University of Thessaly
Faculty of Engineering
Department of Electrical & Computer Engineering

Robust backbone formation for the Internet of Battle Things based on Dominating Sets

Diploma Thesis

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Volos, July 2020

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Πανεπιστήμιο Θεσσαλίας
Πολυτεχνική Σχολή
Τμήμα Ηλεκτρολόγων Μηχανικών & Μηχανικών Υπολογιστών

Σχηματισμός εύρωστου δικτύου ραχοκοκαλιάς για το Διαδίκτυο των Πραγμάτων Μάχης βασισμένος σε κυρίαρχα σύνολα.

Διπλωματική Εργασία

ΑΙΚΑΤΕΡΙΝΗ ΚΥΡΙΑΚΟΥ

Επιβλέπων
Δημήτριος Κατσαρός
Αναπληρωτής Καθηγητής

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Abstract

In recent years, there has been an interest in researching the field of Military Multilayer Wireless Networks which are based on Ad Hoc Networking technologies and their purpose is the optimization of communication between allied entities in a battlefield. Those networks could be described as a complex overconnected network of multiple levels that combines different, independent operating units, such as groups of soldiers, drones, helicopters, vehicles, etc. The specific units, working together towards a common operational goal, could be able to achieve an improved and faster dissemination of information in a military environment.

One of the most important issues related to the design of Tactical Multilayer Network is to maintain reliable communication between its nodes without it being easily interrupted, either by disasters, or by malicious attacks. Therefore, it is necessary to design a virtual backbone that is able to make the online network of nodes robust and resistant to the loss of nodes or links.

The contribution of the present dissertation is the design of a distributed algorithm that achieves the construction of a more robust Multilayer Ad Hoc Network, which is based on the concept of Connected Dominating Sets (CDS) as well as Maximal Independent Sets (MIS). Our research leads to the construction of m-Connected Dominating Sets in Multilayer Networks which have not been examined in the literature so far. During the creation of the m-CDS, nodes are included to the network according to their centrality in their layer as well as in other layers, producing a robust network. The result highlights the use of clPCI centrality measure as the best option, so far, for the construction this network topology.

Keywords

Maximal Independent Sets, m-Connected Dominating Sets, clPCI Centrality Measure, Robustness

Περίληψη

Τα τελευταία χρόνια ερευνάται εκτενώς η ανάπτυξη Στρατιωτικών Πολυεπίπεδων Ασύρματων Δικτύων που βασίζονται στην τεχνολογία των Ad Hoc Δικτύων και αποσκοπούν στην βελτίωση της επικοινωνίας μεταξύ συμμάχων σε ένα πεδίο μάχης. Τα συγκεκριμένα δίκτυα μπορούν να θεωρηθούν ως ένα σύνθετο υπερδίκτυο πολλαπλών επιπέδων που συνδυάζει διαφορετικές, ανεξάρτητες λειτουργικές μονάδες, όπως αυτές των στρατιωτών, των drones, των ελικοπτέρων, των οχημάτων, κ.α. Οι μονάδες αυτές αποτελούν μέρη του δικτύου τα οποία συνεργάζονται με στόχο την επίτευξη της βελτιωμένης και ταχύτερης διάχυσης της πληροφορίας.

Ένα από τα πιο σημαντικά ζητήματα που αφορούν τον σχεδιασμό ενός Τακτικού Πολυεπίπεδου Δικτύου είναι η διατήρηση της αξιόπιστης επικοινωνίας μεταξύ των αδιαφανώς συνδεδεμένων κόμβων του χωρίς αυτή να διακόπτεται εύκολα, είτε από καταστροφές, είτε από κακόβουλες επιθέσεις. Συνεπώς, κρίνεται απαραίτητος ο σχεδιασμός ενός εικονικού δικτύου ραχοκοκκαλιάς που θα καθιστά το υπερδίκτυο των κόμβων εύρωστο και ανθεκτικό στις απώλειες κόμβων ή ζεύξεών του.

Η προσφορά της παρούσας διπλωματικής εργασίας είναι η σχεδίαση ενός κατανεμημένου αλγορίθμου που επιτυγχάνει την δημιουργία ενός εύρωστου Πολυεπίπεδου Ad Hoc Δικτύου, το οποίο βασίζεται στην θεωρία των Connected Dominating Sets (CDS) και των Maximal Independent Sets (MIS). Η έρευνά μας καταλήγει στη δημιουργία m-Connected Dominating Sets σε πολυεπίπεδα δίκτυα τα οποία δεν έχουν εξεταστεί μέχρι στιγμής στη βιβλιογραφία. Κατά τη δημιουργία του m-CDS προστίθενται κόμβοι λαμβάνοντας υπόψη την κεντρικότητά τους τόσο στο επίπεδο που ανήκουν όσο και στα υπόλοιπα επίπεδα του δικτύου γεγονός που του προσδίδει ευρωστία. Το αποτέλεσμα αναδεικνύει τη χρήση του μέτρου κεντρικότητας clPCI ως την βέλτιστη επιλογή για την δημιουργία της συγκεκριμένης τοπολογίας δικτύου.

Λέξεις Κλειδιά

Μέγιστα Ανεξάρτητα Σύνολα, m-Συνδεδεμένα Κυρίαρχα Σύνολα, clPCI Μέτρο Κεντρικότητας, Ευρωστία

Dedicated to my family.

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Abbreviations

CDS	Connected Dominating Set
MIS	Maximal Independent Set
DS	Dominating Set
m-CDS	m-Connected Dominating Set
m-Dominated	Node that has at least m dominators
Not m-Dominated	Node that does not have at least m dominators
clPCI	Cross-Layer PCI
PCI	Power Community Index
IoT	Internet of Things
IoBT	Internet of Battle Things

Chapter 1

Introduction

1.1 Introduction

As the adoption of Internet of Things evolves rapidly in various fields, the emergency of the development of IoT for military services becomes more and more essential. As observed in a variety of applications, the tendency to create smart devices that have the ability to communicate with each other and, also, to adapt and learn according to the conditions accelerates the desired outcome of each application with less effort, energy and cost. Based on the effects of IoT applications, there have been scenarios of future conduction of military environments comprised of intelligent ”things”, working together in order to improve the conditions of communication of human warfighters inside a battlefield. As mentioned in [1], it is likely that the Internet of Things will become a reality in warfare over the next few decades.

The implementation of such an infrastructure would require the creation of an integrated management system, which should provide to each category of military ”things” the necessary information for the execution of a successful operation. Moreover, it is vital that every part of such an environment is capable of receiving and transmitting information to every part of the network, allowing the faster dissemination of data, the more effective analysis of the network status and the improved decision making for each case in the battlefield. Therefore, all of the entities should become parts of a seamless network that would increase the capabilities of military environments dramatically, as described in more detail in [7].

A US Army vision [1], [10] defined IoBT as a densely populated set of interconnected and interdependent ”things” performing a wide range of operations such as sensging, communicating with each other and with human warfighters and acting upon necessary occasions. Between those ”things”, there will be sensors, weapons, human-wearable devices, robots and vehicles.Towards the implementation of such an environment, there have been studies illustrating that the ad hoc network technology constitutes an approach that provides the necessary mobility of the devices in the lower levels of the network in [11]. The suggested infrastructure would consist of multiple networks that act as layers of a heterogeneous network of networks, where each layer includes a different category of the ones mentioned before. There would be links between each layer as well as between nodes from different layers in order to achieve the whole network’s successful

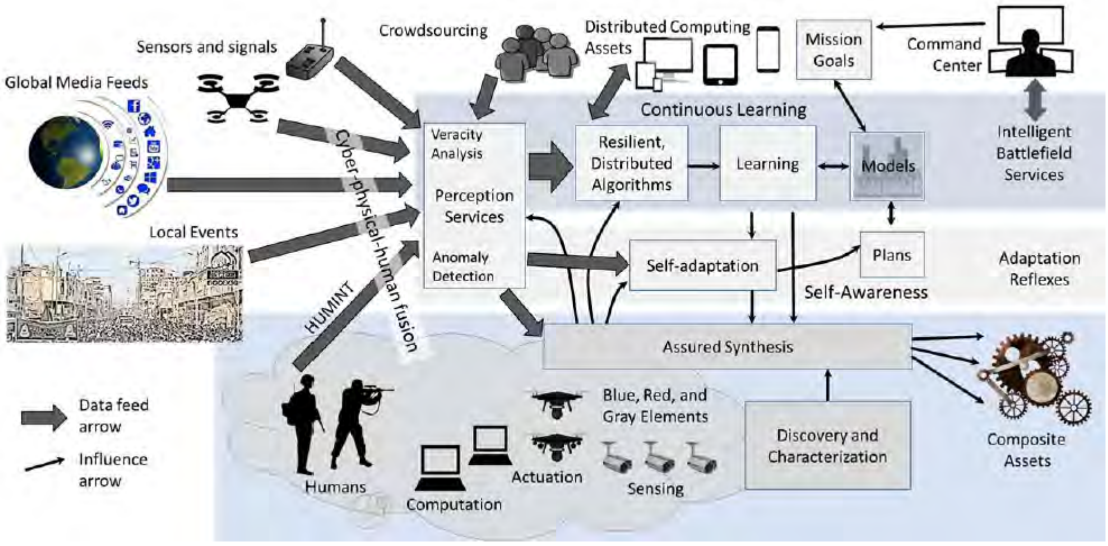

Figure 1.1: A representation of an Internet of Battle Things (Image taken from [14])

communication flow. A simplified image of such a Tactical Ad Hoc Network is shown in Figure 1.1.

