Dynamic Cybersecurity Modelling and Analysis

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Abstract

It is difficult to assess the security of modern networks, such as Cloud and software defined networks, because they are usually dynamic with configuration changes (e.g., changes in topology, firewall rules, *etc*). Graphical security models, such as Attack Graphs and Attack Trees, are widely used to systematically analyse the security posture of network systems using various security metrics. However, there are challenges in using them (i.e., the graphical security models and security metrics) to assess the security of dynamic networks. First, the existing graphical security models are unable to capture dynamic changes occurring in the networks over time. As a result, there is a lack of techniques to efficiently capture and manage the security changes that are happening in dynamic networks.

Secondly, the existing security metrics which are used with the models are not designed for the analysis of dynamic networks, and hence their effectiveness to the dynamic changes in the network remains unclear. Moreover, they may not quantitatively represent the changes in the security posture of the dynamic networks.

Thirdly, finding the optimal security solution for the dynamic networks is a difficult task due to their complexity and uncertainty of changes made. That is, an optimal solution for the current network configuration may not be optimal when the dynamic network changes in the future. As a result, it is difficult to select the best set of security solutions to deploy for modern networks that are dynamic. This thesis aims to address the aforementioned issues in three primary goals: (1) to develop an adaptable graphical security model to

capture changes in dynamic networks, (2) to develop new security metrics that can effectively represent the security posture of dynamic networks, and (3) to develop optimal security hardening selection methods for dynamic networks taking into account multiple objectives and constraints.

To achieve the goal (1), two variant security models namely Temporal-Hierarchical Attack Representation Model (T-HARM) and Time-Independent HARM are proposed. The main idea behind the T-HARM is to capture and assess the security posture of the dynamic network at every time t, where the frequency of measurements could be time driven, event-driven or user-driven. On the other hand, the Time-Independent HARM is developed to provide an overview of the security posture of dynamic networks by aggregating all the observed multiple security states (i.e., without showing the multiple GSMs generated for every t).

To achieve the goal (2), first, a systematic classification of the different type of network and security changes is presented. Based on the network changes, an evaluation of the existing security metrics is performed in order to identify which ones are suitable for the analysis of dynamic networks. Then, a new set of security metrics for assessing dynamic networks is developed. The proposed security metrics capture the dynamic changes that affect the security posture of the networks.

To achieve the goal (3), an approach to select the best set of security hardening solutions for dynamic networks given multiple constraints (e.g., limited budget and downtime) is developed. T-HARM with three dynamic security metrics is used to evaluate the effectiveness of heterogeneous security hardening options. In addition, multi-objectives genetics algorithm is adapted to compute Pareto optimal deployment solutions that minimise security risk, security costs and downtime of implementation of the hardening options. The feasibility of the proposed approach is demonstrated in a real-world scenario by taking into account both patchable and non-patchable vulnerabilities. Further, a sensitivity analysis of the parameters of the genetic algorithm with respect to

the dynamic networks are performed. Then, the results of the effect of varying multiple network states on the optimal solutions obtained are shown.

In summary, the main contribution of this thesis are: (1) the development of adaptable security models to capture and assess the security of dynamic networks; (2) the evaluations of existing security metrics for the analysis of dynamic networks; (3) the development of metrics for the quantitative assessment of dynamic networks; and (4) the development of optimal defence approaches for dynamic networks given multiple constraints.

Publications Arising from this Thesis

A significant part of this thesis has been published or submitted for publication in the peer-reviewed journals and conferences as listed in the following.

1. Simon Yusuf Enoch, Mengmeng Ge, Jin B. Hong, Hani Alzaid and Dong Seong Kim. A Systematic Evaluation of Cybersecurity Metrics for Dynamic Networks. In *Computer Networks*, Elsevier, Vol. 144, pp 216-229, October 2018.

2. Simon Yusuf Enoch, Jin B. Hong and Dong Seong Kim. Time Independent Security Analysis for Dynamic Networks using Graphical Security Models. In *Proceedings of the 17th IEEE International Conference on Trust, Security and Privacy in Computing and Communications* (TrustCom-18), July 31st - August 3rd 2018, New York, USA.

3. Simon Yusuf Enoch, Jin. B. Hong, Mengmeng Ge, Hani Alzaid and Dong Seong Kim. Automated Security Investment Analysis of Dynamic Networks. In *Proceedings of the 2018 Australasian Information Security Conference* (AISC - 18), In ACSW, 2018, January 30 - February 2, 2018, Brisbane, QLD, Australia.

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5. Simon Yusuf Enoch, Jin B. Hong, Mengmeng Ge and Dong Seong Kim. Composite Metrics for Network Security Analysis. *Software Networking Journal*, River Publishers, 2017. 1 (2017):137-160.

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List of Abbreviations

The following abbreviations are used in this thesis.

AG	Attack Graph
AT	Attack Tree
MPAG	Multiple Prerequisite Attack Graph
BAG	Bayesian Attack Graph
GSM	Graphical Security Model
DT	Defense Tree
PT	Protection Tree
ADT	Attack-Defense Tree
ACT	Attack Countermeasure Tree
HARM	Hierarchical Attack Representation Model
T-HARM	Temporal Hierarchical Attack Representation Model
TI-HARM	Time-Independent Hierarchical Attack Representation Model
SLE	Single Loss Expectancy
ALE	Annual Loss Expectancy
ARO	Rate of Occurrence
PLE	Periodic Loss Expectancy
PRO	Periodic Rate of Occurrence
BS	Benefit of Security
ROSI	Return on Security Investment
CS	Security Investment Cost
AC	Attack Cost
ROA	Return on Attack
NIST	National Institute of Standards and Technology
SAP	Shortest Attack Path

