\hat{z}_\delta)\} \\ = CRLB_{e_1,e_2,e_3,e_4}(\hat{z}_\delta) \tag{9.75}$$

Using the results in “Step 3-i",

$$CRLB_{e_1,e_2,e_3,e_4}(\hat{z}_\delta) > CRLB_{e_1,e_2,e_3,e_4}(\hat{z}) \tag{9.76}$$

With this result, it can be concluded with the proof that for any point $\hat{z}$ that is closer to g_1 than z^* is not the optimal location since another location is found and the CRLB value is greater.

9.3.9 Proposition 7

In this proposition, $N_T > 4$ cases are investigated. It is considered that the target nodes l_1, l_2, l_3, and l_4 are the elements of the network. The CRLB value for l_1, l_2, l_3, and l_4 target nodes is represented with $CRLB_{l_1,l_2,l_3,l_4}$. It is assumed that i, j, k and t target nodes achieve the minimum of $CRLB_{l_1,l_2,l_3,l_4}$, where $l_1, l_2, l_3, l_4 \in \{1, \ldots, N_T\}$ and $l_1 \neq l_2 \neq l_3 \neq l_4$. The optimum jammer location is represented with $z_{i,j,k,t}^{opt}$; namely, $(l_1, l_2, l_3, l_4) = (i, j, k, t)$. The corresponding CRLB for the target nodes i, j, k and t is denoted by $CRLB_{i,j,k,t}$. If the optimum jammer location is $z_{i,j,k,t}^{opt}$, then at least two of the CRLB values are equalized for the optimum solution for the target nodes. Therefore, it can be stated that the optimal jammer location is determined by no more than four of the target nodes when the distance constraint is small. Moreover, if the optimum solution for the jammer location is gathered by this proposition, the solution also satisfies the general version of the problem if $\|z - x_i\| \geq \varepsilon$ for all $i \in \{1, \ldots, N_T\}$.

9.3.9.1 Proof

The optimal jammer placement problem is defined as follows;

$$\max_{z} \min_{m\in\{1,2,\dots,N_T\}} CRLB_m(z) \tag{9.77}$$

The aim is to prove that the optimizer and the corresponding optimal value are equal to $z_{i,j,k,t}^{opt}$ and $CRLB_{i,j,k,t}$, respectively. According to the "Proposition 4", $z_{i,j,k,t}^{opt}$ is inside or on the boundary of the convex hull, namely, the pyramid. This pyramid is formed by the locations of the target nodes i, j, k, and t. This proof is investigated under two cases. The first case is $z_{i,j,k,t}^{opt}$ belongs to the interior of the pyramid constructed by i, j, k, and t. By "Proposition 5 (3D Extension)", it can be said that the solution equalizes the CRLB values. Therefore,

$$\begin{gathered} CRLB_i\left(z_{i,j,k,t}^{opt}\right) = CRLB_j\left(z_{i,j,k,t}^{opt}\right) = CRLB_k\left(z_{i,j,k,t}^{opt}\right) \\ = CRLB_t\left(z_{i,j,k,t}^{opt}\right) = CRLB_{i,j,k,t} \end{gathered} \tag{9.78}$$

Now, a new target node l^* can be considered. Since all the target nodes are in the three-dimensional space, $z_{i,j,k,t}^{opt}$ must be inside (or on the boundary) of the pyramid formed by l^* and any three elements of i, j, k, and t. Without loss of generality, a new pyramid that is formed by l^*, i, j, and k can be considered. The solution of these four target nodes is defined with $CRLB_{i,j,k,l^*}$. The corresponding optimizer is denoted by z_{i,j,k,l^*}^{opt}. By the definition, the following is known;

$$CRLB_{i,j,k,l^*} > CRLB_{i,j,k,t} \tag{9.79}$$

Define the following set as C^{opt},

$$\left\{CRLB_i\left(z_{i,j,k,l^*}^{opt}\right), CRLB_j\left(z_{i,j,k,l^*}^{opt}\right), CRLB_k\left(z_{i,j,k,l^*}^{opt}\right), CRLB_{l^*}\left(z_{i,j,k,l^*}^{opt}\right)\right\} \tag{9.80}$$

$$\begin{gathered} CRLB_{i,j,k,l^*} = \min\{C^{opt}\} \geq CRLB_{i,j,k,t} \\ = CRLB_i\left(z_{i,j,k,t}^{opt}\right) = CRLB_j\left(z_{i,j,k,t}^{opt}\right) = CRLB_k\left(z_{i,j,k,t}^{opt}\right) = CRLB_t\left(z_{i,j,k,t}^{opt}\right) \end{gathered} \tag{9.81}$$

Therefore, the followings can be deduced;

$$\begin{gathered} CRLB_i\left(z_{i,j,k,l^*}^{opt}\right) \geq CRLB_i\left(z_{i,j,k,t}^{opt}\right) \\ CRLB_j\left(z_{i,j,k,l^*}^{opt}\right) \geq CRLB_j\left(z_{i,j,k,t}^{opt}\right) \\ CRLB_k\left(z_{i,j,k,l^*}^{opt}\right) \geq CRLB_k\left(z_{i,j,k,t}^{opt}\right) \end{gathered} \tag{9.82}$$

According to the definition of the CRLB values, the following can be obtained;

$$\begin{aligned}\left\|x_i - z^{opt}_{i,j,k,l^*}\right\| &\leq \left\|x_i - z^{opt}_{i,j,k,t}\right\| \\ \left\|x_j - z^{opt}_{i,j,k,l^*}\right\| &\leq \left\|x_j - z^{opt}_{i,j,k,t}\right\| \\ \left\|x_k - z^{opt}_{i,j,k,l^*}\right\| &\leq \left\|x_k - z^{opt}_{i,j,k,t}\right\|\end{aligned} \tag{9.83}$$

