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Modelling and Optimisation of UHF-band EW based WTA Problem within the Scope of Threat Assessment

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ABSTRACT

The classical weapon target allocation (WTA) problem has been evaluated within the scope of electronic warfare (EW) threat assessment with an electromagnetic effect-based jammer- tactical radio engagement approach. As different from the literature, optimum allocation of non-directional jammers operating at different operating UHF frequencies under constraints to RF emitters is aimed in this study. The values of the targets are modelled using an original threat assessment algorithm developed that takes into account operating frequencies, jamming distance, and weather conditions. The computed jammer-target effect matrix has been solved under different scenarios according to the efficiency and cost constraints. It is seen at the end of the simulations that the allocation results for EW applications largely depend on the effect ratio used. The better results are taken in the case of under 0.5 effect ratio. Finally, jammer-radio allocation problem specified at the suggested model is solved successfully and effectively.

Keywords: Electronic warfare; Threat assessment algorithm; Jamming systems; Weapon target assignment; Optimisation problem

1. INTRODUCTION

The Weapon-Target Allocation (WTA) problem aims to optimally allocate a set of weapons to a set of targets in a way that minimises the survival probability of targets[1-2]. The WTA problem is considered a classic optimisation problem encountered in military operations research and constitutes one of the basic and current issues of defense applications. The goal is to match enemy targets with available weapons to achieve certain tactical results as quickly as possible. Generally, WTA is divided into two groups as “Static WTA Problem (SWTA)” and “Dynamic WTA Problem (DWTA)”.

Signal jamming, on the other hand, is a type of Electronic Attack (EA) used in Electronic Warfare (EW), in which jammers send out signals that interfere with an enemy’s system and block the receiver with high-intensity energy signals. Signal jamming is used to prevent the enemy from effectively using the Electromagnetic (EM) spectrum. These signals could be in the form of radio or radar transmissions[3]. Nowadays, EA mechanisms include hard kill or soft kill methods. While the purpose of hard kill methods is to physically destroy EM-based threats, the soft kill method aims to render these threats ineffective or dysfunctional without destroying. The method is preferred when secondary damage to the environment is not desired while the threats are neutralised[4]. Jamming is a soft kill method as it temporarily neutralises an enemy presence. By transmitting strong distortion signals, it is aimed to block the enemy signals and make them uncontrollable by the user. When EW applications of the WTA problem are investigated, very few studies are seen and most of them are related to the allocation of directional jammers to the radar threats. In general, the problem of optimal allocation is to find the optimal assignment of jammers to radars in order to minimise the expected detection probability[4]. Most traditional jammer-target assignment algorithms are based on point-to-point allocation, and this means that a jammer is interfering with single radar. According to the study of Wang[5], *et al.*, the development of multiple jammers of various models to intercept multiple single-center operating radars has exploded due to their wide application based on radar networks technology. Actually, the problem has two purposes: the first goal is to maximise the expected rate of suppression or deception of defense radar (radar-based). The second is to minimise the probability of target detection (jammer-based). Darren[6], *et al.* worked on radar and a jammer in a non-cooperative two-player game. Bogdanowicz[7] derived weapon target impact tables, based on the efficiency handbook of jammers, radars, and ammunition. Bayram[8], *et al.* proposed an optimum power distribution policy for the jammers. From traditional algorithms to the new search algorithm, there are studies such as the auction algorithm[9], very large-scale neighborhood[10], and heuristic algorithms[11] in the algorithm research to solve the jammer allocation problem. While some researchers try to provide a definitive solution to small-sized instances or specific situations of the problem,

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the optimal jammer allocation problem involves the complete search process with non-deterministic polynomials, and as the number of weapons and targets increases, it becomes much more computationally difficult. So far, Malhotra[12], *et al.* and Bisht[13] suggested heuristic optimisation approaches for the different WTA problems. Guangsheng[14], *et al.* reviewed the intelligent-based optimisation methods for WTA problem in their survey studies. Research on heuristic algorithms has also recently become a hot spot in the field of jammer allocation. Lee[15], *et al.* and Xu[16], *et al.* proposed the Genetic Algorithm (GA) for radar assignment. Analyses for directional antennas were also performed with Particle Swarm Optimization (PSO) Algorithm by Chen[17], *et al.*, the Ant Colony Algorithm, and the Tabu Search Algorithm by Wang[18], *et al.* In addition, Pan[19], *et al.* studied radar-jamming allocation strategy based on Improved Chaos Genetic Algorithm in 2020.

In this study, the classical SWTA problem has been combined within the EW threat assessment with an EM effect-based jammer-radio engagement approach. In this context, optimum allocation of non-directional jammers operating at different operating frequencies to a large number of RF emitters, under appropriate EW constraints is aimed as different from the literature. It is assumed that the jammers and targets broadcast 360° in the UHF frequency bands as different from the jammers and emitters having directional antennas such as radars. In addition, the values of the targets are determined using an original threat assessment algorithm that takes into account operating frequencies, jamming distance, and weather conditions. The resulting jammer-target effect matrix has been solved with MATLAB under different scenarios using Simplex Algorithm according to the efficiency and cost constraints, as an optimisation problem. It is seen that the most appropriate allocation solutions for omnidirectional jammers and threats could be obtained efficiently in order to start the EA operation rapidly after ES activities.