NAP	Number of Attack Paths
MAPL	Mean of Attack Path Lengths
NMPL	Normalised Mean of Attack Path Lengths
SDPL	Standard Deviation of Attack Path Lengths
MoPL	Mode of Attack Path Lengths
MePL	Median of Attack Path Lengths
NCP	Network Compromise Percentage
CVSS	Common Vulnerability and Scoring System
BS	Based Score
CVE	Common Vulnerability and Exposure
MTTC	Mean Time to Compromise
MTTR	Mean Time to Recovery
MTFF	Mean Time to First Failure
MTTB	Mean Time to Breach
AIM	Attack Impact
SIMM	Structural Important Measure
Pr	Probability of attack success
PVE	Probability of Vulnerability Exploited
PAD	Probability of Attack Detection
PHC	Probability of Host Compromised
VHP	Vulnerable Host Percentage
WAM	Weakest Adversary Metric
ARM	Attack Resistance Metric
GA	Genetic Algorithm
NSGA-II	Non-dominated Sorting Genetic Algorithm
DMZ	Demilitarised Zone
NVD	National Vulnerability Database
PSV	Prioritised Set of Vulnerabilities
OS	Operating System
AV	Asset Value
SDN	Software-Define Networking

MWT	Minimum Weight Threshold
MTD	Moving Target Defence
BYOD	Bring Your Own Device
APN	Attack Path Number
APE	Attack Path Exposure
ACE	Attack Cost of Exploitability
ACD	Attack Cost Duration
NDT	Node Downtime
ECC	Edge Changing Cost
ECT	Edge Changing Time
SC	Security Cost
PAP	Persistent Attack Path Number
SR	Stateless Risk
ISM	Information Security Management
ARO	Annualise Rate of Occurrence
SRS	Security Rating System
PRO	Periodic Rate of Occurrence

List of Notations

The general notations used in this thesis are given below.

	Vulnerability level
v	is a vulnerability v
v_{t_i}	is a vulnerability v at time t_i
ac_v	is the attack cost of a vulnerability
r_v	is the attack risk of a vulnerability
pr_v	is the probability of attack success of a vulnerability
aim_v	is the attack impact of a vulnerability
roa_v	is the return on attack of a vulnerability
$Ep(v_k)$	is the exploitability of a vulnerability v_k using the CVSS
$t(v_k)$	is the time taken to exploit a vulnerability v_k
	Host level
$ac^h_{t_i}$	is a host attack cost at t_i
$r^h_{t_i}$	is a host attack risk at t_i
$pr^h_{t_i}$	is the probability of attack success of a host at t_i
$aim^h_{t_i}$	is a host attack impact at t_i
$roa^h_{t_i}$	is the return on attack of a host at t_i
$et(h_j)$	is the time taken to update the edge pairs of a host h_j
$hc(cm_k, h_j)$	is the cost of implementing a security measure cm_k on a host h_j
$cm(h_j, i)$	is the security measure of the host h_j in the ith network state
$dt(cm_k, h_j)$	is the downtime of implementing a security measure cm_k to the host h_j
h_i	is a network host h_i
h_i^α	is a host with weight value α
e_i	is a network edge e_i

e_i^{α}	is an edge with weight value α
nc_j^{α}	is the weight value for a component nc_j
	Attack Path level
ap_i	is an attack path i which includes a sequence of hosts
$ac_{t_i}^{ap_i}$	is an attack path i which includes a sequence of hosts
$r_{t_i}^{ap_i}$	is the attack risk on a path at t_i
$aim_{t_i}^{ap_i}$	is the attack impact on a path at t_i
$pr_{t_i}^{ap_i}$	is the probability of attack success on a path at t_i
$roa_{t_i}^{ap_i}$	is the return on attack on a path at t_i
$t(ap_i)$	is the time duration of an attack exploiting the attack path ap_i
$vuls(ap_i)$	is the set of vulnerabilities associated with an attack path ap_i
f	is a function that identifies the length of the ap_i that occurs most frequently
	Network level
NS	is a set of network states
AP	is the set of attack paths for all the states
$AP_{ns_{t_i}}$	is all the possible paths from an attacker to a target for the network state at t_i. Each $ap_i \in AP_{ns_{t_i}}$
AC_{t_i}	is the cost on attack paths at t_i
R_{t_i}	is the risk on attack paths at t_i
ROA_{t_i}	is return on attack paths at t_i
Pr_{t_i}	is the probability of attack success on paths at t_i
AIM_{t_i}	is impact on attack paths at t_i
SAP_{t_i}	is shortest attack path at t_i
NAP_{t_i}	is the number of attack paths at t_i
$MAPL_{t_i}$	is the mean of attack path lengths at t_i
$SDPL_{t_i}$	is the standard deviation of attack path lengths at t_i
$MoPL_{t_i}$	is mode of attack path lengths at t_i
$NMPL_{t_i}$	is the normalised mean of attack path lengths at t_i
PSS_{t_i}	is the percentage of severe systems at t_i
NSS_{t_i}	is the number of severe systems at t_i
TNH_{t_i}	is the total number of network hosts at t_i

cm_k	is a of security hardening measure/countermeasure k
CM	is a set of hardening security measure
$t(ns_{t_i})$	is the time duration of a network state at t_i
$et(ns_{t_i})$	is the time duration of the edge pair changes in ns_{t_i}
nc_j	is a network components nc_j (e.g., hosts, edges)
OC_{nc_j}	is the observed count for nc_j in a time window T
$t(nc_j)$	is the time duration of a network component nc_j per state
w	is the weight value threshold

Chapter 1

Introduction

Achieving security goals (i.e., Confidentiality, Integrity and Availability [64]) for networked systems has long been a difficult task for many organisations [117]. This has become even more difficult with modern network technologies (such as Cloud and SDN) allowing their components to be more dynamic with configuration changes over time. Such changes can be hosts joining or disconnecting [106], applications and services update, vulnerability added or removed [76], *etc.* As a result of these changes, the attack surface of the network changes as well [19]. Therefore, it is of paramount importance to assess the security of dynamic networks in order to understand how the security posture changes, and also to effectively prevent damages caused by cyber-attacks. To fully understand the security posture of the dynamic networks, one must take into account all observable attributes of dynamic networks, which includes changes of vulnerabilities, the visibility of hosts (components) over time, the connectivity of network components (e.g., changes in host-to-host reachability as a result of users' activities), multiple network states, *etc.*

In this thesis, the term *network states* is used to represent different network configurations and settings at various times. These configuration changes include, but not limited to applications and OS changes, network topology changes, vulnerability patches and other possible network configuration change.