For the rest of the proof, there are two possible cases for $z^{opt}_{i,j,k,t}$. The first case also has two parts. The first part of the first case is that $z^{opt}_{i,j,k,t}$ belongs to the interior of the pyramid that is constructed by target nodes l^*, i, j, and k. Therefore, the following can be said by the technique used in "Proposition 5 (3D Extension)", which is about the distances between the vertices of the pyramid and a change in the location of an inside point;

$$\left\|x_{l^*} - z^{opt}_{i,j,k,t}\right\| \leq \left\|x_{l^*} - z^{opt}_{i,j,k,l^*}\right\| \tag{9.84}$$

Therefore, the relation between the CRLB values is the following;

$$CRLB_{l^*}\left(z^{opt}_{i,j,k,t}\right) \geq CRLB_{l^*}\left(z^{opt}_{i,j,k,l^*}\right) \geq CRLB_{i,j,k,l^*} \geq CRLB_{i,j,k,t} \tag{9.85}$$

The obtained inequality shows that the optimal jammer location $z^{opt}_{i,j,k,t}$ results in a larger CRLB value for any target node l^* than $CRLB_{i,j,k,t}$. Therefore,

$$\min_{m\in\{1,2,\ldots,N_T\}} CRLB_m\left(z^{opt}_{i,j,k,t}\right) = CRLB_{i,j,k,t} \tag{9.86}$$

The other part of the first case is that $z^{opt}_{i,j,k,t}$ is on the surface of the pyramid formed by the target nodes l^*, i, j, and k. Without loss of generality, choose the triangular surface formed by the target nodes l^*, i, and j. By the definition of CRLB and the above statements, the followings are known;

$$CRLB_{i,j,l^*} \geq CRLB_{i,j,k,l^*} \geq CRLB_{i,j,k,t} \tag{9.87}$$

In this case, $CRLB_{i,j,l^*}$ is the solution of the target nodes l^*, i, and j. The optimizer for this solution is denoted by z^{opt}_{i,j,l^*}. The above inequality implies the following, according to the properties in "Proposition 5", "Proposition 5 (3D Extension)", "Proposition 6", and "Proposition 6 (3D Extension);

$$CRLB_{l^*}\left(z_{i,j,k,t}^{opt}\right) \geq CRLB_{l^*}\left(z_{i,j,l^*}^{opt}\right) \geq CRLB_{i,j,l^*} \\ \geq CRLB_{i,j,k,l^*} \geq CRLB_{i,j,k,t} \tag{9.88}$$

Similary in the first part of this case, the solution is $z_{i,j,k,t}^{opt}$.

The other case is that $z_{i,j,k,t}^{opt}$ is on the surface of the pyramid formed by the target nodes i, j, k, t. Without loss of generality, choose the surface of the pyramid with the target nodes i, j, and k. The corresponding optimal jammer location for this surface is denoted by $z_{i,j,k}^{opt}$. By the help of "Proposition 6 (3D Extension)", the optimal jammer location $z_{i,j,k,t}^{opt}$ equalizes the CRLB values at the target nodes. Therefore,

$$z_{i,j,k,t}^{opt} = z_{i,j,k}^{opt} \tag{9.89}$$

$$CRLB_{i,j,k,t} = CRLB_{i,j,k} \tag{9.90}$$

In addition, the network for target nodes i, j, and k is a subnetwork of the target nodes l^*, i, j, and k. Hence, the followings hold;

$$CRLB_{i,j,k} \geq CRLB_{i,j,k,l^*} \tag{9.91}$$

Moreover, it is known that $CRLB_{i,j,k,l^*} \geq CRLB_{i,j,k,t}$. Therefore,

$$CRLB_{i,j,k,l^*} \geq CRLB_{i,j,k} \tag{9.92}$$

According to the inequalities, the following is obtained;

$$CRLB_{i,j,k,l^*} = CRLB_{i,j,k} \tag{9.93}$$

$$z_{i,j,k,l^*}^{opt} = z_{i,j,k}^{opt} \tag{9.94}$$

As a result, the new target node l^* does not affect the optimal solution.

9.3.10 Corollary

In the previous section, seven different propositions are mentioned. The first three propositions are also investigated in the literature [30], and they are identical for the two-dimensional and three-dimensional problems. However, "Propositions 4, 5, 6, and 7” are not identical for two and three-dimensional problems. Therefore, these propositions are investigated for three-dimensional cases. By using the propositions, the corollary given in this section is gathered.

The corollary considers the scenarion in the “Proposition 7”. It assumes that the optimal jammer location is denoted by $z_{i,j,k,t}^{opt}$ and this location belong to the interior of the pyramid convex hull that is constructed by the target nodes i, j, k and t. Moreover, the $CRLB_{i,j,k}$ is the minimum of the CRLB set $\{CRLB_{i,j,k}, CRLB_{i,j,t}, CRLB_{i,k,t}, CRLB_{j,k,t}\}$. In addition, $z_{i,j,k}^{opt}$ is given as the jammer location for $CRLB_{i,j,k}$. Therefore, $z_{i,j,k,t}^{opt}$ cannot be inside any of the spheres centered at target nodes i, j, k and t with the radius of $\|x_i - z_{i,j,k}^{opt}\|$, $\|x_j - z_{i,j,k}^{opt}\|$, $\|x_k - z_{i,j,k}^{opt}\|$, and d_{thr}, respectively. d_{thr} can be defined as the following.

$$d_{thr} = \sqrt[v]{K_t P_j \left(\frac{CRLB_{i,j,k}}{R_t} - \frac{N_0}{2}\right)} \qquad (9.95)$$

According to the corollary definition, the optimal jammer location cannot be inside of the spheres with given radius values. Therefore, by using this corollary, the search space can be reduced. As a result, the new search space is the volume inside of the pyramid and the outside of the given spheres.