The article is organised as follows: first, brief information about the SWTA problem and optimisation method is given. Second, the proposed EW threat assessment algorithm and modelling approach are explained. After that, the results and the discussion are presented. Finally, the conclusion includes suggestions for further studies.

2. SWTA PROBLEM AND OPTIMISATION METHOD

2.1 SWTA Problem Basics

While the majority of WTA literature has focused on the defensive side, some has addressed the offensive side as well. Originally, WTA problem is defined by Manne[1] as minimizing the survival probability of targets aiming to destroy a protected entity. The problem is separated in two: static and dynamic. In the static version of the WTA solution, all inputs in the model are known, including weapons, targets, and death probabilities. Also, weapons are assigned to the targets only in one stage. On the other hand, at the dynamic version, the weapons are assigned consecutively and the results are tracked, to reach the final result[20]. In this study, the static WTA solution is chosen to highlight the proposed model.

Although many cost functions and solution methods have been offered based on different parameters and applications so far, the original formulation defined by Manne[1] takes into account a scenario with weapons of type w_i = 1, ..., m and targets number of j = 1, ..., n. Each type i weapon has a p_{ij} chance of killing target j and each target j has a damaging V_j value. SWTA is formulated as follows using decision variables x_{ij}, which indicates the number of i-type weapons to be assigned to target j:

$$\min \sum_{j=1}^{n} v_j \prod_{i=1}^{m} \left(1 - p_{ij}\right)^{x_{ij}} \tag{1}$$

$$\sum_{j=0}^{n} x_{ij} \le w_i \quad \text{for } i = 1,\ldots,m \tag{2}$$

$$x_{ij} \in Z_+ \quad \text{for } i = 1,\ldots,m \text{ and } j = 1,\ldots,n \tag{3}$$

The surviving form of the formulation, on the other hand, is more commonly written. For $q_{ij} = \left(1 - p_{ij}\right)$ it can be written in Eqns (4-6):

$$\min \sum_{j=1}^{n} v_j \prod_{i=1}^{m} \left(q_{ij}\right)^{x_{ij}} \tag{4}$$

$$\sum_{j=0}^{n} x_{ij} \le w_i \quad \text{for } i = 1,\ldots,m \tag{5}$$

$$x_{ij} \in Z_+ \quad \text{for } i = 1,\ldots,m \text{ and } j = 1,\ldots,n \tag{6}$$

where the number of weapon type is m, the number of targets is n, the number of weapons of type i assigned to target j is x_{ij}, the probability of survival of target j attacked by weapon I is q_{ij}, the damaging value of target j is V_j, the number of weapons of type I is w_i. The non-linear objective function in (1) looks for weapon-target assignments that minimise the expected survival value. Constraints (2) and (5) state that these pairings are integers and the total number of i-type weapons can't exceed the total number of weapons accessible, which equals the number of w_i. Other models and recent applications of the WTA problem can be reviewed from the survey study of Ghanbari[21], *et al.* In this study, the SWTA problem modelled within the scope of EW threat assessment is solved by using the Simplex method for simplicity and to make the EW threat assessment model stand out. The other recent differential or heuristic may be used to obtain more optimal solutions.

2.2 Simplex Method

Simplex method[22] which is one of the basic linear programming techniques was first introduced by George Dantzig who was a mathematical adviser for the U.S. Air Force, in 1947. In general, the inequality constraints of the optimisation problem are defined as a polygonal region. One of the vertices is evaluated as the probable solution of the problem. The simplex method checks these vertices in a systematic way. Although it is thought that the algorithm has reached its final form in the 1970s, it has gained importance again with the new developments made after the 1980s and started to find new application areas for the optimisation problems at present[23].

3. THREAT ASSESSMENT ALGORITHM AND MODELLING

3.1 Proposed Threat Assessment Algorithm

The main purpose of jamming is to prevent enemy communications performed on the EM spectrum. The interference signal in the receiver becomes effective when it is powerful enough to prevent the enemy from retrieving the intended information from the signal, as the interference signal suppresses the information content in the desired signal. Because the RF bands are where the EM spectrum is most heavily used for communications systems, jammers frequently operate in this area. In general, the tactical radios operating in VHF/UHF-bands emit their waveforms with 360° propagations. Therefore, it is evaluated that the jammers used against these radios will broadcast 360° as well. In jamming application, information to start the prioritisation process according to the characteristics of threats is essential. This data is classified to determine the order of the threats. Three parameters are defined to classify threat information in the literature:

(i) Capability Parameters: To provide information about the threat's capacity to threaten the defended asset. When sorting threats by ability parameters, the skill index describes the threat's ability to damage a defended asset[24].