1.1 Problem Statement

Graphical Security Models (e.g., AGs [3,127] and ATs [137,139]) are widely used to assess the security of networks systematically [75,94] (the surveys in [75] and [94] describes the whole family of GSMs with their various capabilities). However, there are problems in the GSMs being applied to dynamic networks. First, research on GSMs did not consider how the security assessment can be affected when the network changes. As a result, it becomes difficult to analyse the security of networks that are dynamic. Besides, they assumed that GSMs use static information, e.g., vulnerabilities [105], the hosts, edges (i.e., links connecting hosts), services running on the hosts, etc. However, those components change over time (for example, the installation of a new application software changes the attack surface by increasing the attack vectors for the host [105]) and as such, the security analysis using those models is only applicable for one particular state of the network. For dynamic networks with frequent changes, the process of analysing only a single network state is not comprehensive enough, especially for large-sized networks [74]. Therefore, it needs an approach to efficiently model and analyse the security of the dynamic network.

Secondly, many quantitative security metrics for assessing cybersecurity have been developed and formalised [34, 79, 114, 123, 126, 130, 136]. While these metrics remain useful in assessing the security of networks, their effectiveness concerning dynamic changes in the network is still unclear. Moreover, those metrics are not designed for the analysis of dynamic networks and thus, may not be capable of representing the security posture of different states of the dynamic networks. This is often crucial information for high-level decision makers to understand the security overview without the technical details. Hence, it is important to investigate how different security metrics are affected by changes in the network, in order to identify which ones are suitable, or not suitable, for security analysis of dynamic networks. Moreover, dynamic security metrics are

needed to capture the changing attack surface of dynamic networks in order to provide effective security solutions.

Thirdly, the complexity and dynamicity of modern networks make it difficult to select the best set of security hardening options to deploy. A security hardening option refers to any strategy deployed to reduce an attacker's ability to compromise the security goals of networked systems. Here, as the network configurations change, manually selecting the optimal security hardening options becomes time-consuming and infeasible, especially when the size of the dynamic network becomes larger. Moreover, security administrators often have a limited security budget that restricts them from implementing all possible security hardening options. Consequently, the security administrator needs to select an optimal set of security hardening options, which will maximise the security of the network under given constraints (e,g., taking into account a limited security budget and various security objectives). Besides, computing the optimum set of security hardening options for dynamic networks should also be done within a feasible time frame. However, the solution search space increases exponentially as the size of the network grows, as well as incorporating the dynamic nature of the network components.

1.2 Research Questions and Goals

This thesis uses the security modelling approach to answer the following questions:

- Q1: what are the approaches that be used to systematically capture and model the attack scenarios in dynamic networks?
- Q2: what are the characteristics of dynamic networks, and how can we quantitatively measure the security of the dynamic networks?
- Q3: what approach can be used to select the optimal security hardening solutions for dynamic networks taking into account multiple objectives

(e.g., maximise security and minimise cost)?

The goals of this thesis are to advance the cybersecurity modelling and assessment for the dynamic networks. Three sub-goals corresponding to the research questions are described below:

- G1: *To develop an adaptable graphical security model to capture security changes in dynamic networks.* The outcomes of this goal include new security models to capture security changes over time, a formal definition of its structure and functionality, and the classification of potential network changes and their relationships to the possible security changes (in the GSM).

- G2: *To develop new security metrics that effectively represent the security posture of dynamic networks.* The outcomes of this goal consist of a comprehensive evaluation of existing security metrics, classifications of security metrics, a new approach to combining existing security metrics, and new dynamic security metrics, and their formalisms.

- G3: *To develop optimal security hardening selection methods for dynamic networks taking into account multiple objectives and constraints.* The outcome of achieving this goal is a new approach to selecting a set of security hardening options from a pool of potential security solutions for dynamic networks while satisfying multiple objectives and constraints.

1.3 Methodology

In the following, the five phases to answer the proposed research questions are described.

System Model: A dynamic enterprise network is used as the system model, wherein there are subnets, firewalls, hosts (e.g., servers and users' workstations), *etc.* It is assumed that the network has multiple states with each network states having different network configurations (e.g., new hosts joining,

new vulnerabilities found, existing vulnerability patched, *etc*). Besides, it is assumed that the changes in the network state are captured at various time or when changes occur in the network (depending on the scenario). The changing configurations information and the network states are used as input to the security models and the metrics calculations.

Attacker Model: The attacker model provides the interactions between the attacker and the system model. As the attacker model is needed for the GSMs, this thesis assumed the attackers' entry points, target and goals. Based on the network hosts' vulnerabilities and reachability information, the GSM computes the potential attack scenarios with the assumptions that the attacker can exploit the vulnerabilities. Also, it is assumed that the attacker can find multiple attack paths to reach the target at any time.

Defence Model: Both the reactive and proactive defence mechanisms are used for different network scenarios. These mechanisms can be deployed on either the hosts level, the network level or on both levels. For example, a vulnerable application can be disabled on a host (other types of the mechanisms such as host isolation, traffic redirection, *etc.* are used as well) to mitigate against exposure to attacks as a result of non-patchable vulnerability (i.e., the host level).

GSMs: Security models are developed to capture and analyse the security of dynamic networks. The security models use both the system model, the attacker model and defence model (if there is) as input. The system model provides the changing network reachability information and the hosts' vulnerabilities explicitly over time, including the metrics for the vulnerabilities. While the attacker model specifies the location of the attacker, the target, the goal and the entry points for the attacker. The defence model specifies the possible security hardening measure for the network.

Evaluation: Scenarios via simulations are used to evaluate the approaches. The evaluation aims to show the feasibility of the proposed GSMs, security metrics and the optimal defence selection mechanism developed.

1.4 Research Contributions

Five major contributions are proposed to the graphical security modelling and analysis, which are as follows.

1. Development of a temporal graphical security model to capture and analyse the security of dynamic networks at every time t (the work has been published in [47, 48]). The temporal GSM captures the security changes onto two layers at the various time; the temporal network topology is captured at the upper layer using AGs and the vulnerability information for each node at the lower layer using a set of ATs. By doing so, the possible security of the network states can be captured and analysed at the various time. Thus, showing the changes in the network states at every time t.

2. Development of time-independent graphical security model that capture all potential attack scenarios of dynamic networks regardless of network states and time (the work has been published in [51]). The main idea of the time-independent security model is to model the security of dynamic networks by aggregating the security components of multiple states to form a single GSM. By doing so, all the possible network components observed in various network states can be captured, and thus allowing us to model all possible attack scenarios including ones carried out in multiple network states on a single GSM without having to look at multiple GSMs. Moreover, the overall overview of the network security (using metrics) can be calculated without looking at the multiple metrics for every time t.