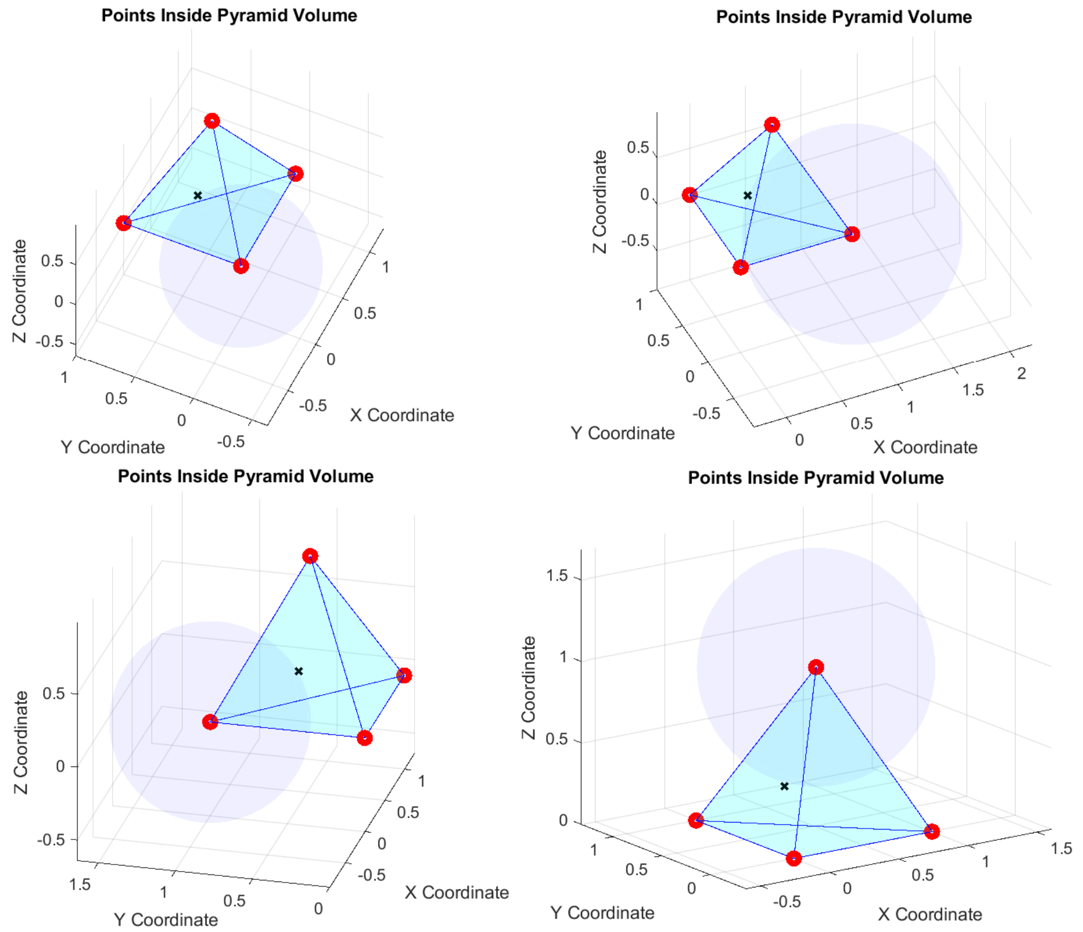

Figure 9.2. Corollary Visualization

9.3.11 Algorithm

Until this section, propositions are defined and proven for the jammer location optimization problem. In this section, the using technique of these proposition are given as an algorithm in order to solve the optimization problem. The first three steps does not create a three dimensional space; therefore, these steps are also investigated in the literature (Red: Pdf49). However, after the third step, the optimization problem completely turns into a three dimensional problem.

1. If $N_T = 1$, then the optimum jammer location z^{opt} should be at any point that has a distance of ε from the target node.

2. If $N_T = 2$, then the optimum jammer location z^{opt} should be found by the help of "Proposition 3".
3. If $N_T = 3$, then the optimum jammer location z^{opt} should be found according to the following steps.
    a. If the "Proposition 1" conditions are satisfied, then the optimum jammer location z^{opt} should be at any point that has a distance of ε from the target node.
    b. If the "Proposition 2" conditions are satisfied, then the optimum jammer location z^{opt} should be found by the help of "Proposition 3".
    c. If (a) and (b) are not satisfied to find the optimum jammer location, the following steps should be implemented. Let the target nodes are denoted by l_1, l_2 and l_3.
        i. Calculate the pairwise CRLB values by using the equalizer property.
        ii. Find the minimum of the pairwise CRLB values. Consider that it is $CRLB_{l_1,l_2}$.
        iii. Check the condition in "Proposition 6"; if it is satisfied, then $CRLB_{l_1,l_2,l_3} = CRLB_{l_1,l_2}$. If it is not satisfied, find $CRLB_{l_1,l_2,l_3}$ by using the "Proposition 5".
        iv. Find the minimum of $CRLB_{l_1,l_2,l_3}$ and the corresponding z_0^{opt}.
        v. If the z_0^{opt} satisfies the distance constraint, then $z^{opt} = z_0^{opt}$. Otherwise, z^{opt} should be found directly.
4. If $N_T \geq 4$, then the optimum jammer location z^{opt} should be found according to the following steps.
    a. If the "Proposition 1" conditions are satisfied, then the optimum jammer location z^{opt} should be at any point that has a distance of ε from the target node.
    b. If the "Proposition 2" conditions are satisfied, then the optimum jammer location z^{opt} should be found by the help of "Proposition 3".