(ii) Objective Parameters: To prioritise threats in terms of willingness to attack the defended asset. The goal parameters are the most difficult to predict[25].

(iii) Proximity Parameters: To measure the proximity of threats to the defended asset. These parameters are the most important parameter class in determining threat values. Calculating the distance between the threat and the closest point of the defended asset is the key point of measurement proximity[26]. Naem[24], *et al.* stated that the best way to rank threats can be obtained by combining two or three of these parameters. In the model, it is aimed to cover the targets with jammers broadcasting 360°. For this reason, a scenario aimed at allocating a set of weapons to a set of targets in the most appropriate way in order to minimise the probability of survival of targets within the scope of EW threat assessment is created. All three of the above parameters have been used to prioritise threats attacking the protected area. First of all, targets are prioritised by being subjected to threat assessment algorithm according to distance, target valence, and weather conditions, then jammer-target assignments are made. While making these assignments, two main cost functions is worked on and results have been obtained for maximum effect and minimum cost purposes.

In order to model a jammer operating in UHF-band, it is assumed that a jammer affects the sidebands by a certain percentage in the band it broadcasts. For this purpose, it is assumed that the jammer powers are bigger than the powers received by the targets because avoiding model complexity and providing a reference for the sideband effect. Therefore, the Fourier transform of a square signal is taken and assuming that each peak is jamming at a certain percentage. An example signal created with this assumption is depicted in Fig. 1. For simplicity, the example signal suppresses maximum at basically

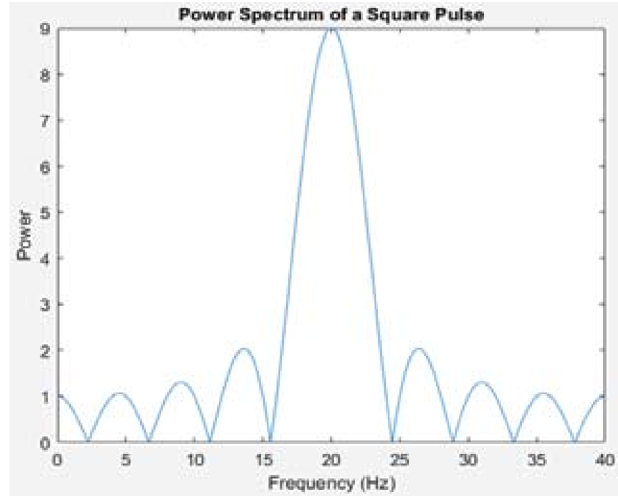

Figure 1. Fourier transform of a square signal for modelling sideband effect.

20 Hz. The suppression power of the sidebands decreases to 26% between 24-28 Hz and 11-15 Hz, and decreases to 14.5% between 6-11 Hz and 28-33 Hz.

In addition, the operating frequencies of eight jammers and eight targets are summarised in Table 1. From the table, the frequency at which the 2nd jammer makes maximum suppression is 320 MHz. According to the sideband assumption, it provides maximum suppression at 314.5-324.5 MHz, while its sidebands decrease to 26% in the range of 324.5-328 MHz and 311-314.5 MHz, and 14.5% between 306-311 MHz and 328-333 MHz. So, the effective coverage region of this jammer is between 306 MHz and 333 MHz. Under these conditions, it can be said that the targets 2, 3, 4, and 5 can be suppressed by this jammer according to the ratio stated with the sideband approach.

When the above target-jammer matches are made, the effect-matrix created according to the acceptances for the model is presented as in Table 2.

From Table 2.a, the 1st jammer suppresses the 1st target with 0.1456, 2nd target with 1, 3rd target with 0.2265, and 4th target with 0.1456 probabilities. Other targets cannot be suppressed by this jammer. Since the jammer-1 is suppressed at 310 MHz and the target-2 broadcasts at 310 MHz, the jammer can suppress at the rate of 1/1. Other targets, on the other hand, make less jamming by their harmonics due to the model in Fig. 1.

Under threat assessment, the threats and owned jammers are randomly placed in an area presented in Fig. 2 and the

Table 1. Operating frequencies of the jammers and targets

	Operating frequency [MHz]		Operating frequency [MHz]
J1	310	T1	300
J2	320	T2	310
J3	330	T3	315
J4	340	T4	320
J5	350	T5	330
J6	365	T6	350
J7	370	T7	360
J8	375	T8	372

Table 2. Effect-matrices

(a) According to the side band approach

JAMMERS \ TARGETS	1	2	3	4	5	6	7	8
1	0.1456	1	0.2265	0.1456	0	0	0	0
2	0	0.1456	0.2265	1	0.1456	0	0	0
3	0	0	0	0.1456	1	0	0	0
4	0	0	0	0	0.1456	0.1456	0	0
5	0	0	0	0	0	1	0.1456	0
6	0	0	0	0	0	0	0.2265	0.2265
7	0	0	0	0	0	0	0.1456	1
8	0	0	0	0	0	0	0	1