3. A systematic evaluation of cybersecurity metrics for the analysis of dynamic networks (the work has been published in [46,49]). As of the time of this research, there is no systematic evaluation of the existing security metrics to determine their effectiveness for the analysis of dynamic

networks. In this thesis, the security metrics are evaluated based on various network changes at the various time. The temporal GSM is used to capture the security changes that happened as a result of the network changes. Moreover, an approach to develop composite security metrics for the analysis of network security is proposed (the work has been published in [50]).

4. Development of dynamic security metrics to assess the security of dynamic networks. New security metrics are developed to measure the security posture of dynamic networks (part of this work has been published in [70, 71]). As current security metrics are not designed for dynamic networks, the changes in dynamic networks are characterised, and based on the characteristics, the properties of metrics that will capture the changes are identified in order to develop the new set of dynamic metrics.

5. Development of optimal defence mechanisms for the dynamic networks (the work has been submitted to IEEE ICC 2019 [52]). Several defence mechanisms were considered in order to harden the security of dynamic networks (the network is having a mix of patchable and non-patchable vulnerability). A multi-objective optimisation algorithm is used to search for the optimal solutions from the pools of security hardening options.

1.5 Thesis Structure

The rest of the thesis is organised as follows. Chapter 2 summarises the related work on the GSM approaches for enterprise networks, security metrics and security hardening optimisation methods. Chapter 3 present the propose Temporal Hierarchical Security Model to improve the adaptability of existing security models. The classifications and formalisms of network change with respect to security changes are presented as well (addressing the research goal

G1). Chapter 4 described various real-world scenarios of networks changes, and also present the results for the simulation studies conducted on the effectiveness of the current security metrics for the analysis of dynamic networks (this is towards addressing the research goal G2). Chapter 5 presents the Time-Independent HARM to present the overview of the security of dynamic networks (addressing the research goal G1). Chapter 6 develops a new set of security metrics for assessing dynamic networks. Their formalisms and quantifications (addressing the research goal G2). Chapter 7 provides the proposed approach for multi-objective security hardening optimisation problem of dynamic networks under multiple constraints (addressing the research goal G3). Chapter 8 discusses the usability and limitations of the thesis and highlights the possible directions for extensions. Finally, Chapter 9 concludes the thesis.

Chapter 2

Literature Review

This chapter discusses the related work on GSMs, security metrics and security optimisation. Section 2.1 discusses the GSMs used to analyse the security of traditional networks and the dynamic networks. Section 2.2 discusses the current security metrics and provides the classifications of the current security metrics. Section 2.3 presents the existing approaches on the optimal selection of defence mechanisms for network systems. Section 2.4 summarises the challenges of the existing approaches and highlighted the proposed approaches.

2.1 Graphical Security Models

A GSM is a tool for security assessment of real-life systems [94]. Most popular applications domain are internet related attacks [103, 153], voting systems [26, 99], supervisory control and data acquisition systems [27, 31], online banking systems [43], *etc.* The interest of this thesis is using GSMs for the analysis of cyber-attack and defence scenarios. In the following, they are discussed in two aspects: GSMs for static networks and GSMs for dynamic networks, respectively.

2.1.1 GSMs for Static Networks

Several papers addressed the problem of assessing the security of network systems using different approaches. In this section, the Graph-based, Tree-based and the Hierarchical approaches are presented. The Graph-based approach employ the graph structure to represent attack scenario. The Tree-based approach models attack scenario in a tree-like structure. While the Hierarchical approach models the attack scenarios onto multiple layers.

Graph-based models: One of the earlier work is presented in [131] where an AG is proposed to model computer attacks. In particular, the AG is used to show all possible sequences of attack steps to gain access to a target using network reachability information and a set of vulnerability. Some other graph-based approaches for assessing the security of network systems include [3, 63, 79, 81, 87, 127, 149] *etc.* However, analysing all possible sequences of attack paths using the AG has a scalability problem [65, 74, 75]. As a result, various work proposed different approaches to improve the scalability of the AG [30, 66, 127, 132, 159]. For instance, Homer *et al.* [66] proposed two approaches. First, they proposed an approach that automatically identifies the portions of an AG that is not important in understanding the core security problems and subsequently, removed it. Secondly, they proposed an approach that grouped similar attack steps which they said it represents the number and type of security problems. On the other hand, Ingols *et al.* [82] proposed a MPAG which grouped multiple subsets of nodes in order to reduce the size of the AG. Even at that, the generation of the MPAG still suffers from the scalability problem since modern networks have become very large and highly dynamic [74].

Tree-based models: Another type of the GSMs is the tree-based models such as AT in [40, 111, 139, 151] *etc.* The AT is a tree-like structure which systematically presents attack scenario in a network with the target as the root node and the different ways of reaching the target as leaf nodes. They are used

to analyse the security of systems, but they cannot be generated from network system specifications (e.g., using hosts reachability information to know how an attacker can move from one host to another host (i.e., cannot capture the attack paths information explicitly)) unless when logical connections (e.g., sequential AND gates) are used for the tree-based models [68, 75]. Moreover, they also suffer from the scalability problem.

Hierarchical models: In order to address the scalability problem in the graph-based and tree-based model, a multi-layer security model named HARM was proposed in [74] which simplifies the evaluation of all possible attack scenarios. In particular, the work in [74] presented a three-layer HARM where the reachability of network subnets is captured at the upper layer, the host reachability information for each subnet is captured in the middle layer (using an AG), and the vulnerability information is captured in the lower layer (using an AT). Further, they showed that the scalability and the computational complexity is improved when more layers (hierarchy) are used in the multi-layer HARM.

With respect to this research, the major challenges with the approaches as mentioned earlier is that they do not take into account the various changes that happen in the network for their security analysis. However, modern networks are now dynamic. For instance, a network attack surface changes when a new host is connected to the network (e.g., bring your own device [106]), update of software vulnerabilities [7], the discovery of new vulnerabilities [7,76], firewall configuration and settings changed, *etc* and hence, those GSMs may not effectively model and analyse the security of dynamic network since the attack surface from scenarios may be changing.