c. If (a) and (b) are not satisfied to find the optimum jammer location, the following steps should be implemented. Let the target nodes are denoted by l_1, l_2, l_3, and l_4 for every distinct groups.

   i. Calculate the trio CRLB values by using the equalizer property.

   ii. Find the minimum of the trio CRLB values. Consider that it is $CRLB_{l_1,l_2,l_3}$.

   iii. Check the condition in "Proposition 6 (3D Extension)"; if it is satisfied, then $CRLB_{l_1,l_2,l_3,l_4} = CRLB_{l_1,l_2,l_3}$. Since the dimension reduced from three to two go to the "Step 3". If it is not satisfied, find $CRLB_{l_1,l_2,l_3,l_4}$ by using the "Proposition 5 (3D Extension)".

   iv. Find the minimum of $CRLB_{l_1,l_2,l_3,l_4}$ and the corresponding z_0^{opt}.

   v. If the z_0^{opt} satisfies the distance constraint, then $z^{opt} = z_0^{opt}$. Otherwise, z^{opt} should be found directly.

9.4 Simulations and Results

In this section, the theoretical results that are given in "Solution Technique" part are illustrated with the numerical examples. All the parameters that are not the element of the optimization process are set to constant values. These parameters and their values are given in the following table.

Table 9.1 Set of Simulation Parameters

Parameters	**Values**
ε (m)	1
N_0	2
v	2
$K_i,\, i = 1, \ldots, N_T$	1
P_J	$\bar{P}_J = 2\dfrac{P_J}{N_0}$

Table 9.1 (continued)

λ_{ij}	$100\|x_i - y_i\|^{-2}$ (Free-Space)
$\overline{P_J}$	$\{0.1, 0.2, \ldots, 15\}$

For all of the scenarios, the number of anchor nodes (N_A) is chosen 8. The positions of these anchor nodes are not changed. Therefore, positions of the anchor nodes are the following set in terms of meters;

$\{[10\ 0\ 0], [0\ 10\ 0], [10\ 20\ 0], [20\ 10\ 0], [0\ 0\ 20], [20\ 0\ 20], [0\ 20\ 20], [20\ 20\ 20]\}$

The number and positions of the target nodes are changed for different scenarios. Hence, their position and number information are given in the corresponding scenario sections.

For all the scenario network and solution figures, the following set of information holds;

- The blue square points are the locations of the anchor nodes.
- The red circle points are the locations of the target nodes.
- The cyan and magenta shaded areas are the surfaces of some of the pyramids in the scenarios.
- The black line is the set of points with respect to the different normalized power values.

9.4.1 Scenario-1

In this scenario, there are 4 number of target nodes (N_T). The positions of these target nodes (in terms of meters) are the following set in ascending target node number ordering;

$$\{[5\ 5\ 5], [15\ 5\ 5], [10\ 15\ 5], [10\ 10\ 15]\}$$

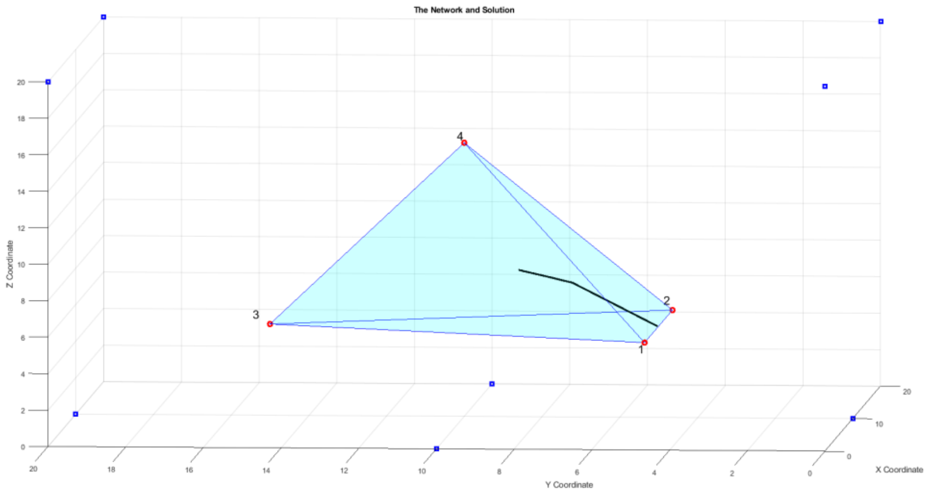

Figure 9.3. Scenario-1 Network and Solution

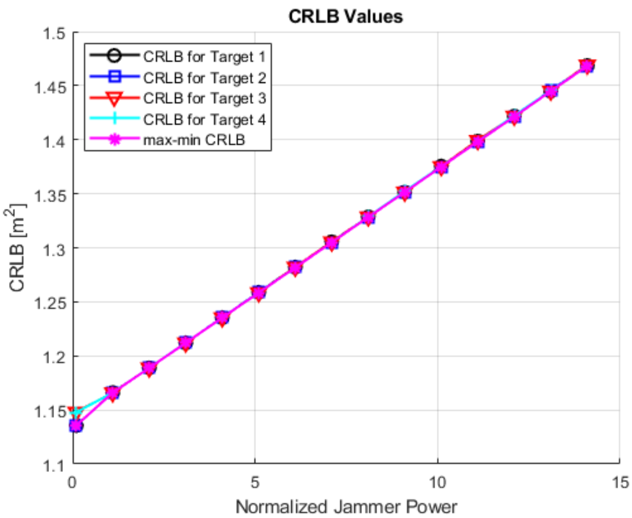

Figure 9.4. Scenario-1 CRLB Values

According to the solution and CRLB values, “Proposition 6” is satisfied for lower normalized jammer power values. Therefore, the optimal jammer location is on the edge between “Target-1” and “Target-2”. After the normalized jammer power is increased, “Proposition 5 (3D Extension)” is satisfied and the optimal jammer location belongs to the interior of the pyramid convex hull. In this scenario, the solutions start from edge and go into the convex hull for increasing jammer power values.