1.2 Motivation

In order for the vision of Military Multilayer Ad Hoc Networks to become a reality, there are some crucial challenges that need to be encountered. Detailed discussion in [14], [1] has pointed out the main categories of challenges that such an infrastructure could confront. Those include the diversity of operations and goals, the highly dynamic environment, the extreme heterogeneity of devices, the varying scale concerning the density and the size of the network and, at last, the adversarial environments.

In this dissertation, we will only consider the latter case regarding to the robustness of a multilayer ad hoc network. In a modern battlefield, the enemy could destroy the regular operation flow by either threatening the devices and their communication, e.g by jamming RF Channels, destroying fiber channels, and depleting the power sources of the devices, or by defeating the availability, integrity and confidentiality of the network's information by eavesdropping, interfering and alternating it. Consequently, in the case of the adversary destroying ”things”, a robust backbone seems to provide the problem with a solution by augmenting the network with an amount of redundant nodes that can recover the communication flow in cases of node failures.

1.3 Contribution

This dissertation contributes in the construction of a more robust topology of a multilayer network, which has not yet been examined in the literature, by creating a backbone where each node has at least m dominators and is connected, therefore called m-CDS. Moreover, it provides detailed experiments on various cases of networks, evaluating the robustness, the resulting CDS size and the connectivity of dominators after the applying the proposed algorithm.

The rest of the dissertation is organized as follows:

- **Chapter 2**
  This chapter sets the theoretical background on Dominating Sets and the necessary variations of them as well as the definition of Multilayer Networks with graph theory terms, which are used for the backbone formation. Additionally, it explains the centrality measures used for the dominators election in our algorithm. Finally, the m-CDS problem is defined along with its two constraints that ensure the robustness of the network.

- **Chapter 3**
  In this chapter, we will present an algorithm named RECLB for the formation of the m-CDS Problem. The algorithm consists of two phases in which it exploits the centrality measure clPCI in order to achieve a dominating set including nodes with strategic position, therefore, leading to improved coverage of their neighbors. We user r-CDS algorithm as the competitor and the difference between RECLB and r-CDS relies on the ranking mechanism for the construction of the MIS and will be evaluated in another chapter.

- **Chapter 4**
  This chapter analytically presents the performance evaluation of RECLB algorithm by making general observations on the robustness achieved from it, comparing the consideration of the clPCI centrality measure in the election of nodes for the Maximal Independent Set with the ranking mechanism of r-CDS algorithm and comparing the effects of the augmented network on the integrity with the robustness on the 1-CDS. Moreover, there are charts and tables with observations on the impact of RECLB algorithm on the CDS size and the connectivity of the dominators.

- **Chapter 5**
  Chapter 5 includes a brief overview on the technical implementation of the backbone construction and the experimental evaluation.

- **Chapter 6**
  In chapter 6 we conclude the work conducted in the context of the current dissertation and we state the benefits and the drawbacks of our approach. Finally, we provide a direction on the area of future work that could further improve our problem.

Chapter 2

Preliminaries and Network Model

2.1 Introduction

For the purpose of creating a robust infrastructure for the management of Tactical Networks a common approach is the construction of hierarchical topologies consisting of Ad Hoc Networks aiming to achieve efficient communication as well as scalability. In this dissertation we take advantage of the Dominating Sets theory in order to effectively describe the network's components and the connectivity between them. We also use "nodes" and "vertices", and "edges" and "links" interchangeably in the context of wireless networks and graph theory. Before formulating the problem, to properly describe such a network model, we adopt a number of definitions to illustrate our work.

2.2 Multilayer Network Virtual Backbone Construction

The concept of the Virtual Backbone is crucial for the construction of such topologies since there is no fixed infrastructure in the specific networks. A virtual backbone of a Multilayer Ad Hoc Network consists of a set of nodes, where each one belongs to one layer, and is connected to a number of nodes towards nodes in the same layer as well as in other layers through links. As for the part of a single layer ad hoc network, it is considered to be a subnet of nodes working together to form a communication layer, transmitting data only to the nodes belonging to it. Only the nodes that have links towards other layers have the ability to broadcast information to nodes outside of their layer. This design results in reduction of unnecessary information transmission, saving the energy of nodes and the simplification of the network topology. The most commonly used methods are those based on clustering and those based on dominating sets as described in [11]. In the current research we focused only on the latter. Additionally, we focused on centrality measures such as clPCI, described in [3], for the identification of efficient cross layer dominators in the formation of the Backbone Network.

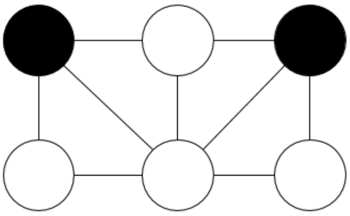

Figure 2.1: Nodes in black denote a Maximal Independent Set

2.2.1 Dominating Set Theory

Before we proceed to the explanation of the network model we will first provide some necessary terms of graph theory as illustrated in [4], [16]. A graph $G = (V, E)$ is considered to represent a wireless network, where V represents the set of all nodes in the network and E represents the set of all links in the network. For a node $v \epsilon V$, $N(v) = \{u|(u, v) \epsilon E\}$ is the one-hop neighbor set of v and $N^2(v)$ is the two-hop neighbor set of v. Also, $d(v) = |N(v)|$ is the degree of node v and $id(v)$ denotes the unique id for v. For a subset S of V, $G[S]$ is a subgraph of G induced by S. At last, let D be a subset of V and $V \backslash D$ be the induced subset containing all nodes of V that are not included in D.

Definition 2.1

An Independent Set (IS) is a subset S of V such that there is no edge in $G[S]$.

Definition 2.2

A Maximal Independent Set (MIS) is an IS such that adding any node not in the set breaks the independence property of the set. Thus, any node not in the MIS must be adjacent to some node in the set. An example is given in figure 2.1.

Definition 2.3

Let D be a subset of V, D is a DS if each node in $V \backslash D$ is adjacent to at least one node in D. Thus, every MIS is a DS. However, since nodes in a DS may be adjacent to each other, not every DS is an MIS. An example is given in figure 2.2 (LEFT).

Definition 2.4

A CDS C is a DS of G, and $G[C]$ is connected. An example is given in figure 2.2 (RIGHT).

Definition 2.5

An m-DS D is a subset of V such that each node in $V \backslash D$ is dominated by at least m nodes in D. An example is given in figure 2.3.

Definition 2.6

A multilayer network which consists of n layers is a pair (G^{ML}, E^{ML}), where $G^{ML} = \{G^i, i = 1, ..., n\}$ is a set of ‘networks’ (G^i , E^i) ($|G^i|$ nodes belonging to layer i , and $|E^i|$ edges connecting nodes belonging to layer G^i), and a set of interlayer links $E^{ML} = \{E_{i,j} \subseteq G_i \times G_j; i,j \epsilon \{1, ..., n\}, i = j\}$. An example is given in figure 2.4

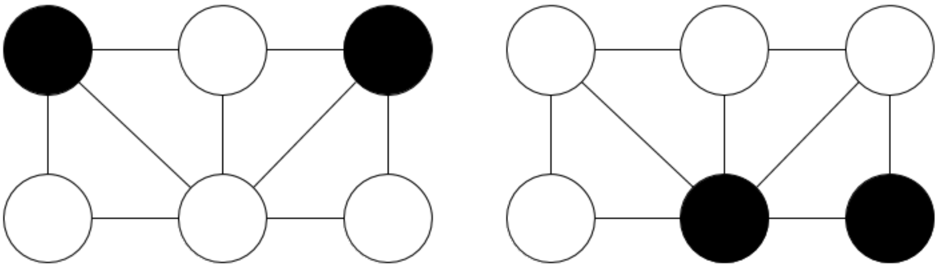

Figure 2.2: (LEFT) Nodes in black denote a Dominating Set. (RIGHT) Nodes in black denote a Connected Set (Πηγή: [3])

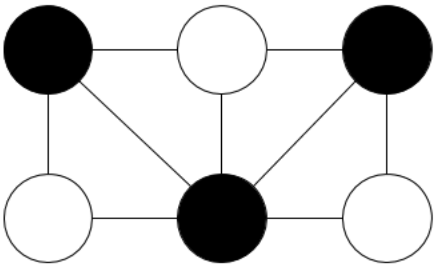

Figure 2.3: m-Dominating Set

2.2.2 Centrality Measure

After describing the importance of Dominating Sets in the formation of our problem, it is crucial to present the theoretical background behind the centrality measure used to establish which nodes are going to form the Connected Dominating Set in the Virtual Backbone. It is necessary to take into consideration that the identification of a node's significance should be fast and low-cost. Therefore, we need a method that could demonstrate the node's importance by relying only on connectivity information of its local neighborhood. For the sake of this goal, we exploit a locally computable measure for the identification of efficient cross layer dominators, where the chosen dominators should be considering both their connectivity in the current layer and to the rest of the layers. The measure chosen for our implementation is clPCI which has been studied in [3]. In order to understand the usefulness of the specific measure we will present some important definitions from previous work.