2.1.2 Dynamic Models for Dynamic Networks

A few studies have focused on developing GSMs for assessing the security of dynamic networks. Frigault *et al.* [56] proposed a dynamic Bayesian network-based model to capture the evolving vulnerabilities in a network. It is a

theoretical framework, and they expect it to be used for analysing the changing security aspects of a network. Besides, it is limited to only changes in vulnerabilities, as network changes (e.g., changes in topology which changes the hosts reachability information) are not taken into account. Another similar approach is BAG proposed by Poolsappasit *et al.* in [132], however, in the BAG, they adopt the idea of Bayesian belief networks and AG to encode different security conditions and the relationship between the various network states and the possibility of exploiting those relationships as well. Almohri *et al.* [5] presented a success measurement graph model where they analyse the chances of attacks in the presence of uncertainties and further showed how to deploy security and service across the dynamic network optimally.

A few research for the social network analysis [146] modelled the dynamic network in different ways. For instance, Lerman *et al.* [100] modelled a dynamic network by taking snapshots of every connected node at different times. They used their model to assess the number of paths that exist over time in the network. Moreover, they also used dynamic centrality metric to rank the importance of each node (i.e., by how well connected they are over time to the rest of the network). Similarly, Braha and Bar-Yam [22] studied how degree centrality evolves in a dynamic network. They represented a dynamic network by creating a time series of the network. They characterised the centrality of nodes in the daily networks using the nodal "degree" (i.e., the number of nodes a particular node is connected to). In their work, they found that the degree of a node varied dramatically over time.

Kostakos [155] represented a dynamic network using temporal graphs (a graph in which the components are active at a specific time). They defined some metrics for temporal graphs (e.g., temporal proximity, temporal availability) and analysed the relationship between nodes over time, and also finds the role of each node in the temporal context of the entire network. Kempe *et al.* proposed a temporal network model in which each edge is annotated with a time label specifying the edge time (duration) of connection. In the model,

each path needs to obey the time order of the appearance of the edges [91]. Casteigts *et al.* [28] used time-varying graphs (also known as temporal graphs) to model and analyse dynamic networks using a unified framework which they proposed. In their paper, they studied the evolution of network properties as they dynamically change in a complex network system using network metrics. Similarly, Wehmuth *et al.* [160] presented a unified finite time-varying graph models for dynamic networks which represent several previous models proposed in [25, 28, 54, 152]. Their proposed unified model allows one to model the periodic behaviour of components in dynamic networks inherently. They also showed how node, path and connections are processed in their model.
Santoro *et al.* [141] presented a time-varying graph and its formalism, in which they concisely showed the network temporal concepts and their properties. In addition, they analysed the behaviour of network properties (e.g., temporal sub-graph, sequences of a static graph) during the lifetime of a time-varying graph using network metrics (e.g., temporal centrality, temporal diameter).

2.1.3 Graphical Security Models for Security Investment Analysis

Only a few studies have considered the evaluation of IT security investments using GSMs and economic metrics. Bistarelli *et al.* [14] evaluated IT security assets by using DTs (i.e., extended ATs) where they placed countermeasures on each leaf of the AT. Further, they compute SLE, ALE, BS and ROSI. Roy *et al.* [137] proposed ACT in which both attack scenarios and security countermeasures are taken into account. In the ACT, countermeasures (detection and mitigation) are also placed on every node and not only at the leaf nodes. Roy *et al.* showed the practical usability of their approach by computing CS, AC, ROA and ROSI. Baca and Petersen [9] developed an extension of AT, where they began by evaluating and prioritising the attack countermeasures, then assigning the countermeasures to the leaves of ATs. In

their work, they automated the calculation of the countermeasures cost and showed the effectiveness of the proposed automation. Edge *et al.* [45] proposed a PT which is based on the AT. In the PT, they used a protection component (i.e., countermeasure) for every leaf node of ATs to construct PTs. Further, they showed how to compute the CS and the Pr.

Kordy *et al.* [93] proposed ADT which is an extended AT in which countermeasures are used as a node and they are allowed to appear at any level of AT. Ji *et al.* [88] used the ADT for risk assessment and countermeasures evaluation for cyber-physical systems. They showed how they had evaluated the performance of the ADT using the metric ROSI and ROA.

Ingols *et al.* [82] developed a tool named NetSPA (which is based on the AG) which can capture all possible ways that an attacker can compromise the targeted network (and used it for risk analysis). In [81], Ingols *et al.* extended their earlier work by incorporating countermeasures. In particular, they added personal firewalls at the host and the network level, and further, they added an intrusion prevention systems and proxy firewalls for all network hosts. However, they did not calculate any economic metrics for the countermeasures deployed.

Table 2.1 summarises the most commonly used GSMs (where applicable) and the economic metrics used in the previous work to automate security investments analysis. From the table, only a few of the work automated the computation of economic metrics, while the others described them (e.g., the work in [16, 33]). However, none of the previous work considered all the following; (1) dynamic security analysis, (2) all economic metrics identified, (3) the use of dynamic models and (4) the use of several countermeasures in the GSM. Hence, this thesis automates the analysis of security investments for changing networks using a dynamic GSM (T-HARM) along with various economic metrics. In the table, ✓means it is considered.

Table 2.1: GSMs and Economic metrics in previous work.

	GSMs used	SLE	ALE	BS	CS	ROI	ROA	Dynamic analysis
Frigault *et al.* [55]	BAG							✓
Bistarelli *et al.* [14]	DTs	✓	✓	✓	✓	✓	✓	
Böhme and Moore [15, 16]		✓	✓	✓	✓	✓		
Roy *et al.* [136, 137]	ACT				✓	✓	✓	
Breu *et al.* [23]	Threat Graphs	✓	✓	✓		✓		
Poolsappasit *et al.* [132]	BAG							✓
Tsiakis and Katsaros [154]				✓	✓	✓		
Gossen *et al.* [61]	ATs and DTs	✓	✓	✓	✓	✓		
Sonnenreich *et al.* [148]		✓	✓	✓	✓	✓		
Noel *et al.* [122]	AGs					✓		
Hong and Kim *et al.* [74]	HARM			✓	✓	✓		
This thesis	T-HARM	✓	✓	✓	✓	✓	✓	✓
This thesis	TI-HARM	✓	✓	✓	✓	✓	✓	✓

2.2 Security Metrics

In this section, a review of the existing security metric is presented. According to the NIST [11, 85], security metrics are designed to facilitate security decision-making through collection and analysis of network security settings and configurations. Security metrics are used to quantitatively or qualitatively assess an organisation's security posture. A network administrator can use a security metric to answer some security related questions such as "how is our security posture today compared to the way it was before ?" or "does our change to the network configuration and settings improve/degrade our security posture?".