9.4.2 Scenario-2

In this scenario, there are 4 number of target nodes (N_T) and the orientation of the pyramind is inversed. The positions of the target nodes (in terms of meters) are the following set in ascending target node number ordering;

$$\{[5\ 5\ 15], [15\ 5\ 15], [10\ 15\ 15], [10\ 10\ 5]\}$$

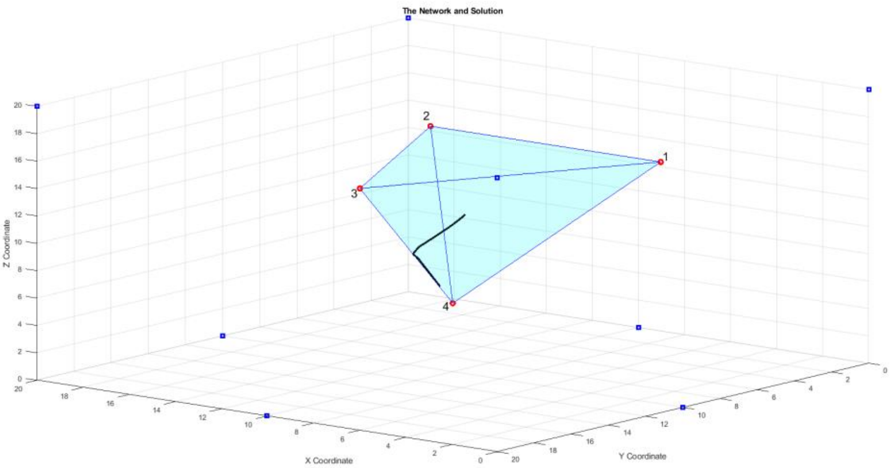

Figure 9.5. Scenario-2 Network and Solution

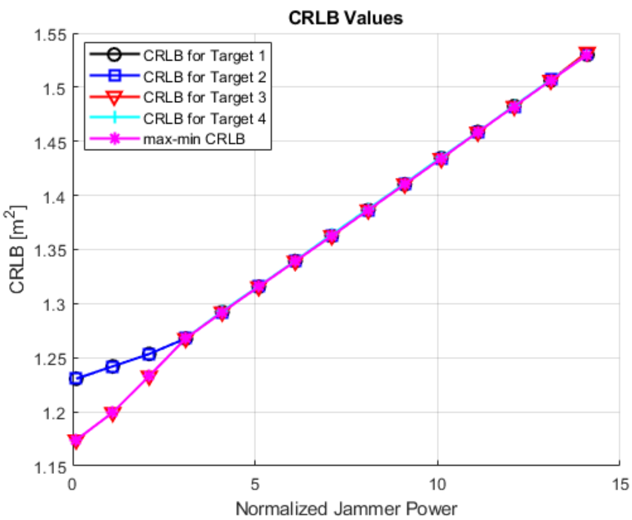

Figure 9.6. Scenario-2 CRLB Values

According to the solution and CRLB values, "Proposition 6" holds for the lower normalized jammer power values. Therefore, the solutions for these power values are on the edge between "Target-3" and "Target-4". After the power values are increased, "Proposition 5 (3D Extension)" starts to hold. Therefore, the optimal jammer locations go to the interior of the convex hull while the normalized jammer power is increasing. In this scenario, the solutions start from the edge, move on the edge, and go into the convex hull.

9.4.3 Scenario-3

In this scenario, there are 4 number of target nodes (N_T). The positions of these target nodes (in terms of meters) are the following set in ascending target node number order;