(b) According to the distance measurement

JAMMERS \ TARGETS	1	2	3	4	5	6	7	8
1	0.1456	0.8	0.2265	0.1165	0	0	0	0
2	0	0.1165	0.1812	0.8	0.1165	0	0	0
3	0	0	0	0.1165	0.8	0	0	0
4	0	0	0	0	0.1456	0.1456	0	0
5	0	0	0	0	0	0.8	0.1165	0
6	0	0	0	0	0	0	0.1812	0.2265
7	0	0	0	0	0	0	0.1456	1
8	0	0	0	0	0	0	0	0.8

(c) According to the weather conditions

JAMMERS \ TARGETS	1	2	3	4	5	6	7	8
1	0.1266	0.7273	0.1970	0.1110	0	0	0	0
2	0	0.1059	0.1576	0.7619	0.1110	0	0	0
3	0	0	0	0.1110	0.7619	0	0	0
4	0	0	0	0	0.1387	0.1456	0	0
5	0	0	0	0	0	0.8	0.1165	0
6	0	0	0	0	0	0	0.1812	0.2265
7	0	0	0	0	0	0	0.1456	1
8	0	0	0	0	0	0	0	0.8

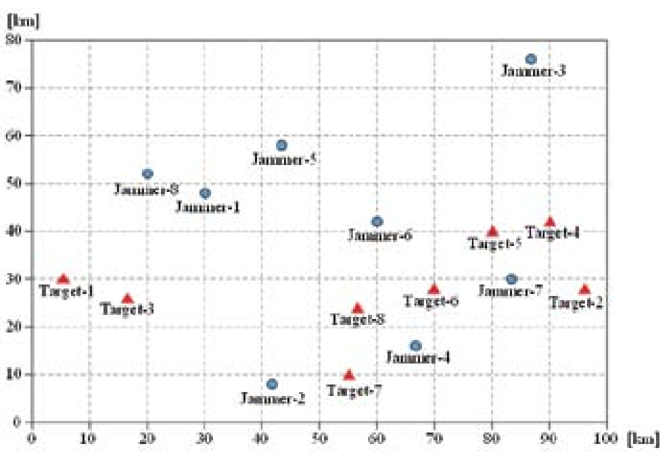

Figure 2. Jammer-target location area.

Euclidean distances between them are measured. These distances are inversely proportional to the significance of the threats. The updated effect-matrix presented in Table 2.b is computed according to these distances. On the other hand, the atmospherically conditions[3] are added to the model. Although it is known that atmospheric effects are less in this frequency band, in order to see the effect of these events on transmission for jammers and targets, intense atmospheric events were selected and their effect levels were limited in accordance with the literature[3]. The weather condition for each target is randomly assigned. These are downpour for target-1, rainy for target-2, downpour for target-3, and little rain for target-4. According to these conditions, the possibility of jamming all four targets of the jammer according to the weather conditions has decreased due to the effect of precipitation at the frequencies studied. After this process, the impact-matrix has been updated to prioritise the most easily destructible threat, as presented in Table 2.c.

3.2 SWTA Modelling

In this article, two different models have been studied according to two different constraints: In the first, maximising the total impact on targets; in the second, minimising the total energy that the jammers consume. In addition, different scenarios are created by modelling the distance between the targets and jammers, and the weather conditions between their locations. The tables of effect of each jammer on each target in each scenario are obtained by the proposed threat assessment algorithm. The minimum jamming level and total energy amount of the system are also determined. The aggregate impact of strategies for each target should be equal to or less than minimum damage levels while achieving a total energy constraint.

3.2.1 *Total Impact Based Optimal Jammer-Target Allocation Model*

In this model, the total damage on targets is maximised. Since each of the attack strategies has different types of jammers uses, and each jammer type has different impact values on different target types, they will have different damage on targets. The model is explained as Eqns (7-14):

$$\max \sum_{z=1}^{Ts} \left(Stet_z \right) \tag{7}$$

$$Stet_z = 1 - \prod_{i=1}^{a} \left(1 - P_{i,Tz} \right)^{C_{z,i}} \tag{8}$$

$$\min \sum_{z=1}^{Ts} \left(S_z \right) = 1 \tag{9}$$

$$S_z \in \{0,1\} \tag{10}$$

where $Stet_z$ is the effect of the strategy-*z*, T_s is the total number of strategies, a is the total number of jammer, $P_{i,Tz}$ is the target attacked in the strategy-*z*, i-matrix showing the possibility of jamming with the jammer, T_z is target attacked in strategy-*z*, $C_{z,i}$ is the matrix showing that the jammer-i is used in strategy-*z*, S_z is strategy-z (z = 1, 2, .., T_s).