Most organisations use qualitative approaches (such as questionnaires to rate its network security as high, medium or low) to evaluate the security of their networks [129]. These approaches are based on subjective methods and insights and do not systematically quantify the different network security posture (for example, a network administrator cannot quantitatively identify which part of a network is most secured). So, security administrators are in need of a general method to quantitatively assess network security.

For several decades now, many quantitative security metrics for assessing network security have been developed and formalised (e.g., the work [4, 13, 67, 79, 122, 131, 136, 150]). However, these security metrics are static and cannot be

used to assess the security of a dynamic network [19]. For instance, Philips and Swiler [131] proposed SAP metric, the metric presents the minimum amount of effort an attacker needs to compromise a target. It is a metric from the perspective of an attacker who has the options of different steps to compromise a security policy.

Similarly, Pamula and Ammann [129] proposed the WAM that is based on the analysis of AG. The metric assesses the security strength of a network in terms of the attacker's strength to successfully penetrate a network. These security metrics are not effective security assessment metrics for dynamic networks which are characterised by frequent topological changes [19]. This is because the quantitative values produced by these metrics do not change even when there is a topological change. Ortalo *et al.* [126] proposed the NAP metric to assess the number of ways an attacker can compromise a target host. This metric presents the total number of attack paths that can be available to the attacker in order to launch an attack. Li and Vaughn [102] mention the average attack path length metric (also called MAPL metric), they however, did not describe nor formalise the metric but Idika and Bhargava described the metric as the average of all attack path lengths and that the metric can be used to shows the expected effort that an attacker may use to violate a security countermeasure [79].

While all these metrics remains useful in assessing the security of networks, they however cannot effectively assess the security of a dynamic network [19], and this is because they were developed from the view of a static network (where hosts and vulnerabilities information does not change). For example, in a network, when the security status (e.g., vulnerability, reachability information) of a host change, the structure of the AG changes also, when this occurs the security has to be re-analysed as vulnerabilities and topology information have changed. For dynamic networks with frequent changes, this process of re-analysing the security becomes inefficient, especially for large sized networks.

Idika and Bhargava developed sets of AG-based metrics that assess the

properties of a network in order to determine the network security. The metrics are: the NMPL metric, the SDPL metric, the MoPL metrics and the MePL metric [79]. The metrics are used to evaluate the different attributes of a network's security. Though the proposed security metrics were computed over the whole AG, they are not able to capture the various security changes that happen in a network over time [19].

The NCP is a metric developed by Lippmann *et al.* [104]. The NCP is the percentage of the total assets across all hosts that have been captured by the attacker. A value of zero indicates that no hosts have been compromised, and a value of 100 indicates that all hosts have been compromised and all assets have been captured. This metric is not useful in assessing the security of a dynamic network because the NCP does not change even when a host vulnerability status changes [124]. For example, if a host in the network has multiple vulnerabilities and one of the host vulnerability is patched, the NCP does not change provided there is at least one exploitable vulnerability remaining on the host.

There are also economic security metrics for assessing cybersecurity [13,17]. For instance, the AC [136] is a metric that quantity's the cost spent by an attacker to successfully exploit a vulnerability (i.e., security weakness) on a host. The ROA [34] is also a security metric that is defined as the gain the attacker expects from successful attack over the losses he sustains due to the countermeasure deployed by his target. The return on attack is a metric from the attacker perspective, and is used by organisations to evaluate the effectiveness of a countermeasure and in discouraging a specific type of intrusion attempts on a host. Bistarelli *et al.* [13] used the defender's ROA and the attacker's ROA to evaluate the effectiveness of a countermeasure using DT model. Roy *et al.* [136] used the AC metric and ROSI metric to perform security analysis. Both studies did not consider the changing security components of modern networks. Therefore, it is difficult to estimate how these metrics will change as the network change over the period.

Bopche and Mehtre [19] proposed graph distance metrics which is based on

maximum common subgraph and graph edit distance to measure the temporal change in a dynamic network attack surface (an attack surface is a set of ways that an attacker can use to penetrate a network system). They showed that their proposed security metrics is able to capture the impact of events that cause significant change in the network attack surface and also locate the most vulnerable hosts in a dynamic network. Their proposed metric can only be used to detect the changes that happen in a network attack surface and does not maximise the granularity provided by the CVSS [36] in order to assess the overall dynamic security in terms of risk, cost, impact, *etc* (e.g., risk analysis, impact analysis). The CVSS is an industry open standard designed to convey vulnerability severity and risk [35].

2.2.1 Classification of Security Metrics

There are a few research on the classification of security metrics. However, most of the classification methods are based on organisation's point of view [143]. For instance, Savola [142] proposed three categories of security metrics; namely, (i) business-level security metrics, (ii) metrics for ISM in organisations, and (iii) dependability and trust metrics for products, systems and services. The business-level security metrics are business goals directed and are used for cost-benefit security analysis in organisations. The information security management metrics are used to evaluate the ISM security controls, plans and policies, and are divided into three subcategories (i.e., management, operational and information system technical security metrics). The dependability and trust metrics are used to assess the organisation's trust, relationships and dependability issues [8]. In general, this classification only addresses the security needs of companies that produce information and telecommunication technology products, systems or services.

Vaughn *et al.* [156] presented two categories of security metrics (organisational security metrics and metrics for technical target assessment). The organisational security metrics assess the organisation's security

assurance status (the metrics in this category include security effectiveness, operational readiness for security incidents and information assurance program development metric). The metrics for technical target assessment are used to assess the security capabilities of a technical system (it is further divided into metrics for strength assessment and metrics for weakness assessment [156]). This classification is tailored towards an organisation's needs.