$$\{[4\ 4\ 5], [12\ 5\ 5], [7\ 13\ 5], [12\ 12\ 11]\}$$

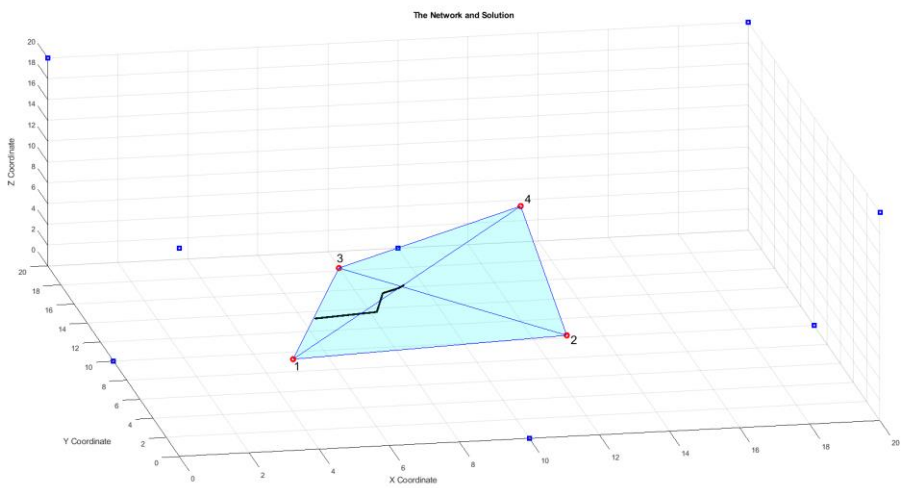

Figure 9.7. Scenario-3 Network and Solution

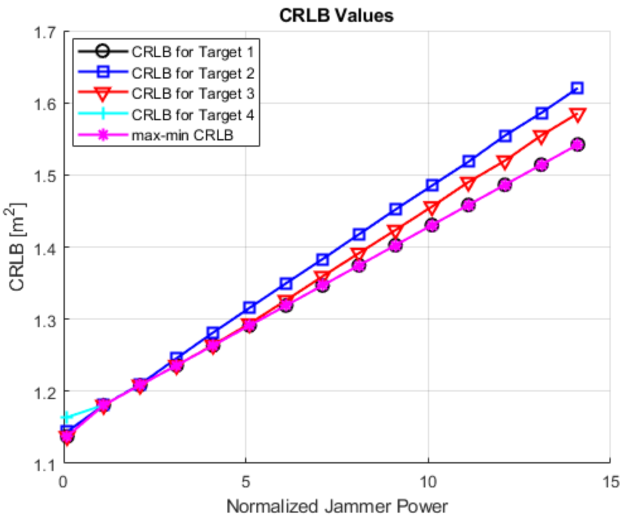

Figure 9.8. Scenario-3 CRLB Values

According to the solution and CRLB values, “Proposition 6” holds for the lower power values; hence, the optimal locations are on the edge between “Target-1” and “Target-3”. When the normalized power is increased, “Proposition 5 (3D Extension)” is satisfied and the optimal jammer locations move to the interior of the pyramid. After the increase in the power, the optimal jammer locations belong to the surface formed by “Target-1”, “Target-3”, and “Target-4” since the “Proposition 6 (3D Extension)” holds. While the normalized power jammer continues to increase, “Proposition 6” is satisfied again and optimal jammer locations are on the edge between “Target-1” and “Target-4”.

9.4.4 Scenario-4

In this scenario, there are 5 number of target nodes (N_T). The positions of these target nodes (in terms of meters) are the following set in ascending target node number order;

$$\{[5\ 5\ 10], [15\ 5\ 10], [10\ 15\ 10], [10\ 10\ 17], [10\ 10\ 5]\}$$

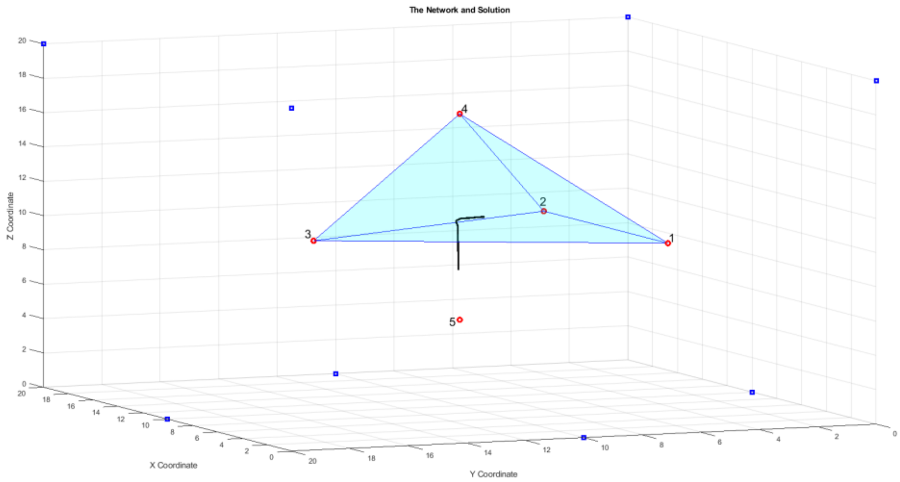

Figure 9.9. Scenario-4 Network and Solution

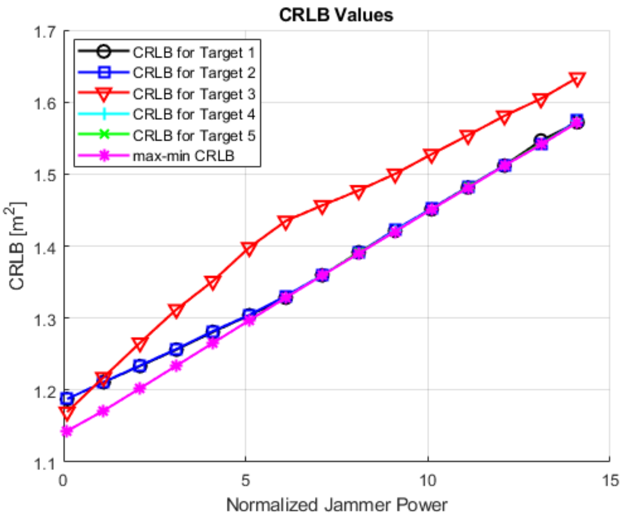

Figure 9.10. Scenario-4 CRLB Values

According to the solution and CRLB values, “Proposition 6” holds for the lower power values; hence, the optimal locations are on the edge between “Target-4” and “Target-5”. When the normalized power is increased to around 5.5, “Proposition 5 (3D Extension)” and “Proposition 7” hold. Therefore, the optimal jammer locations belong to the pyramid formed by “Target-1”, “Target-2”, “Target-4”, and “Target-5”.