3.2.2 *Total Energy Based Optimal Jammer-Target Allocation Model*

With this model, it is aimed to minimise the total cost of the allocation. Because each of the strategies shows different jammer uses for different target, the costs of the jammers differ according to their energy usage. The total energy of the strategies must be less than or equal to the total energy that can be drawn from the system.

$$\min \sum_{z=1}^{Ts} \left(Sten_z \right) \tag{11}$$

$$Sten_z = \sum_{i=1}^{a} C_{z,i} \times Energy_i \tag{12}$$

$$\min \sum_{z=1}^{Ts} \left(Sten_z \right) \leq TotalEnergy \tag{13}$$

$$\min \sum_{z=1}^{Ts} \left(Stet_z \right) \leq MinEffect \tag{14}$$

where $Sten_z$ is the energy of the strategy, a is the total number of jammer, $C_{z,i}$ is the matrix that shows the jammer-i is used in strategy-z, $Energy_i$ is the amount of energy drawn by the jammer, *TotalEnergy* is the total amount of energy that can be received from the system, T_s is total number of strategies, $Stet_z$ is the effect of the strategy-*z*, *MinEffect* is the minimum amount of damage effect to be given, S_z is strategy-z (z = 1, 2, .., T_s).

3.2.3 *Assumptions for Modelling*

The assumptions for two different scenarios created in order to maximise the effect and minimise the total energy used are as follows;

- Up to five jammers can be activated at the same time in order to avoid overcharging.
- The jammers broadcast 360°.
- There are eight types of jammers and eight targets.
- Each jammer operates in a different frequency range.
- The jamming possibilities of each jammer type for each target have been created according to the model in Fig. 1.
- The jamming possibilities differ for each target due to both the distance variable and the weather conditions in the environment where the target is located.
- A jammer can give damage based on the damage coefficient.
- The amount of energy consumed by each jammer type is given.
- The minimum jamming effect for each jammer is equal to each other and has been taken to vary between 0.1 and 0.9.
- The system can consume energy as much as TotalEnergy.
- A single jamming is applied to one target.
- There is no ready-to-use time for jammers.
- Total number of strategies, Ts, is computed 1744.
- Energy amounts for each jammer are 10W, 25W, 30W, 40W, 55W, 60W, 75W and 80W, respectively. The jammer powers are bigger than the signal powers received by the targets.

4. RESULTS AND DISCUSSION

The results are computed for the models specified below in accordance with different cost functions, and they are compared using a Jamming Success Ratio;

- Results based on applied total effect
  - With base effect matrix:
    - (For 0.1 < effect < 0.5), (for 0.5 < effect < 0.9)
  - With distance and weather condition effect matrix:
    - (For 0.1 < effect < 0.5), (for 0.5 < effect < 0.9), (for effect > 0.9)
- Results based on consumed total energy
  - With base effect matrix:
    - (For 0.1 < effect < 0.5), (for 0.5 < effect < 0.9)
  - With distance and weather condition effect matrix:
    - (For 0.1 < effect < 0.5), (for 0.5 < effect < 0.9), (for effect > 0.9)

In accordance with the proposed EW threat assessment modelling, the effect ratios such as 0.1 or 0.5 define the minimum effect to be created on the targets by the jammer by using its sideband effect. For example, in the case of 0.5 < effect < 0.9 effect condition, if the target is subjected to the 2th harmonic of the jammer (14% suppress) according to its frequency value, the jammer cannot suppress this target. The suppress ratio of the jammer have to be bigger than the effect ratio in order to obtain effective jamming. An evaluation coefficient named "Jamming Success Ratio - JSR" has been established as in (15) to evaluate the effectiveness of jamming. For determining the success range of JSR,

- 100% success means that one jammer suppresses all targets in the given area.
- In the case of one jammer suppress only one target, the success ratio is taken as "1/number of targets".

- Maximum number of targets must be suppressed with minimum number of jammers.
- Weighted penalty score is taken into account for each unsuppressed target.

Under these acceptances, the coefficient is calculated as below;

$$JSR = \frac{10x\left(NST - NJU\right) + 70 - 7.5xUST}{140} x100 \qquad (15)$$

where *NST* is the number of suppressed targets, *NJU* is the number of jammers used and *UST* is the number of non-suppressed targets. If all targets are suppressed, *JSR* will be bigger than 50%. If at least one target cannot be suppressed, *JSR* will decrease under 50%. The results obtained for these conditions are presented in Fig. 3, Fig. 4, Table 3, and Table 4. While the jammer-target allocation results are given in the tables, the visual representations of these allocations are depicted in the figures.

The allocation results obtained based on total effect show that each target is subjected to suppress by at least one jammer in each case. Jammer-8 has not been used for any cases due to relatively bigger frequency difference with the targets around it. Also, some other jammers such as Jammer-4 and Jammer-6 are not needed from time to time to accomplish the task.