Definition 2.7

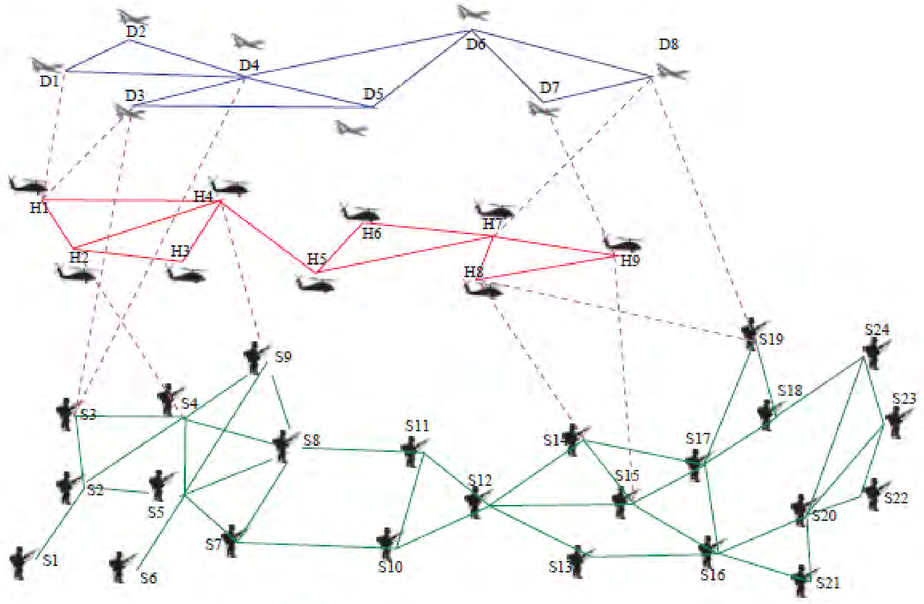

Figure 2.4: (G^{ML}, E^{ML}) Multilayer Network composed by 3 layers. (Image taken from: [11])

The Power Community Index (PCI) [2, 12]index of a node v is the maximum number k, such that there are k 1-hop neighbors of this node with degree larger than or equal to k[9].

Definition 2.8
The Minimal-Layers PCI$_n$ ($mlPCI_n(v)$) index of a node v is the maximum number k, such that there are at least k direct (1-hop) neighbors of v with the number of links towards n different layers greater than or equal to k .
$mlPCI_n$ characterizes a node for its connectivity in a predefined number of layers. We further combine $mlPCI_n$ values for all n, thus defining $mlPCI$ as follows:

$mlPCI(v) = \sum_{i=1}^{\#layers} mlPCI_i(v).$

However, those measures lack the information about the connectivity of the nodes that do not participate in the calculation of PCI. Therefore, in [3] Exhaustive PCI ($xPCI$) was proposed as a measure which calculates for each layer:

- The PCI index for a node,
- A new PCI index, after excluding the nodes that were included for the previous calculation

Then, the two values are added to form the $xPCI$ which has the disadvantage of the large amount of ties that occur during its computation, in order to achieve reasonable values for even for large networks and similar values for nodes with similar connectivity.

Aiming to solve the problem of the resulting ties, research in [3] proposed the multiplication of each PCI value by log_2 of the number of unique links participating in the calculation, leading to the formation of a new measure named Cross-layer PCI ($clPCI$).

2.3 The m-CDS Problem

Let (G^{ML}, E^{ML}) be a given undirected wireless network consisting of multiple different layers. This chapter investigates the problem of m-Connected Dominating Set formation in a distributed manner.

Definition 2.9

The m-Connected Dominating Set (m-CDS) identification for a Multilayer Network in a distributed way such that:

1. The induced subgraph that comprises the CDS is connected with intra- or inter-layer links.
2. Each node that is not a member of the induced subgraph is dominated by at least m nodes in the initial network.
3. Every node has only knowledge of the k-hop neighborhood around it. Here, we set $k = 2$.

Constraint (1) ensures the connectivity of the Multilayer Network and as a result the successful communication between each node that belongs in it, while constraint (3) declares the problem as distributed, since each node will be able to receive information only from the nodes that are at most two hops away from it. Constraint (2) establishes the construction of a robust network where in case of loss of a dominator, its dominatees will not be cut off the network and, thus, the network could maintain its successful information flow. As a result, the m-CDS should provide the network with a robust Virtual Backbone that is resilient to damages.

Chapter 3

Distributed Robust Backbone Formation Algorithm

3.1 Introduction

Tactical Wireless Networks are characterized of a large amount of nodes, frequent changes of topology and repeated destruction of nodes either because of damage or due to opponent's malicious attacks. Consequently, we need to find heuristics that can demonstrate the topology of the network in a fast way while exploiting nodes that are considered to be significant for the achievement of an assured communication flow.

In this chapter we will describe in detail the proposed algorithm for the construction of m-Connected Dominating Sets. As mentioned in previous chapters, for the requirements of this distributed approach to form a robust Multilayer Ad Hoc Network, we exploit the clPCI centrality measure and also the redundancy of the nodes that belong to the Dominating Set. The first one, as mentioned before, ensures that the nodes selected to form the Dominating Set will maintain strategic positions in the Network in order to achieve a successful connectivity and, therefore, functionality. The second one results to an m-CDS which is a fault tolerant Virtual Backbone that can support communication even in cases of node failures, since even if (m-1) dominator nodes fail there will still be a node for the transmission of information.

The suggested algorithm considers in both cases the constraints of the military multilayer ad hoc networks by approaching the problem in a distributed way, since it takes into account only the 1-hop and 2-hop neighborhood of each node for the construction of the Virtual Backbone. Moreover, in both the proposed techniques, the amount and the size of the messages exchanged are not significant and, as a result, the Virtual Backbone formation will be quick and inexpensive, in means of not consuming a large portion of the node's residual energy.

We propose an algorithm named RECLB (Robust Efficient Cross Layer Backbone) which consists of two different phases. In the first phase we use an algorithm that exploits clPCI centrality measure in order to find a 1-Connected Dominating Set on the Multilayer Network and in the Second Phase it calculates (m-1) Maximal Independent Sets, using the clPCI as well, and later adds to the network that occurs from Phase 1. The result is a m-Connected Dominating Set Network in which all nodes in the DS are connected and each node is dominated by at least m nodes.

3.2 1-CDS Construction Phase

Before delving into details of this phase we will provide a short overview of the algorithm used in [3], [11]. The Connected Dominating Set Construction Phase consists of the following two phases:

- *CDS Construction Phase*
- *Redundant Relay Node Pruning*

Prior to these phases taking place, another necessary process needs to be fulfilled. Since the algorithm approaches the problem in a distributed manner, each node u should be able to learn the topology of its $N(u)$ and $N^2(u)$ via the exchange of 'Hello' messages. After discovering the topology, it is necessary for each node to calculate its own clPCI index and to broadcast this value to all its one hop neighbors. Thus, after this step, each node u is aware of each clPCI value in $N(u)$.

When this information is distributed to the nodes, the CDS construction step is initiated with a relay node set selection process that is executed by every node. However, this process leads to a large amount of redundant dominator nodes and a Pruning Phase is needed to reduce the CDS Size [2], [3], [11]. The steps described above lead to the creation of a Connected Dominating Set with efficient Cross Layer Dominators.

3.2.1 clPCI Calculation

In the current dissertation, as described in Section 2.2.2, we make extensive use of a specific centrality measure called clPCI. The current measure is computed locally and it considers the strategic position of a node as its significance in order to be chosen as a dominator. In our case it is used as a ranking mechanism both in the 1-CDS Construction Phase and in the m-CDS Construction Phase.

Algorithm **1** presents a distributed approach for the calculation of the clPCI index for each node in a Multilayer Network which is required for the following phases of our proposed algorithm. The algorithm requires the knowledge of the one-hop ($N(u)$) and two-hop ($N^2(u)$) neighborhood of node u and produces a result of the clPCI calculated for node u by calculating the Exhaustive PCI (*xPCI*) for each node and multiplying it by $log_2(Links_{unique})$.

3.2.2 CDS Construction Phase

CDS Construction Phase (Algorithm 2) is comprised of two parts. The first one is the gathering of all the clPCI index values while the second one is the formation of the CDS. During the first part, all nodes calculate their own clPCI indexes and broadcast them to their $N(u)$ and at the same time receive all their neighbors clPCI values. Then, the values received in each node are sorted in a

Algorithm 1 clPCI index value calculation.

precondition : Known 1-hop ($N(u)$) and 2-hop ($N^2(u)$) neighbor connectivity info (ID) of node u
postcondition : Calculation of the *clPCI* index value of node u
remarks : m = number of layers in the multilayer network, $layer(u)$ = network layer that node u is situated, S = node set, $PCI(u)$, $xPCI(u)$, $clPCI(u)$: indexes related to node u

```
for $layer\ i \leftarrow 1\ to\ m$ do
    $PCI(u) = xPCI(u) = 0$;
    Build $S = u_1, u_2, ..., u_n | u_{k(1 \leq k \leq n} \epsilon N(u), layer(u_{k(1 \leq k \leq n}) = i$ ;
    while $S \neq empty$ do
        Calculate $PCI(u)$ for $S$;
        Calculate unique links ($Links_{unique}$) of nodes participating in $PCI(u)$;
        $xPCI(u) += PCI(u) * log2(Links_{unique})$;
        Remove nodes that participated in $PCI(u)$ from $S$;
        $PCI(u) = Linksunique = 0$;
    end while
    $clPCI(u) += xPCI(u)$;
end for
```

decreasing order and they are later used in the construction step. Since the algorithm is distributed, node u first selects as its relays those 1-hop neighbors that have already been selected as dominators by other neighboring nodes (if any)[2]. The algorithm chooses to include the next node from $N(u)$ with the largest clPCI value which covers at least one new node in $N^2(u)$. The process continues until there are no more nodes in $N^2(u)$ that are not dominated.