Pendleton *et al.* [130] classified security metrics into four categories, namely: metrics for measuring the system vulnerabilities, metrics for measuring the defences, metrics for measuring the threats, and metrics for measuring the situations. The metrics for measuring vulnerabilities are intended to quantify the enterprise and computer systems vulnerabilities through their user's password, software vulnerabilities, and the vulnerabilities of the cryptographic keys they use. The metrics for measuring defences is aimed to quantify the countermeasure deployed in an enterprise via the effectiveness of blacklisting, the ability of attack detection, the effectiveness of software diversification, and the overall effectiveness of these countermeasures. The metrics for measuring threats are aimed to assess the threats against an enterprise through the threat of zero-day attacks, the power of individual attacks and the sophistication of obfuscation. The metrics for measuring the situations aims to assess situations via security investments, security states and security incidents. This classification is centred on the perspective between attackers and defenders in enterprise systems. Other classifications provided by industries such as the NIST, the Center for Internet Security [33] and the Workshop on Information Security System Scoring and Ranking are exclusively geared towards cyber defence administrations and operations [130]. Here, a classification of the existing security metrics based on network reachability information is presented. Mainly, it is classified into two types: host-level metrics and network-level metrics, as shown in Figure 2.1.

The host-level metrics do not use any network-level information (e.g., reachability, protocols, *etc*) whereas the network-level metrics take into account

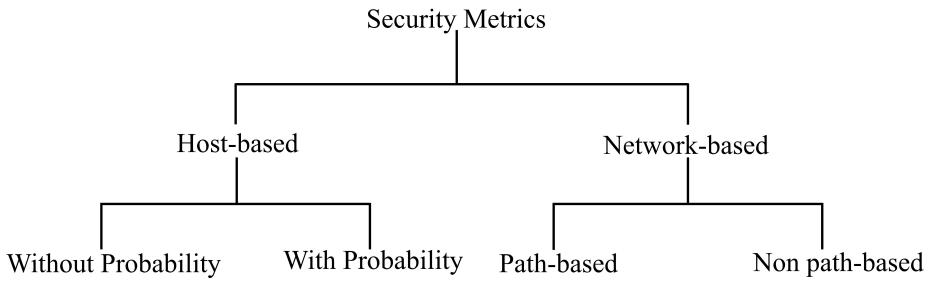


Figure 2.1: Classification of security metrics.

network structure, protocol and reachability information to quantify the security of a system. The description of the host-level metrics given in Section 2.2.1.1 and the network-level metrics in Section 2.2.1.2, respectively.

2.2.1.1 Host-based Security Metrics

The host-level metrics are used to quantify the security level of individual hosts in a network. It is classified into two types: "without probability" and "with probability". The reasons for this classification are: (i) sometimes it is infeasible to find a probability value for an attack, and (ii) some analysis and optimisation can be done with or without probability assignments as described in [137].

Metrics without probability values:

The metrics "without probability" is summarise in Table 2.2. Examples of metrics without probability values are AIM, AC, SIMM [136], mincut analysis [136], MTTC [59, 101], MTTR [86], MTFF [140], MTTB [89], ROSI [34], ROA [34], *etc.*

Metrics with probability values:

Conversely, the security metrics with probability include Pr [157], CVSS metrics [36] *etc.* Wang *et al.* [157] proposed an AG-based security metric that incorporates the likelihood of potential multi-step attacks combining multiple vulnerabilities in order to reach the attack goal. We summarise the metrics with probability in Table 2.3.

Table 2.2: Description of Metrics without Probability Values.

Metrics	Description
AC [136]	is the cost spent by an attacker to successfully exploit a vulnerability (i.e., security weakness) on a host.
AIM [136]	is the quantitative measure of the potential harm caused by an attacker to exploit a vulnerability.
MTTC [59, 101]	is used to measure how quickly a network can be penetrated. This type of metrics produces time values as end results.
SIMM [136]	is used to qualitatively determine the most critical event (attack, detection or mitigation) in a graphical attack model. This metric is useful when the probability of event such as attack, detection or mitigation are unknown.
MTTR [86]	is used to assess the effectiveness of a network to recovery from an attack incidents. It is defined as the average amount of time required to restore a system out of attack state. The shorter the time, the less impact is the attack on the overall performance of the network.
ROA [34]	is defined as the gain the attacker expects from successful attack over the losses he sustains due to the countermeasure deployed by his target. This security metric is from the attacker perspective and it used by organisations to evaluate the effectiveness of a countermeasure in discouraging a certain type of intrusion attempts [34].

2.2.1.2 Network-based Security Metrics

This category of metrics uses the structure of a network to aggregate the security property of the network. These metrics are divided into two types: path based and non-path-based metrics (according to the use of path

Table 2.3: Description of Metrics with Probability Values.

Metrics	Description
PVE [44]	is used to assess the likelihood of an attacker exploiting a specific vulnerability on a host. This takes into account the severity of the host vulnerability.
PAD [136]	is used to assess the likelihood of a countermeasure to successfully identify the event of an attack on a target.
PHC [67]	is used to assess the likelihood of an attacker to successfully compromise a target
CVSS [36]	is an industry standard used to assess the severity of computer vulnerabilities. Details of the CVSS probability is provided in [128].

information).

Non-Path Based Metrics: In non-path-based metrics, the structure and attributes of a network are not considered; instead, the security of a network is quantified regardless of the network structure. One example of this type of metrics is NCP metric [104]. The NCP metric is defined in Table 2.4. This metric indicates the percentage of network assets an attacker can compromise. The aim of the NCP metric is to minimise this percentage. Another example is a set of vulnerabilities that allows an attacker to use them as entry points to a network. For instance, web-services running on a host could be the very first targets for an attacker to compromise. The weakest adversary metric is also a network-based metric that is used to assess the security of a network. In the WAM, a network configuration that is vulnerable to a stronger set of attribute is define as more secure than a network configuration that is vulnerable to a weaker set of initial attacker attributes [129].

Path Based Metrics Path based metrics use the reachability information of a network (for example, reachability between hosts, shortest path from a host X to a host Y, and so on) to quantify the security level of the network. We

Table 2.4: Description of Non-Path Based Metrics.