9.4.5 Scenario-5

In this scenario, there are 5 number of target nodes (N_T). The positions of these target nodes (in terms of meters) are the following set in ascending target node number order;

$$\{[4\ 4\ 4], [16\ 7\ 5], [11\ 14\ 4], [8\ 16\ 13], [17\ 15\ 14]\}$$

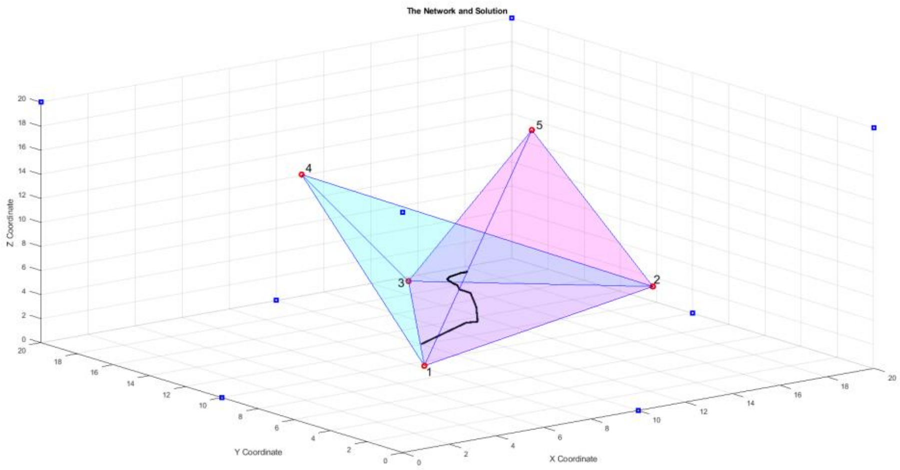

Figure 9.11. Scenario-5 Network and Solution

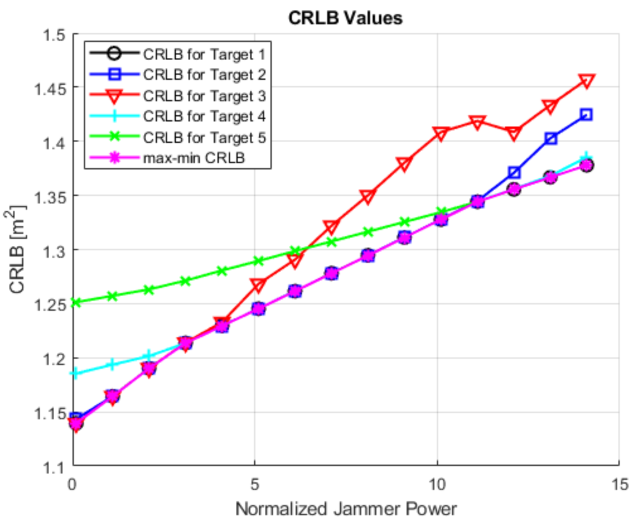

Figure 9.12. Scenario-5 CRLB Values

According to the solution and CRLB values, “Proposition 6” holds for the lower power values; hence, the optimal locations are on the edge between “Target-1” and “Target-3”. When the normalized jammer power is around 3, the optimal jammer locations belong to the pyramid formed by “Target-1”, “Target-2”, “Target-3”, and “Target-4” since the “Proposition 5 (3D Extension)” and “Proposition 7” hold. In addition, the optimal jammer locations move to the surface formed by “Target-1”, “Target-2”, and “Target-4” as the “Proposition 6 (3D Extension)” is satisfied, when the power is between 5 and 10. After the normalized power increases above 10, “Proposition 5 (3D Extension)” holds again for the “Target-1”, “Target-2”, “Target-4”, and “Target-5”. After this, “Proposition 6 (3D Extension)” is satisfied again for the “Target-1”, “Target-4”, and “Target-5” and “Proposition 6” holds for the “Target -1” and “Target-5”. Therefore, after the normalized power increases 11, the optimal jammer locations belong to the mentioned triangular surface and the edge between “Target-1” and “Target-5”.

CHAPTER 10

CONCLUSION

In this section, the conclusion of the study, obtained results, and possible works can be studied in the future are mentioned.

10.1 Summary and Conclusion

In this thesis, optimum jammer deployment strategies against communication networks are studied. In order to explain the thesis topic and the importance of jamming against communication, the concept of EW and jamming event is mentioned in the introduction part. In addition, the improvements in jamming in history are explained in the literature review. Moreover, current studies for jammer deployment and jamming strategies have also been published in the literature review.

In the second chapter, the models and methods that are used in this thesis are investigated. DTED has a crucial role in this thesis for its novelty and applicability. Therefore, an overview of DTED is published in this chapter. Since the thesis focuses on stationary and mobile jamming systems, the road map data is also important for the study. Therefore, the road map that is obtained from OSM is explained in the models and methods section. In addition to the data used in this study, there are crucial models and methods such as LOS, signal level, and detectability. Therefore, these concepts are explained in the thesis with the using methods of them. In the signal level section, the signal propagation models used are also examined. At the end of this section, the mathematical models to calculate these parameters in the study are published.

After the crucial methods and models are investigated, the initial problem is defined and formulated. The initial problem is the most basic version of the thesis problem, which is the deployment of jammers into a predefined set of locations. The solution technique for this problem is published, and the results obtained are given by various scenarios. At the end of this section, the inadequacy of this problem is examined and the next chapter is created.

The next chapter focuses on the optimum jammer deployment for stationary jammers and stationary targets. In this chapter, the nonlinear problem is defined and formulated. In the solution technique, MPSO is used and the jammer deployment algorithm is developed in order to prevent the communication in a network. In this study of the thesis, the performance of the algorithm is investigated via 15 different scenarios. The aim of the scenarios is to examine the optimal jammer deployment strategy against the real-world challenges in terms of the altitude values of feasible regions, restricted zones, and detectability by the enemy forces.