3.2.3 Pruning Phase

Such a pruning phase seems quite important in our case because of the amount of redundant nodes that the CDS Construction Phase produces. The algorithm proposed is distributed and it requires knowledge of the domination status of each node. Each relay node waits until it is aware of all its neighbors relay 'status'. The clPCI index is once again used as a ranking mechanism to set priority values aiming to set a total order among nodes participating in the CDS. The complete pruning algorithm is described in detail in Algorithm 3 which was studied and developed in [3], [11] .

3.3 RECLB (m-CDS formation)

In this dissertation we propose an algorithm that uses redundant dominator nodes in order to achieve fault tolerance as well as alternative routing protocols. Moreover, it is a well known fact that Large Wireless Networks, in our case Military Multilayer Ad Hoc Networks, require conservation of energy and also fast formation of the occuring topology, because of their unstable nature. This motivates us to design a distributed algorithm to solve the problem of m-Connected Dominating

Algorithm 2 Relay Node Set Election

precondition : Known 1-hop ($N(u)$) and 2-hop ($N^2(u)$) neighbor connectivity info (ID) of node u
postcondition : Elected relay node set ($R(u)$) of node u
remarks : *clPCI*(u) : index related of node u, $M(u)$: status of node u with regards to being [True (T)]or not [False (F)] a relay node

```
Calculate and broadcast own clPCI index value;
Gather the clPCI index values of the nodes in $N(u)$;
Sort nodes in $N(u)$ in decreasing order of their clPCI index values;
while each node in $N^2(u)$ has at least one neighbor in $N(u)$ do
    Select the node from $N(u)$ with the largest clPCI index value that covers at least one new node in $N^2(u)$;
    Include the selected node in $R(u)$;
end while
Broadcast $R(u)$
if selected as a relay node and $M(u) = F$ then
    $M(u) = T$;
    Broadcast status change;
end if
Update 1 -hop neighborhood node status (if req);
```

Set construction in order to gain a robust network without the depletion of its energy sources.

It is worth mentioning that there is no relevant work of m-CDS construction in the field of Multilayer Networks. Based on this fact, the only research we were able to accomplish in a theoretical level is the one referring to constructing $(k,m)-CDS$ in single layer wireless networks [16].

Before proceeding to the detailed explanation of our proposed algorithm, we will provide a brief overview pointing out its crucial parts. RECLB requires a Connected Dominating Set, which in our case is provided by the process described in the previous section. When all the nodes are aware of their domination 'status', the algorithm may move on to the removal of the dominator nodes from the initial network.

Therefore, the network that remains is comprised of dominatee nodes only. In this phase, a construction of (m-1) Maximal Independent Sets is required so they will be augmented to the initial Multilayer Ad Hoc Network. To create the Maximal Independent Sets *clPCI* is used along with another measurement called effective degree ($deg(u)$) of node u and its unique id ($id(u)$).

Since it is important for the environment of Tactical Networks to design a distributed algorithm, we propose a message-optimal source-initiated algorithm that constructs the (m-1) MISs. In the following section the algorithm is described in detail.

3.3.1 MIS Construction

The construction of (m-1) Maximal Independent Sets for the purposes of the m-CDS formation is a localized procedure that is based on the ranking mechanism chosen.

Algorithm 3 Pruning Phase

precondition : Completed relay node set election process from 1-hop neighbors

postcondition : Node updated status

remarks : $T_{pruning}$: a timer, $S_{constrained}$: a node set, $M(u)$: status of node u with regards to being [True (T)] or not [False (F)] a relay node

```
Start $T_{pruning}$;
Build $S_{constrained} = u_1, u_2, .., u_n | u_{k(1 \leq k \leq n} \epsilon N^{(}u) \bigwedge N^2(u),\ M(u_{k(1 \leq k \leq n}) = T, clPCI(u) < clPCI(W_{k(1 \leq k \leq n})$;
if $S_{constrained}$ is subject to $N(u) \subset N(u_1) \cup N(u_2) ... \cup N(u_n) and u_1, u_2, ..., u_n$ form a connected graph then
    Wait for expiration of $T_{pruning}$;
    if $M(u_{1 \leq k \leq n}) = T$ then
        $M(u) = F$;
        Broadcast status change;
        Exit pruning stage;
    else
        Restart pruning stage;
    end if
else
    $M(u) = T$;
    Broadcast status;
    Exit pruning stage;
end if
```

Let all nodes of a wireless multilayer network be colored white at initialization phase. Each node calculates a tuple of values containing its clPCI, effective degree and id $(clPCI(u), deg(u), id(u))$ and broadcasts it to the nodes belonging in the $N(u)$. Each vertex in the network learns its neighbors tuples via a periodic exchange of 'hello' messages containing those values. Eventually, every node in the network will become either a dominator(black) or a dominatee(gray).

Before proceeding to the algorithm, we need to declare that there are three possible cases for the nodes of the network. There can exist white nodes, which denote the initialization phase and the fact that they have not received any message from either dominators or dominatees. The other categories are black nodes which denote the dominators and gray nodes which denote the dominatees.

A new definition is introduced in order to describe RECLB [17]:

- Effective degree of node u $(deg(u))$. The effective degree of a node is the number of the white nodes of u.

We now proceed to the detailed explanation of RECLB. Initially all nodes are white. After each node u transmits its $(clPCI, deg(u), id(u))$ values to all the nodes in $N(u)$ and it has received all the tuples from the nodes included in $N(u)$, the ranking process can begin.

If node u has the largest *clPCI* compared to all its neighbors' *clPCI*s, it declares itself as a dominator and broadcasts a **BLACK** message to the nodes in $N(u)$. In case more than one nodes have their *clPCI* values equal to *clPCI* of u and it is the largest one in the $N(u)$, u will become dominator only if it is characterized by the largest effective degree $(deg(u))$ value between its one-hop neighborhood. If there still exist ties in the case of $deg(u)$, u will become a dominator node if u has the smallest unique id $(id(u))$ between the nodes in $N(u)$. Whenever a node decides to declare itself as dominator, it broadcasts a **BLACK** message to its one hop neighbors to inform them about the status change.

Upon receiving a **BLACK** message from its neighbor v, a white node u turns from color white to gray and broadcasts a **GRAY** message to its one-hop neighbors. There occurs a specific case in which a node can have no neighbors after the removal of the dominator nodes from the 1-CDS construction phase. In this scenario, the node colors itself gray and transmits a **GRAY** message to the nodes in its $N(u)$. We choose to color this kind of nodes with gray, since if they appear to have no connections to any neighbors we consider that all of their 1-hop neighbor nodes in the initial topology are dominators. Therefore, they are probably dominated and they get colored gray because of this fact. Additionally, if a node has only gray neighbors, we consider that it should be a dominator since it could have no dominators for itself. So, the specific node is colored black and broadcasts a **BLACK** message.

When a white node u receives either a **GRAY** or a **BLACK** message, u decrements its effective degree $deg(u)$ by 1 and broadcasts its new value of $deg(u)$. The procedure will terminate when each node of the network is colored either gray or black, leading to a Maximal Independent Set where there is no node that is not dominated by at least one dominator node. Details of Algorithm **4** are shown in the scheme following.