When the obtained allocation results in the case of applied total effect are investigated from Table 3 and Fig. 3, it can be seen that all targets are successfully suppressed by the jammers. In accordance with JSR criteria, all JSR values are

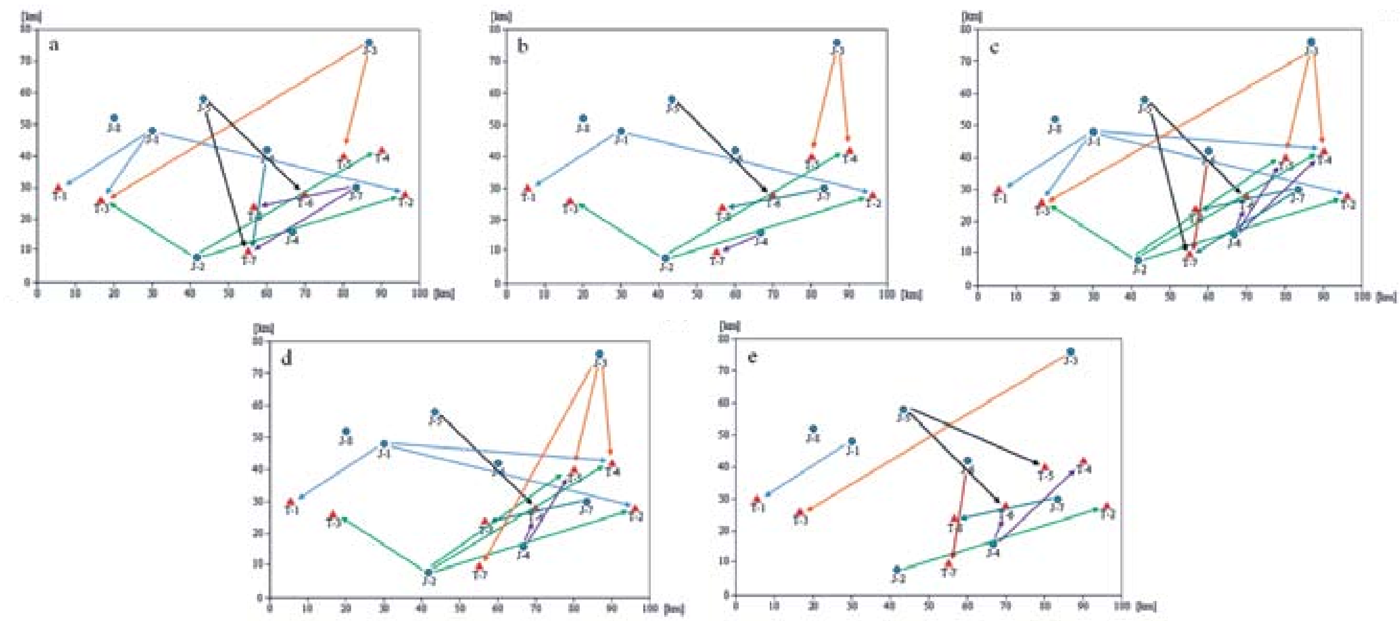

Figure 3. Allocation results based on applied total effect.