After the stationary jammers and stationary targets, the focus of the problem is changed into the mobile jammers. Therefore, the concepts of mobile jammers and stationary targets are studied in the next section. When a deployed jammer is detected by the enemy forces, it should change its position so as to prevent the enemy attacks. Hence, the problem of this part focuses on relocating some of the jammers by using the fully-connected roads. This problem is defined and formulated in this section. In addition, the solution technique and algorithm are published. In order to investigate the effects of the changes to the optimum jammer deployment, seven scenarios from stationary jammers and stationary targets section are used. After the simulations, the obtained results are published and compared with the results in the previous section.

Until this section, the jammers are investigated under stationary and mobile systems concepts. However, the problem may have mobile targets. Therefore, stationary jammers and mobile targets are investigated in this section. In order to install the mobile targets to the problem, the possibility of being somewhere concept is used. Namely, the mobile enemy target may be somewhere on the map with different probability values. As a result, a new problem is defined and formulated in this chapter. The algorithm based on MPSO is modified to solve this problem and investigated under 11 scenarios. These scenarios test the optimum jammer deployment strategies under varying conditions.

After this chapter, the mobility of the enemy targets is investigated by using mobile jammers. Similar to the mobile jammers concept, this problem includes the change in the locations of the detected jammers by keeping the optimization constraints satisfied. Therefore, a new problem is defined and formulated in this section. In addition, the solution technique for the problem that uses fully connected roads against mobile enemy targets is published. In order to test the solution technique, 6 of the scenarios in the previous section are chosen. By using the same scenarios, the results are compared for mobile and stationary jammers against mobile targets.

Until this chapter, the transmitting power is not considered in the problems. However, the next chapter includes the transmitting power of the jammers as an objective function parameter and constraint. Therefore, the new chapter focuses on the deployment of the jammers into real-world locations by arranging the transmitting power. For this problem, only stationary jammers and stationary targets are considered. Therefore, the problem is defined and formulated for the above-mentioned situations. Since the problem includes a new parameter and constraints, the solution technique is changed and published in this section. Moreover, the simulations for this problem are chosen from “Problem-1,” and the selections are similar to “Problem-2”. Thanks to using the same scenarios, the effects of optimizing transmitting power while optimizing the locations of the jammers are investigated.

For the last problem of the study, a more theoretical problem is constructed. In communication networks, the radios publish their location with other radios, which are the elements of the network. Therefore, the self-localization process is conducted in the communication networks. The aim of this problem is to prevent the self-localization capability of the radios by deploying jammers optimally. In the literature, 2D solutions for this problem are published. However, 3D approaches to the problem are not studied. In this thesis, the optimal jammer deployment against self-localization methods is investigated in 3D space. For the solution technique, there are many propositions and an algorithm. In order to show the effects of the propositions, five different scenarios are examined at the end of this section.

In summary, this thesis investigates the prevention of communication networks by deploying jammers optimally. In terms of novelty, the studies done in this thesis are applicable to real-world jamming events since real-world data such as DTED and road maps are used. In addition, the problems for stationary and mobile systems for both jammers and the targets are examined. Therefore, the thesis aims to find optimal jammer deployments for large-scale problems. Moreover, the thesis finds a solution to prevent self-localization systems in 3D space.

10.2 Future Work

This thesis researches the optimal jammer deployment against communication networks. In addition to the communication networks, there are many electronic support tools such as localization and direction finding. These electronic support tools are also sensitive to jamming attacks. Therefore, the optimal jammer deployment against localization and direction-finding systems is future work for optimal jammer deployment research area.

On the other hand, in Chapter 9, the solution is found in a theoretical way. Therefore, there is an assumption that LOS is always possible. By using DTED, the problem is transferred into real-world applications. Since some of the assumptions will not hold in real-world applications, the problem will turn into a more nonlinear problem. Hence, different techniques can be investigated to solve the problem for real-world applications.

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APPENDICES

A. 2D Bicubic Interpolation

Bicubic interpolation in 2D is a method used to estimate the value of a function at a point within a two-dimensional grid by considering not just the immediate neighboring points but also those slightly further away. This technique involves creating a smooth surface that passes through the known grid points, allowing for a more accurate estimation of values between these points. For this interpolation method, grid must have uniform spacing in each dimension, but the spacing does not have to be the same for all dimensions; and, requires at least four points in each dimension. Bicubic interpolation considers 16 pixels (4×4) [75].

For the computation; suppose p is the altitude values function of the map. p_{Lat}, p_{Long}, and $p_{LatLong}$ are the derivatives; namely, the difference functions. At the corners; namely, (0,0),(0,1),(1,1), and (1,0) these function values are known. Therefore, interpolated surface can be written as follows;

$$p(Lat, Long) = \sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} x^i y^j$$

$$p_{Lat}(Lat, Long) = \sum_{i=1}^{3} \sum_{j=0}^{3} a_{ij} i x^{i-1} y^j$$

$$p_{Long}(Lat, Long) = \sum_{i=0}^{3} \sum_{j=1}^{3} a_{ij} x^i j y^{j-1}$$

$$p_{LatLong}(Lat, Long) = \sum_{i=1}^{3} \sum_{j=1}^{3} a_{ij} i x^{i-1} j y^{j-1}$$

Therefore, in this interpolation; 16 different coefficients of a_ij should be found. Hence, the interpolated values for p function can be represented with the following matrix calculation.

$$p(Lat, Long) = [1\ x\ x^2\ x^3] \begin{bmatrix} a_{00} & \cdots & a_{03} \\ \vdots & \ddots & \vdots \\ a_{30} & \cdots & a_{33} \end{bmatrix} \begin{bmatrix} 1 \\ y \\ y^2 \\ y^3 \end{bmatrix}$$