In scheme .. we can observe the initial phase (a) where all nodes are colored white and the MIS that occurs after applying the proposed algorithm(b)

Algorithm 4 Maximal Independent Set Construction

precondition : 1-Connected Dominating Set produced by Algorithms 2 and 3

postcondition : A Maximal Independent Set with every node colored either gray or black

remarks : $deg(u)$: the effective degree of node u = the number of white neighbors of u, *clPCI* of node u: the centrality indicator for node u, $id(u)$, the unique id of node u, *NG*: the resulting graph after removing dominator nodes, $N(u)$: the one-hop neighborhood of node u.

```
Build NG = The initial network after removing all the dominator nodes from phase one;
Color all nodes white;
Calculate clPCI for each node u in NG;
Calculate $deg(u)$ for each node u in NG;
while There are no more white nodes in NG do
    for Each node u in NG do
        if Node u has no neighbors then
            Color node u gray and broadcast GRAY message to its $N(u)$.
        end if
        if Node u has only GRAY neighbors then
            Node u broadcasts BLACK message to its $N(u)$ and becomes dominator.
        end if
        for Each node $u_k$ in $N(u)$ do
            if $clPCI(u) > clPCI(u_k)$ then
                Become dominator and broadcast BLACK message to $N(u)$
            else
                if $clPCI(u) = clPCI(u_k) = max(clPCI)$ then
                    if $deg(u) > deg(u_k)$ then
                        Become dominator and broadcast BLACK message to $N(u)$
                    else
                        if $deg(u) = deg(u_k)$ then
                            if $id(u) < id(u_k)$ then
                                Node u becomes dominator and broadcast BLACK message to $N(u)$
                            end if
                        else
                            Node $u_k$ becomes dominator and broadcasts BLACK message
                        end if
                    end if
                end if
            end if
        end for
    end for
end while
```

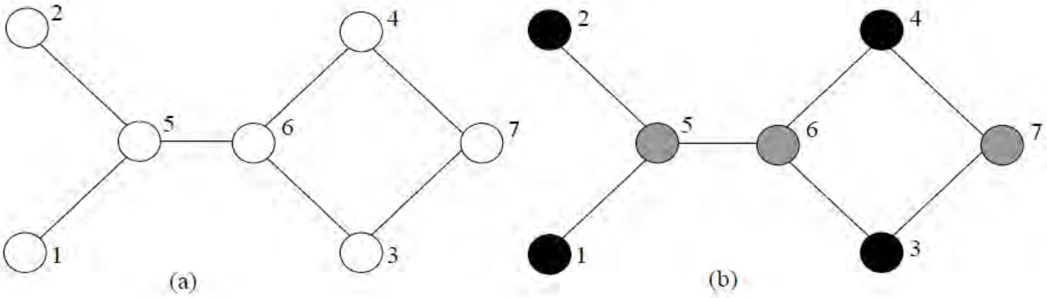

Figure 3.1: (a) Initialization status, (b) Formed Maximal Independent Set

3.3.2 RECLB Algorithm

At this point we have extensively discussed about the details of the two phases of our RECLB. We may now proceed to the combination of the two phases in order to produce our final algorithm for the construction of the *mCDS*. The main idea for this purpose consists of the *CDS* discovery of the Multilayer Ad Hoc Network, at first, and of the augmentation of the resulting *CDS* with $(m-1)$*MIS*s, so as to guarantee that each node that does not belong in the Dominating Set, is adjacent to at least m dominators.

Phase 1 leads to the construction of a 1-Connected Dominating Set which has included efficient cross layer dominators due to the use of *clPCI* centrality measure. The 1-Connected Dominating Set assures that each dominatee is dominated by at least 1 node and the dominator nodes are connected.

Phase 2 constructs a Maximal Independent Sets by using once again *clPCI* along with the effective degree of a node and its unique id. This procedure is repeated $(m-1)$ times. In our case we considered $m = 2$. After each MIS is formed, it is augmented to the whole network. Finally, our network is formed as an m-Connected Dominating Set after having complete the process described in Algorithm **5** which is executed by each node u.

To this point, RECLB algorithm has been presented properly and in detail. In the following section we will describe the algorithm that we chosen as the competitor in order to compare their results and performance in Multilayer Ad Hoc Networks.

3.4 r-CDS Algorithm

For the purposes of this research, we used an algorithm developed for the creation of Maximal Independent Sets [17] which constituted the basis of the idea that we exploited in our recommended algorithm. However, since there is not yet any work on the construction of m-Connected Dominating Sets in Multilayer Ad Hoc Networks, the r-CDS algorithm does not take into consideration any layer. As a consequence, this algorithm treats the whole Multilayer Network as if it was a Single Layer Network.

The algorithm is completely localized 1-phase algorithm in which each node needs to be aware only of the connectivity information within its two-hop neighborhood $N^2(u)$. Before proceeding to the analysis of the r-CDS algorithm, it is required that we denote some notations for the process.

Algorithm 5 m-CDS Construction

```
postcondition : A connected dominating set where each dominatee is dominated by at least $m = 2$ nodes.
remarks : clPCI: the centrality measure of node $u$, $deg(u)$: effective degree of node $u$, $id(u)$: unique identifier of node $u$, $N(u)$: the one-hop neighborhood of node $u$.
Exchange of 'hello' messages in order to discover the topology of $N(u)$ and $N^2(u)$.
Calculate clPCI index of node $u$ and broadcast it to $N(u)$.
1-CDS Construction Phase using clPCI indexes.
for (m-1) times do
    Remove the dominators from the initial network and set a new network NG containing only WHITE nodes.
    Calculate the tuple $(clPCI(u), deg(u), id(u))$ of node $u$ and broadcast it to the $N(u)$.
    The node $u$ compares its tuple with the tuples of $N(u)$ nodes and decides if it is going to broadcast BLACK and become a dominator or GRAY and become a dominatee.
    After MIS is created, mark the corresponding nodes in the initial network as dominators.
end for
```

- $d(u)$ is the degree of node *u*, that is the number of nodes in its one-hop neighborhood $N(u)$

- $deg(u)$ is the effective degree of node *u* and is equal to the number of white one hop neighbors of *u*

- $r(u)$ is the number of 2-hop neighbors - $d(u)$. It is referred to as *r* for brevity

- $N(u)$ is the one hop neighborhood of *u*

Since the approach performed in a distributed manner, the first part of the algorithm consists of the exchange of messages for the acknowledgment of the connectivity information. When the topology in the local neighborhood of each node is known, the calculation of *r* can begin. Finally, all nodes comprising the network are aware of their status about being whether a dominator or a dominatee.

In the beginning, all nodes are colored white. After having calculated the *r* value, each node *u* transmits it along with its $deg(u)$ and $id(u)$. Upon receiving all of the information about the r values of all the one hop neighbors, the coloring process is developed. If a node *u* has the smallest *r* value compared to its neighbors' *r* values, *u* becomes a dominator and broadcasts a **BLACK** message. If there exist ties in the *r* comparison, *u* will color itself black if *u* has the largest $deg(u)$. After that, if there still exist any ties, *u* will become a dominator if *u* has the smallest $id(u)$.

Upon receiving a **BLACK** message from its neighbor *v*, a white node *u* is colored grey and *u* broadcasts a *GRAY* message. Upon receiving a **GRAY** message or a **BLACK** message, a white node *u* decrements its effective degree $deg(u)$ by 1 and broadcasts $deg(u)$. A more detailed description on the proofs of correctness can be found in [17]. The scheme following represents Algorithm **6**.

Algorithm 6 Maximal Independent Sets Construction by r-CDS

1-Connected Dominating Set produced by Algorithms 2 and 3

postcondition : A Maximal Independent Set with every node colored either gray or black

remarks : $deg(u)$: the effective degree of node u = the number of white neighbors of u, $r(u)$, or r of node u: the difference between the number of 2-hop neighbors minus the degree of node u, $id(u)$, the unique id of node u, $N(u)$: the one-hop neighborhood of node u.

```
Calculate $r$ for each node $u$;
Calculate $deg(u)$ for each node $u$;
Broadcast tuple $(r, deg(u), id(u))$;
while There are no more white nodes in the network do
    for Each node $u$ do
        for Each node $u_k$ in $N(u)$ do
            if $r(u) < r(u_k)$ then
                Become dominator and broadcast BLACK message to $N(u)$
            else
                if $r(u) = r(u_k) = max(r)$ then
                    if $deg(u) > deg(u_k)$ then
                        Become dominator and broadcast BLACK message to $N(u)$
                    else
                        if $deg(u) = deg(u_k)$ then
                            if $id(u) < id(u_k)$ then
                                Node $u$ becomes dominator and broadcast BLACK message to $N(u)$
                            end if
                        else
                            Node $u_k$ becomes dominator and broadcasts BLACK message
                        end if
                    end if
                end if
            end if
        end for
    end for
end while
```

3.5 Computational Cost

In order to evaluate our decisions for the measures and topologies included in the proposed algorithm we first need to cover their computational cost complexities. In the following sections we provide some details gathered from various publications, since we are interested in providing efficient changes that are also considering the complexity of computations. Then, we provide the complexity for our proposed technique in the formation of MIS.

3.5.1 clPCI index [3]

The computation complexity of clPCI index calculation is $O(\Delta^2)$ in the worst case, where Δ is the maximum node degree in the network. clPCI is used both in the CDS Construction Phase and in the m MISs Construction Phase.

3.5.2 CDS Construction Phase [3]

The computation complexity of the relay node set election process is $O(\Delta^3)$, where Δ is the maximum vertex degree in the network.

3.5.3 Pruning Phase [3]

The computation complexity of the pruning phase is $O(\Delta^3)$, where Δ is the maximum vertex degree in the network.

3.5.4 m-CDS Construction Phase

Proposition 3.1. The computational complexity of (m-1) MISs construction produced by the proposed algorithm is $O(\Delta^2)$

Proof 3.1. The MIS formation requires each node to compare itself with its 1-hop neighborhood in order to decide whether it is going to denote a dominator or not. Thus, each node compares itself with Δ nodes in the worst case, where Δ is the maximum vertex degree of the network and the computational complexity is $O(\Delta)$ ([16], [18], [15]). As a result, for (m-1) MISs the complexity is $O((m-1)\Delta)$. Consequently, the computational cost of the m-CDS which includes the computation of clPCI would be equal to $O((m-1)\Delta + \Delta^2) \approx O(\Delta^2)$.