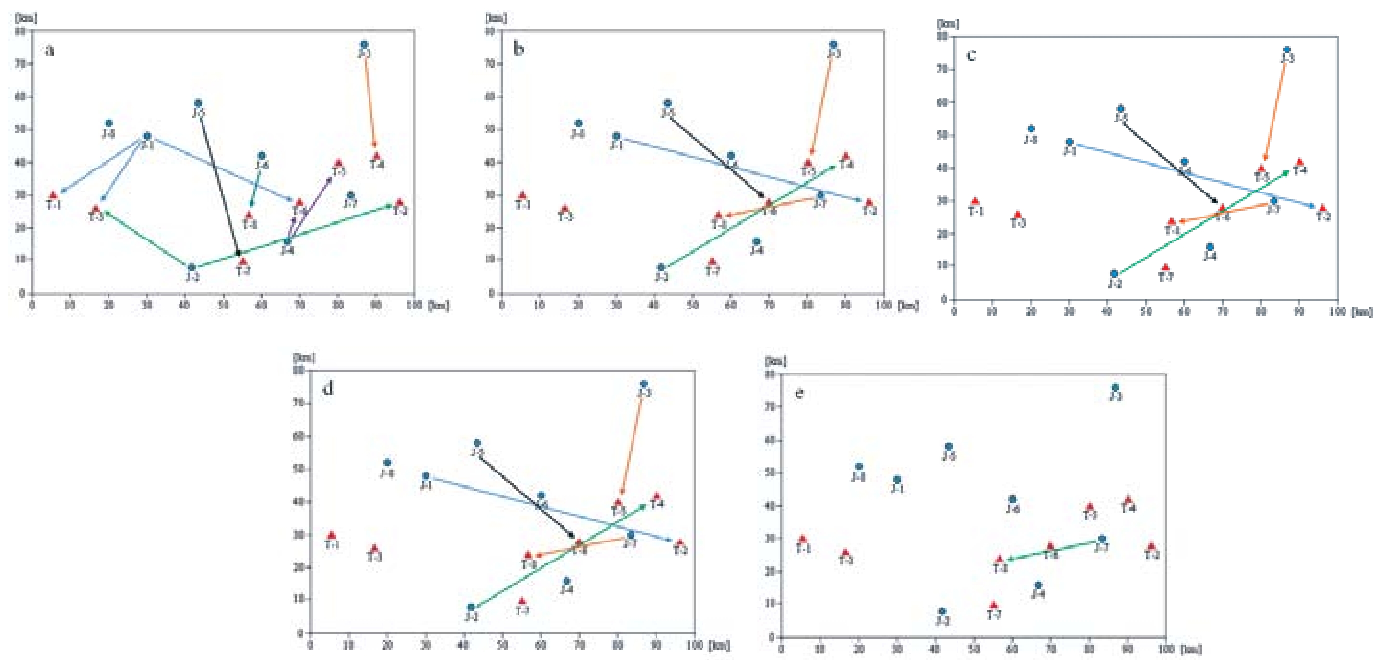

Figure 4. Allocation results based on applied total energy.

Table 3. Allocation results according to the applied total effect

(a) Base Effect Matrix, 0.1 < Effect < 0.5

TARGETS \ JAMMERS	1	2	3	4	5	6	7	8	JSR
1	1	0	0	0	0	0	0	0	
2	1	1	0	0	0	0	0	0	
3	1	1	1	0	0	0	0	0	
4	0	1	0	0	0	0	0	0	64.28%
5	0	0	1	0	0	0	0	0	
6	0	0	0	0	1	0	0	0	
7	0	0	0	0	1	1	1	0	
8	0	0	0	0	0	0	1	0	

(b) Base Effect Matrix, 0.5 < Effect < 0.9

TARGETS \ JAMMERS	1	2	3	4	5	6	7	8	JSR
1	1	0	0	0	0	0	0	0	
2	1	1	0	0	0	0	0	0	
3	0	1	0	0	0	0	0	0	
4	0	1	1	0	0	0	0	0	64.28%
5	0	0	1	0	0	0	0	0	
6	0	0	0	0	1	0	0	0	
7	0	0	0	1	0	0	0	0	
8	0	0	0	0	0	0	1	0	

(c) Distance and Weather Condition Effect Matrix, 0.1 < Effect < 0.5

TARGETS \ JAMMERS	1	2	3	4	5	6	7	8	JSR
1	1	0	0	0	0	0	0	0	
2	1	1	0	0	0	0	0	0	
3	1	1	1	0	0	0	0	0	
4	1	1	1	1	0	0	0	0	57,14%
5	0	1	1	1	0	0	0	0	
6	0	0	0	1	1	0	0	0	
7	0	0	0	0	1	1	1	0	
8	0	0	0	0	0	0	1	0	

(d) Distance and Weather Condition Effect Matrix, 0.5 < Effect < 0.9

TARGETS \ JAMMERS	1	2	3	4	5	6	7	8	JSR
1	1	0	0	0	0	0	0	0	
2	1	1	0	0	0	0	0	0	
3	0	1	0	0	0	0	0	0	
4	1	1	1	0	0	0	0	0	64.28%
5	0	1	1	1	0	0	0	0	
6	0	0	0	1	1	0	0	0	
7	0	0	1	0	0	0	0	0	
8	0	0	0	0	0	0	1	0	

(e) Distance and Weather Condition Effect Matrix, 0.9 < Effect

TARGETS \ JAMMERS	1	2	3	4	5	6	7	8	JSR
1	1	0	0	0	0	0	0	0	
2	0	1	0	0	0	0	0	0	
3	0	0	1	0	0	0	0	0	
4	0	0	0	1	0	0	0	0	57,14%
5	0	0	0	0	1	0	0	0	
6	0	0	0	1	1	0	0	0	
7	0	0	0	0	0	1	0	0	
8	0	0	0	0	0	0	1	0	

Table 4. Allocation results according to the applied total energy

(a) Base Effect Matrix, 0.1 < Effect < 0.5

		JAMMERS								JSR
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
TARGETS	**1**	1	0	0	0	0	0	0	0	
	2	0	1	0	0	0	0	0	0	
	3	1	1	0	0	0	0	0	0	
	4	0	0	1	0	0	0	0	0	64.28%
	5	0	0	0	1	0	0	0	0	
	6	1	0	0	1	0	0	0	0	
	7	0	0	0	0	1	0	0	0	
	8	0	0	0	0	0	1	0	0	

(b) Base Effect Matrix, 0.5 < Effect < 0.9

		JAMMERS								JSR
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
TARGETS	**1**	0	0	0	0	0	0	0	0	
	2	1	0	0	0	0	0	0	0	
	3	0	0	0	0	0	0	0	0	
	4	0	1	0	0	0	0	0	0	33.92%
	5	0	0	1	0	0	0	0	0	
	6	0	0	0	0	1	0	0	0	
	7	0	0	0	0	0	0	0	0	
	8	0	0	0	0	0	0	1	0	

(c) Distance and Weather Condition Effect Matrix, 0.1 < Effect < 0.5

		JAMMERS								JSR
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
TARGETS	**1**	0	0	0	0	0	0	0	0	
	2	1	0	0	0	0	0	0	0	
	3	0	0	0	0	0	0	0	0	
	4	0	1	0	0	0	0	0	0	33.92%
	5	0	0	1	0	0	0	0	0	
	6	0	0	0	0	1	0	0	0	
	7	0	0	0	0	0	0	0	0	
	8	0	0	0	0	0	0	1	0	