Proposition 3.2. The computational complexity of an m-CDS construction phase is $O(\Delta^3)$

Proof 3.2. As mentioned in proposition 3.1, the computational complexity of the (m-1) MISs construction produced by the proposed algorithm is $O(\Delta^2)$. Moreover, The CDS construction phase, which is the first phase of the proposed algorithm, has a computational complexity of $O(\Delta^3)$ and the pruning phase has also computational complexity of $O(\Delta^3)$. Therefore, the m-CDS formation's computational complexity is of $O(\Delta^2 + \Delta^3 + \Delta^3) \approx O(\Delta^3)$.

Chapter 4

Performance Evaluation and Comparisons

4.1 Introduction

This chapter includes the evaluation of the algorithm proposed in Chapter **3** by applying it on various cases of Networks. The topology, size and number of layers of each network varies in our experiments, since more general observations on the robustness of the network are required. Additionally, the Competitor algorithm is also used in more experiments on the same set of Multilayer Networks. Our motive is to illustrate the correctness of an m-Connected Dominating Set formation in Tactical Ad Hoc Networks according to the matter of improved robustness compared to other approaches.

4.2 Performance Measures

In the interest of estimating the impact of the proposed algorithm in the robustness of Tactical Wireless Networks, we will define some metrics that demonstrate whether it benefits the resulting network or not. Each one of the performance measures is used to examine different aspects of the network's functionality and they are described below for each category. Before we proceed to the details of the evaluation metrics, we need to declare a definition which is extensively used in this chapter.

Definition 4.1
A node is characterized as m-dominated if it is adjacent to at least m dominators.

Note: The performance measures concerning the robustness are examined when an $m-CDS$ is formed after the application of our algorithm and also after an amount of nodes is ”killed”.

Next, we provide a list of the evaluation metrics that we adopted to present the results of RECLB algorithm.

1. **Performance measures for the robustness of the network:**

- Percentage of nodes that are not 1-dominated.
- Percentage of nodes that are not 2-dominated.
- Percentage of nodes that are not 3-dominated.

2. **Performance measures for the effectiveness of the dominating set:**
   - Connected Dominating Set Size.
   - The amount of connections of the nodes that are added in the Maximal Independent Set construction phase and, specifically, the percentage of the connections of the nodes to nodes in other layers and the percentage of the connections towards nodes in the same layer.

We suggest that in terms of robustness of the resulting network, the algorithm which is more efficient is the one where the smallest available percentage of nodes is not m-dominated, where $m = 1, 2, 3$. This suggestion applies in both cases before and after removing random nodes from the Network. Additionally, about the effectiveness of the resulting backbone, we characterize as a better choice the *CDS* with smaller size compared to the one with bigger size, since it implies an infrastructure with reduced volume of broadcast message transmissions, and subsequently less node intereference, bandwidth usage and saving energy for the nodes. Finally, we denote as a more efficient *DS* the one where the dominators are positioned strategically in order to exploit both their connectivity with as many nodes as possible and their connectivity with as many layers as possible.

4.2.1 Datasets

A generator for multilayer networks was developed in [12], because of the absence of publicly available, real-world tactical multilayer networks. In order to approach in a more realistic way where obstacles distract the communication flow, this generator produces non-uniform intra-layer network models with a variety of multilayer network topologies with varying network size, degree, diameter and number of layers. Table 4.1 depicts the various values of the network construction varying parameters mentioned above for small networks and table 4.2 for large networks.

Parameter	Range
Average Node Degree	3, 6, 10, 15, 20
Network Diameter	3, 5, 8, 12, 17
Amount of Layers	2, 3, 4, 5, 7

Table 4.1: Experimental parameters for small networks.

4.3 Experimental Results

In this section we will present the numerical results concerning the effectiveness of the $m-CDS$ constructed by the proposed algorithm. The datasets used for the current algorithms can be

Parameter	Range
Average Node Degree	6, 10, 12
Network Diameter	10, 20, 40
Amount of Layers	2, 3, 4

Table 4.2: Experimental parameters for large networks.

divided into two categories: (*i*) the small networks with number of nodes from 100 to 500, (*ii*) the big networks from 1000 to 2000 nodes. For the purposes of the evaluation we performed various experiments to test the performance of our algorithm and we choose to test the challenges regarding to robustness, connectivity and *CDS* size. In order to properly evaluate the results we chose to apply two different ways of 'attacks' to remove nodes from the network and we will present different results for each one of them. One approach is the 'termination' of random dominator nodes in both networks and the alternative is the 'termination of random nodes in both networks.

4.3.1 Results for robustness

- **Robustness of Multilayer Network** First of all, we will evaluate the effect of RECLB in terms of robustness. The experiments performed for this matter are considering the amount of nodes that remain without at least 3 dominators after constructing a 2-CDS of a Multilayer Network. The results show that RECLB leads to networks with a small amount of nodes that are not also 3-dominated, for the cases evaluated. Therefore, after examining the tradeoff between the CDS size and the amount of nodes that are 3-dominated, we decided that the formation of a 3-CDS is not considered necessary for such cases of networks.

- **Comparison of robustness between 1-CDS and 2-CDS**

  In this section, we will present the results of our experiments with regard to the robustness of the network. Before proceeding to the comparison of the performance of both algorithms explained in Chapter 3, we will illustrate the correctness of our approach to form a 2-Connected Dominating Set as a mechanism for the establishment of a more robust Multilayer Network by comparing the effect of destroying nodes in the 1-CDS formed by the initial phase and in the 2-CDS which is produced at the second phase. Tables 4.3, 4.4 and 4.5 depict the effect of varying network degree, diameter and amount of layers respectively on the robustness of the $m - CDS$ produced by RECLB, while tables 4.6, 4.7 and 4.8 illustrates the same for cases of larger networks. In both cases two kinds of evaluations took place. The first one considers removing only dominator nodes from both networks and the second one removes random nodes from both networks.

  As observed in the the above mentioned tables, RECLB leads to a 2-CDS where only an average of 0% of the nodes remains without a dominator after removing nodes either by targeting dominator or random nodes of the network, while the average of nodes remaining undominated in the 1-CDS is in the first case 10.3% and 0.5% in the second. Moreover, there

Parameter	Value	1-CDS (D)	2-CDS (D)	1-CDS (R)	2-CDS (R)
Degree	3	4%	0%	1%	0%
	6	8%	0%	0%	0%
	10	13%	0%	0%	0%
	15	22%	0%	0%	0%
	20	26%	0%	0%	0%
Diameter	3	11%	0%	1%	0%
	5	12%	0%	1%	0%
	8	10%	0%	1%	0%
	12	8%	0%	1%	0%
	17	7%	0%	1%	0%
Layers	2	9%	0%	1%	0%
	3	9%	0%	1%	0%
	4	9%	0%	1%	0%
	5	9%	0%	1%	0%
	7	10%	0%	1%	0%

Table 4.3: Percentage of nodes that are not at least 1-dominated for small networks in the cases of removing (a) random dominators from 1-CDS, (b) removing random dominators from 2-CDS, (c) removing random nodes from 1-CDS and (d) removing random nodes from 2-CDS.

exists a significant difference in the amount of nodes that remain not 2-dominated after the termination of nodes in the 1-CDS and in the 2-CDS. The 1-CDS leads to an average of 35.6% of not 2-dominated nodes after removing dominators from the network and 19.3% after removing random nodes, while in the case of 2-CDS there remain respectively 2.8% and 0.6% nodes that are not 2-dominated. Finally, the nodes that remain without 3 dominators are also a lot more in the cases of 1-CDS compared to the corresponding amount in the 2-CDS after removing nodes in both ways mentioned. Specifically, the average rises to 70.8% in the case of attacking dominators and is equal to 54.9% when terminating random nodes in the 1-CDS and lowers to 19.9% and 12.9% respspectively for the 2-CDS. Another note would be that the results are slightly better in the case where we remove random nodes and not only dominators from both networks, which is logical to imply since in the first approach there could be both dominators and dominatees while in the second there are only dominators. It is, also, worth mentioning that without trying to construct a 3-CDS, most nodes in the network (percentage) are also 3-dominated after the application of the 2-CDS creation. As a first observation, we assume that the formation of a 2-CDS compared to a 1-CDS is more robust in terms of the amount of dominators that are adjacent to a node in the network.

- **Comparison of results between RECLB and r-CDS**

  After having shown that the formation of an m-CDS constitutes an effective approach in terms of robustness, it is necessary to compare the effectiveness of RECLB to the r-CDS's

Parameter	Value	1-CDS (D)	2-CDS (D)	1-CDS (R)	2-CDS (R)
Degree	3	36%	7%	29%	6%
	6	42%	4%	27%	1%
	10	48%	3%	24%	0%
	15	55%	2%	19%	0%
	20	54%	3%	13%	0%
Diameter	3	48%	0%	29%	0%
	5	51%	0%	36%	0%
	8	49%	0%	34%	0%
	12	45%	0%	31%	0%
	17	40%	0%	31%	0%
Layers	2	49%	5%	34%	1%
	3	46%	5%	32%	1%
	4	44%	5%	29%	1%
	5	44%	4%	28%	1%
	7	47%	4%	31%	1%

Table 4.4: Percentage of nodes that are not at least 2-dominated for small networks in the cases of removing (a) random dominators from 1-CDS, (b) removing random dominators from 2-CDS, (c) removing random nodes from 1-CDS and (d) removing random nodes from 2-CDS.

concerning the construction of the Maximal Independent Sets. To accomplish this, we will compare the effects of the 'destruction' of nodes from the network, in a random way as well as choosing random dominators, and we will graphically depict how both the algorithms behave in this matter. Tables 4.9, 4.10 and 4.11 show the percentage of nodes that remain without at least $1, 2$ and 3 dominators after the 'termination' of a set of nodes respectively.

In this case we observe similar results for both algorithms in terms of robustness. We recognize that both networks behave almost the same in all of the networks when compared to each other. Therefore, it is not easy to indicate one algorithm as the one that is more effective for the MIS construction so far. To this end, we will investigate other aspects of the network functionality in the following chapters to identify which algorithm fits the problem in a more efficient way.

4.3.2 Results for CDS Size

Another performance measure that is crucial to determine whether an Ad Hoc Network is effective or not is the produced size of the Connected Dominating Set. The desirable is the smaller size possible due to the fact that it leads to the reduction of information transmission traffic, the limited usage of the bandwidth and it therefore turns the communication flow of the network to be more efficient. The evaluation of this performance measure will occur by the comparison of the CDS sizes produced from both RECLB and r-CDS algorithms. Moreover, various cases of

Parameter	Value	1-CDS (D)	2-CDS (D)	1-CDS (R)	2-CDS (R)
Degree	3	69%	20%	62%	17%
	6	63%	24%	60%	17%
	10	75%	16%	54%	7%
	15	79%	13%	49%	4%
	20	77%	13%	37%	2%
Diameter	3	78%	25%	63%	16%
	5	80%	25%	67%	17%
	8	76%	25%	63%	17%
	12	75%	24%	64%	18%
	17	67%	24%	57%	19%
Layers	2	79%	30%	68%	21%
	3	75%	27%	63%	20%
	4	72%	27%	58%	19%
	5	74%	24%	61%	18%
	7	74%	23%	59%	15%

Table 4.5: Percentage of nodes that are not at least 3-dominated for small networks in the cases of removing (a) random dominators from 1-CDS, (b) removing random dominators from 2-CDS, (c) removing random nodes from 1-CDS and (d) removing random nodes from 2-CDS.

networks will be examined in order to determine whether the network topology formation could be generally applicable in order to protect the Multilayer Network from the disruption of information spreading by opponents or disasters. Figure 4.1 shows the resulting CDS size with respect to the two algorithms.

The figure above illustrates that in all of the cases of network sizes and topologies, RECLB leads to the formation of a smaller by an average of 2.7% of CDS size when compared to r-CDS algorithm. This is due to the fact that the competitor algorithm is layer agnostic while our approach exploits the both the connectivity of the nodes to other nodes in the layer they belong and to nodes belonging to other layers. Centrality measure *clPCI* seems to improve the CDS size because of its preference for nodes with strategical in the network positions which, consequently, cover more nodes in the network leading to a smaller amount of nodes comprising the CDS.

4.3.3 Result for Connectivity

Finally, it is required to examine the connectivity of the nodes chosen to form the Connected Dominating Set since a network comprised of nodes with more a more balanced amount between links to the belonging layer and links to other layers seems to constitute a more adequate approach for this problem. To investigate this subject, we applied both RECLB and r-CDS in a series of networks with varying characteristics and sizes and, then, we analyzed both their behaviours. In figures 4.2 and 4.3 the average percentage of the amount of links towards nodes in the same layer

Parameter	Value	1-CDS (D)	2-CDS (D)	1-CDS (R)	2-CDS (R)
Degree	6	7%	0%	0%	0%
	10	11%	0%	0%	0%
	12	13%	0%	0%	0%
Diameter	10	13%	0%	0%	0%
	20	12%	0%	0%	0%
	40	3%	0%	0%	0%
Layers	2	4%	0%	0%	0%
	3	8%	0%	0%	0%
	4	8%	0%	0%	0%

Table 4.6: Percentage of nodes that are not at least 1-dominated for large networks in the cases of removing (a) random dominators from 1-CDS, (b) removing random dominators from 2-CDS, (c) removing random nodes from 1-CDS and (d) removing random nodes from 2-CDS.

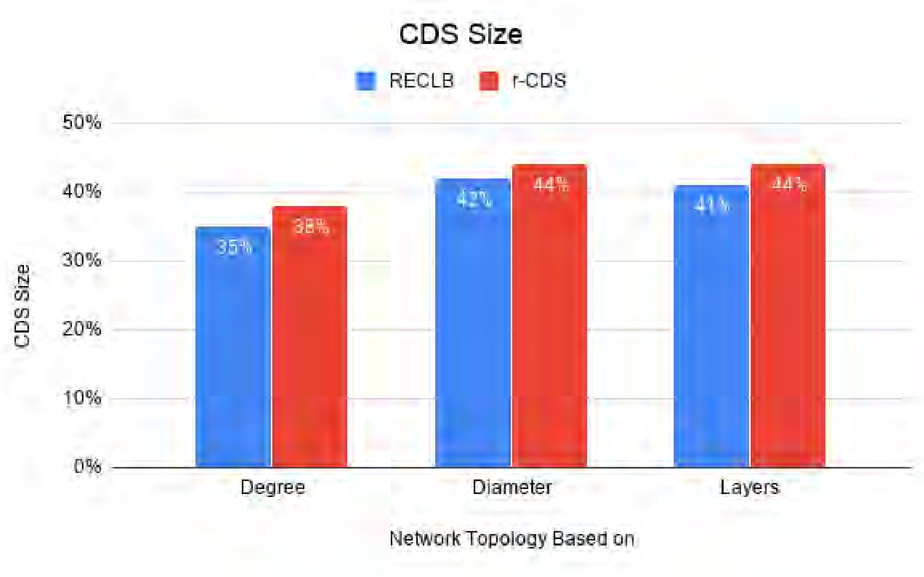

Figure 4.1: Chart showing the produced CDS size for both algorithms with respect to network degree, diameter and number of layers.

and towards nodes in different layers can be observed.

As depicted in the charts of the figures, RECLB algorithm provides backbones with better connectivity of their nodes, and therefore improved communication and more efficient information dissemination, by including dominators with an average of 5.7% less links to nodes towards the same layer and 5.7% more links to nodes towards different layers. This conclusion comes of the extensive use of *clPCI* for the formation of the CDS in the first phase as well as the MIS in the second phase, since *clPCI* takes into consideration the connectivity to other layers and to the current layer.

Parameter	Value	1-CDS (D)	2-CDS (D)	1-CDS (R)	2-CDS (R)
Degree	6	37%	1%	22%	0%
	10	41%	4%	19%	0%
	12	43%	4%	19%	0%
Diameter	10	44%	5%	23%	0%
	20	43%	4%	22%	0%
	40	27%	3%	20%	3%
Layers	2	31%	1%	20%	0%
	3	39%	2%	25%	0%
	4	37%	2%	23%	0%

Table 4.7: Percentage of nodes that are not at least 2-dominated for large networks in the cases of removing (a) random dominators from 1-CDS, (b) removing random dominators from 2-CDS, (c) removing random nodes from 1-CDS and (d) removing random nodes from 2-CDS.

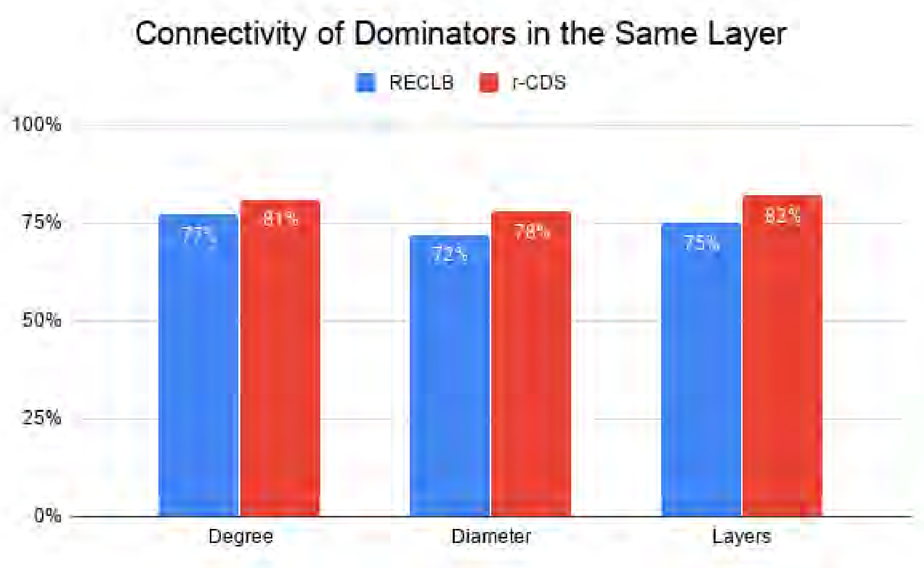

Figure 4.2: Chart that shows the connectivity of dominators to nodes in the same layer.