(d) Distance and Weather Condition Effect Matrix, 0.5 < Effect < 0.9

		JAMMERS								JSR
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
TARGETS	**1**	0	0	0	0	0	0	0	0	
	2	1	0	0	0	0	0	0	0	
	3	0	0	0	0	0	0	0	0	
	4	0	1	0	0	0	0	0	0	33.92%
	5	0	0	1	0	0	0	0	0	
	6	0	0	0	0	1	0	0	0	
	7	0	0	0	0	0	0	0	0	
	8	0	0	0	0	0	0	1	0	

(e) Distance and Weather Condition Effect Matrix, 0.9 < Effect

		JAMMERS								JSR
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
TARGETS	**1**	0	0	0	0	0	0	0	0	
	2	0	0	0	0	0	0	0	0	
	3	0	0	0	0	0	0	0	0	
	4	0	0	0	0	0	0	0	0	12.5%
	5	0	0	0	0	0	0	0	0	
	6	0	0	0	0	0	0	0	0	
	7	0	0	0	0	0	0	0	0	
	8	0	0	0	0	0	0	1	0	

bigger than 50% because entire targets are suppressed. When all targets are suppressed with 7 jammers, the JSR is computed as 57.14%. If all targets are suppressed with 6 jammers, JSR increases to 64.28%. The fewer jammers that can suppress all the targets means the higher the JSR rate will be. The aim is to jam the maximum number of radios with the minimum number of jammers. Also, in some cases, some targets are suppressed additionally by the sideband effect of the other jammers around them. This issue can be an important skill because if it can be performed cooperatively by using cognitive methods, the total energy consumption of the jammer network will be able to decrease. On the other hand, when the results are investigated according to the effect ratios, the effectiveness of the jamming is sufficient while the effect ratio is less than 0.9. But if the effect ratio is wanted bigger than 0.9, the effectiveness of the jamming decreases and the sideband effect also decreases. In addition, it can be clearly seen that the weather conditions do not affect the jamming much due to UHF frequency band used. This issue can also be basically computed by using the literature[3]. In contrast, the distance effect largely affects the jamming performance as clearly seen from the Table 2 and also Table 3, because the area which covers the jamming location as seen from Fig. 2 involves proper distance under 100 km for UHF communications.

In addition, the results obtained in the case of using total energy cost function of the jammers show that JSR ratio when the effect ratio is wanted bigger than 0.5 has fallen below 50% because all targets cannot be suppressed by the jammers. Especially, when the effect ratio is bigger than 0.9, only one target can be suppressed by one jammer, because more power is wanted to suppress the targets and, in contrast, the energy consumption of the jammers is minimised. In this case, JSR is calculated as 12.5% for the worst case.

Actually, the decrease in the effect of jammers on the targets due to the effect of distance and precipitation decreased the number of jammers that could be used as the effect ratio increased. At the same time, as the level of effect desired to be given on the targets increases, it is seen that the total energy used in proportion to the number of suppressed targets increases due to the use of more jammers or the use of jammers that draw more energy in accordance with the EW threat assessment model designed in this study.

As seen from the overall results, the jammer-radio allocation problem specified at the suggested model is solved successfully and effectively. In addition, the jammer-target allocation optimisation in the scope of EW threat assessment is more efficient, when,

- The cost function based on effect ratio should be used.
- The desired effect ratio should be less than 0.5 according to the related effect matrix.

On the other hand, it is clear that more effective optimisation algorithms can increase the optimisation performance and allocation accuracy.

5. CONCLUSION

The jammer-radio engagement approach for WTA problem is studied in this study. For this purpose, non-directional jammers and targets operating in the range of 300-400 MHz UHF frequencies are modelled according to jamming distance, weather condition, and energy consumption at the operating area of 80x100 km, as different from the literature. The jammer-target effect matrix is solved under different scenarios by using simplex algorithm according to the efficiency and cost constraints. To evaluate the optimisation of the allocation, the criterion named JSR is developed at the first time. At the end, unlike EW-based WTA solutions studied in the literature so far, the most appropriate allocation solutions for non-directional jammer and threat are obtained efficiently and optimally. However, the allocation results for EW applications largely depend on the effect ratio used. The better results are taken in the case of under 0.5 effect ratio. In addition, the distance between jammer and target and weather conditions are also affecting the jamming and allocation optimisation according to the operating frequency.

The developed EW-SWTA model is a basic model including only simple effects such as sideband effect, jamming distance, weather conditions, and solved by Simplex algorithm. In the future, more parameters such as individual jammer and target powers, polarisations, landforms, etc. can be added to the model. Also, it can be handled as a dynamic WTA problem, and more powerful heuristic optimisations can be applied to improve the accuracy of the allocation results.

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