4.4 Conclusion

To sum up, the previous sections described and illustrated graphically in detail various case of networks and the results of our algorithm and other algorithms applied to them. First of all, we conclude to the fact that the approach of the $m - CDS$ construction in terms of robustness is an interesting option, due to the significant reduction of the nodes that remain undominated by at least 2 or 3 nodes before and after the 'termination' of network nodes. As for the comparison of the two algorithms constructing the *MIS*s, the main consequence is that both algorithms behave the same way in corresponding cases of networks. However, we attempt to support that the use of *clPCI* in RECLB instead of the *r* value in the r-CDS algorithm as a part of the ranking mechanism of the

Parameter	Value	1-CDS (D)	2-CDS (D)	1-CDS (R)	2-CDS (R)
Degree	6	64%	11%	49%	7%
	10	69%	18%	46%	9%
	12	68%	17%	44%	7%
Diameter	10	70%	21%	49%	11%
	20	69%	19%	47%	10%
	40	55%	14%	47%	12%
Layers	2	61%	10%	50%	7%
	3	66%	15%	51%	11%
	4	65%	13%	49%	9%

Table 4.8: Percentage of nodes that are not at least 3-dominated for large networks in the cases of removing (a) random dominators from 1-CDS, (b) removing random dominators from 2-CDS, (c) removing random nodes from 1-CDS and (d) removing random nodes from 2-CDS.

Parameter	RECLB (D)	r-CDS (D)	RECLB (R)	r-CDS (R)
Degree	0%	0%	0%	0%
Diameter	0%	0%	0%	0%
Layers	0%	0%	0%	0%

Table 4.9: Percentage of nodes that are not at least 1-dominated for large networks in the cases of removing (a) random dominators in RECLB algorithm, (b) removing random dominators in r-CDS algorithm, (c) removing random nodes in RECLB algorithm and (d) removing random nodes in r-CDS algorithm.

nodes leads to the inclusion of nodes with more strategical position and with improved connectivity in the Dominating Set, compared to the ones occuring from the competitor. Therefore, because of the reduced *CDS* size, the better connectivity of the backbone's nodes and the almost equal results in terms of robustness, we tend to believe that RECLB provides a preferable result to our problem.

Parameter	RECLB (D)	r-CDS (D)	RECLB (R)	r-CDS (R)
Degree	4%	4%	1%	1%
Diameter	4%	4%	2%	2%
Layers	4%	3%	2%	2%

Table 4.10: Percentage of nodes that are not at least 2-dominated for large networks in the cases of removing (a) random dominators in RECLB algorithm, (b) removing random dominators in r-CDS algorithm, (c) removing random nodes in RECLB algorithm and (d) removing random nodes in r-CDS algorithm.

Parameter	RECLB (D)	r-CDS (D)	RECLB (R)	r-CDS (R)
Degree	17%	17%	9%	10%
Diameter	17%	17%	16%	16%
Layers	23%	21%	16%	16%

Table 4.11: Percentage of nodes that are not at least 3-dominated for large networks in the cases of removing (a) random dominators in RECLB algorithm, (b) removing random dominators in r-CDS algorithm, (c) removing random nodes in RECLB algorithm and (d) removing random nodes in r-CDS algorithm.

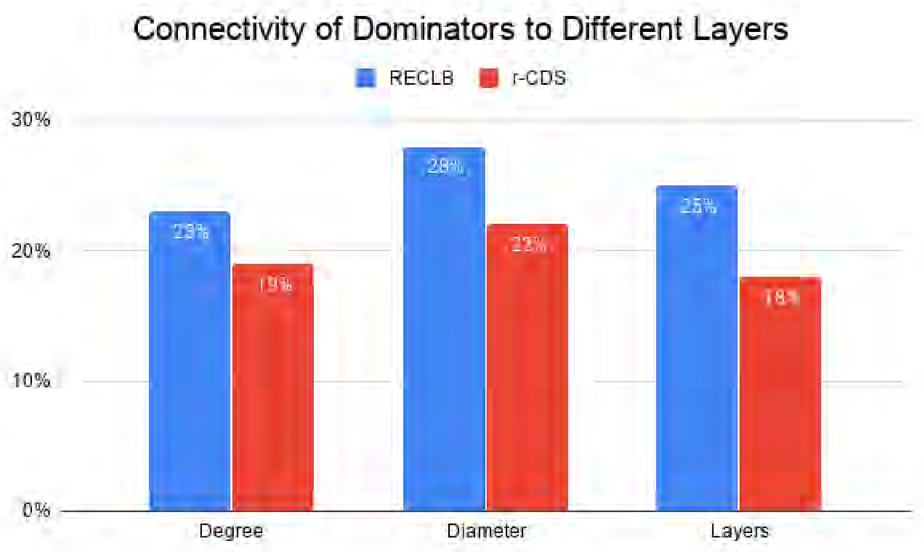

Figure 4.3: Chart that shows the connectivity of dominators to nodes in different layers.

Chapter 5

Technical Details

5.1 Implementation

The implementation of both algorithms and the experiments for the purpose of a backbone formation with improved robustness were conducted using Python[13]. Python is a high-level, general purpose programming language that provides the user with the ability to work quickly and integrate systems in a more effective way. It comes with a variety of libraries for different functionalities. In our case, we exploited some parts of a library which is presented next for the easier manipulation of larger networks. Additionally, we utilized two frameworks for the visualization of our results.

NetworkX [8]
NetworkX is a free software package of Python used for the creation, manipulation, and study of the structure and functions of complex networks. More specifically, it provides

- Storage mechanisms for graphs with nodes, edges and custom characteristics for each one of them according to the developer's will and the networks requirements.
- Functions for retrieving and updating the attributes of nodes and edges, accessing the neighbors of each node, collecting the edges adjacent to a node, removing and adding edges and nodes and more.
- The ability to interact easily with large nonstandard data sets.
- A standard programming interface and graph implementation that is suitable for many applications.
- An interface to existing numerical algorithms and code written in C, C++, and FORTRAN.
- Visualize standard and nonstandard networks graphically with variable options.

Google Sheets [5]
For the purposes of RECLB's results evaluation and its comparison with r-CDS algorithm, we utilized a number of functionalities from the Google Sheets software. Among those functionalities there are Charts and Drawings used to properly characterize our experimental results. Google

Sheets provides a free software that includes almost all of a spreadsheet's functions, is compatible with Google Drive, Docs, and Slides to share files, documents, and presentations online.

In the current dissertation, we created Column Charts for the illustration of the resulting CDS size and the connectivity of the dominators using data for both RECLB and r-CDS algorithms. Moreover, we illustrated graphically examples for the definitions of Dominating Sets theory in order to show an example that would make it easy for the reader of this paper to understand the difference between the current terms.

LaTeX [6]

In order to explain in more detail the experiments regarding the robustness of the resulting networks, we utilized the capabilities of LaTeX. LaTeX is a free, high-quality typesetting system which is designed for the production of technical and scientific documentation. It includes a variety of libraries for various purposes such as mathematical expressions, tables, pseudo-code for algorithms, image integration and more.

The current dissertation is documented using mainly LaTeX. Specifically, we used tables for the illustration of the results and the comparisons for the evaluation of robustness. Moreover, we utilized a package for the visualization of the pseudo-code of RECLB algorithm, as well as for the r-CDS algorithm.

Chapter 6

Summary

6.1 Conclusion

In this dissertation we considered the problem of constructing robust backbones for networks used in military environments utilizing the theory of Connected Dominating Sets. Those environments are constructed as Multilayer Ad Hoc Networks composed by multiple subnetworks, each one denoting a layer with entities of a specific category. The challenge of robustness consists an important factor in the dissemination of information between allied entities and the efficient operation of military management systems.

We proposed an algorithm for the formation of robust backbones which defines, for the first time in the literature, the problem of m-CDS in multilayer networks. Our algorithm exploits cross-layer PCI as the centrality measure used for the determination of dominators in the 1-CDS construction and also in the ranking of nodes in the construction of the m MISs that are augmented to the 1-CDS to form an m-CDS. The experimental evaluation we performed shows that the approach of the m-CDS problem improves the robustness of a network in a way that even if (m-1) dominators of a node fail, there will still be one to spread the information and, consequently, the network communication will probably not get lost that easily.

Even though there is no prior work to this subject, we employed an algorithm as the competitor [17] which varies from approach in the construction of the m MISs by using a measure different from clPCI. In all the experiments, the results illustrated the correctness of both algorithms in terms of robustness, since the results were almost equal. However, each experiment has shown that the CDS size produced by our algorithm is smaller that the one by the competitor and, also, the connectivity of the dominators to different layers in seems to be more satisfying in our approach. As a result, the winning algorithm for the performed experiments occurs to be the one we proposed.

6.2 Future Work

To this end the improvement of the robustness of backbones in multilayer networks will be a core part of our future directions. Our future approach will investigate the formation of the (k, m)-CDS in terms of establishing a more robust backbone. So far, there have been studies on the development of the (k,m)-CDS Problem only in single layer Ad Hoc Networks in [16], [18], [15]. This concept would augment the algorithm we proposed by identifying at least k mutually independent paths between each pair of nodes for the network. Therefore, even if (k-1) links get destroyed by the adversary, the communication between the nodes will remain.

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