Metrics	Description
NCP [104]	is the metric that quantifies the percentage of hosts on the network on which an attacker can obtain an user or administration level privilege.
WAM [129]	is used to assess the security strength of a network in terms of the weakest part of the network that an attacker can successfully penetrate.
VHP [95]	is used to assess the overall security of a network. This metric quantifies the percentage of hosts with vulnerability on a network. The higher the metric value, the less is the security level of the network.

summarise some of these metrics in Table 2.5, which include SAP metrics [131], NAP metrics [126], MAPL metrics [102], NMPL Metrics [79], SDPL Metrics [79], MoPL Metrics [79] and MePL metrics [79].

Table 2.5: Description of Path based Metrics.

Metrics	Description
SAP [126, 131]	is the smallest distance from the attacker to the target. This metric represents the minimum number of hosts an attacker will use to compromise the target host.
NAP [126]	is the total number of ways an attacker can compromise the target. The higher the number, the less secure the network.
MAPL [102]	is the average of all path lengths. It gives the expected effort that an attacker may use to breach a network policy.
NMPL [79]	This metric represents the expected number of exploits an attacker should execute in order to reach the target.
SDPL [79]	is used to determine the attack paths of interest. A path length that is two standard deviations below the mean of path length metric is considered the attack paths of interest and can be recommended to the network administrator for monitoring and consequently for patching.
MoPL [79]	is the attack path length that occurs most frequently. The Mode of Path Lengths metric suggests a likely amount of effort an attacker may encounter.
MePL [79]	this metric is used by network administrator to determine how close is an attack path length to the value of the median path length (i.e. path length that is at the middle of all the path length values). The values that falls below the median are monitored and considered for network hardening.
ARM [159]	is used to assess the resistance of a network configuration based on the composition of measures of individual exploits. It is also use for assessing and comparing the security of different network configurations.

2.3 Security Hardening Optimisation

Various approaches have been proposed for the selection of security hardening of networks. It is discussed as follows.

Jha *et al.* [87] used a greedy approach to find the minimal subset of hardening options needed to secure the network from an attack using an AG. They assumed that not all attack paths will be available to the attacker and therefore, they applied hardening options on only a subset of attack scenario to achieve the cost effectiveness. Phillips and Swiler [131] also used a greedy approach to find a set of cost effective defence approaches. They incorporated cost (financial, loss of services, *etc.*) and a defence budget into an AG in order to reduce probability of attack success (or increase attack cost) for generating hardening suggestions. Noel and Jajodia [121] used a greedy approach and an AG to find the optimum placement of Intrusion Detection System sensors in a network that will cover all critical attack paths. Idika *et al.* [80] modelled the problem of selecting the best security options as a combinatorial optimisation problem. They formulated the problem as a binary knapsack problem (i.e., the security measures choosing problem) where the goal is to maximise security subject to a limited budget. They used dynamic programming (with the binary knapsack problem) to provide optimal solutions.

Kundu and Ghosh [97] modelled network hardening selection method as a multi-objective optimisation problem with three objectives (minimise cost, minimise risk and maximise overall network accessibility). They used a multi-objective strategy search algorithm to select the optimum set of security countermeasures under the given multiple constraints. Noel *et al.* [122] proposed a network hardening option by computing the best network reconfiguration options from the available reconfiguration options. Khanna *et al.* [92] optimised the problem of deploying dynamic mobile sensors using a multiple-objective genetic algorithm. Their approach optimally relocates sensor host which further optimises host assignments, routes and attributes.

Dewri *et al.* developed an approach to solve the problem of selecting optimum security decision with multiple constraints via an AT. They used a genetic algorithm [40] to select a subset of security hardening measures from a given set such that the impact of attack damages and the total cost of countermeasure implementation are minimised within a given budget. In [41], Dewri *et al.* extended their earlier work by using the NSGA-II to find how security controls can be placed in a network to induce a maximum return on investment. Borbor *et al.* [20, 21] proposed a heterogeneous approach to select optimum set of hardening options to deal with unknown and non-patchable vulnerabilities under given cost constraints. They used GA and an extended resource graph to solve this problem. However, all these approaches only considered the optimisation problems based on static network configuration and settings.

Inspired by the work in [92] which uses GA to dynamically deploy secure mobile sensors in a dynamic environment and the work in [21] which also uses GA to consider heterogeneous hardening options for networks, the GA is adapted to select optimum set of heterogeneous hardening options for the dynamic networks (networks with multiple states). In particular, a NSGA-II [110] is used. The NSGA-II has gained a lot of popularity for solving real world problems (e.g., planning [144], scheduling [38], design [38]) because of its effectiveness, ability to converge and ability to maintain a good distribution over the objective functions [110].

The major difference between this work and the aforementioned approaches is that the previous works rely on static network configuration information (where there is no change in the network and security model) for their evaluations. However, in this work, various dynamic network changes are considered (e.g., addition/removal of connections, addition of vulnerability, the availability of a hardening option, *etc*). Moreover, dynamic security metrics are used to evaluate the effectiveness of each defence option in the network.

2.4 Summary

To address the aforementioned problems, the temporal graphs are incorporated into the GSM to create T-HARM and TI-HARM to analyse the security of 'dynamic' networks. Temporal graphs were mainly used to model changes in the social network, but has not been used in the context of graphical security models. The most obvious advantage of the proposed approach is that it will effectively capture the network temporal change into two different layers at different time (thereby, improving the adaptability of the current approaches) and further, provides a way to analyse the security weaknesses of a dynamic network. Moreover, it also provides an approach for the high level decision makers to get the overview of the security of dynamic networks without the technical details.

From the current research in security metrics, the researchers pay much attention to security metrics for assessing the security of a network that does not change, and the current security metrics are not proven to be effective to assess the security of a dynamic network. Therefore, there is a need of metric to effectively capture security changes and also quantitatively assess the security strength of the dynamic network.

From the existing automated optimisation approaches for network systems, most of the models relies on static network configurations and static security metrics. On the other hand, one of the novelty of our work lies in the use of automated security model with dynamic security metric to search for most efficient solutions for the optimisation problem under multiple constraints.

Chapter 3

Temporal Graphical Security Model

This chapter propose a temporal GSM named T-HARM. The T-HARM can be used to capture and analyse the security properties of dynamic networks. First, a brief background on the HARM is presented. Second, the descriptions and formalisms of the T-HARM are presented. The main contributions of this chapter are summarised as follows:

- Develop a temporal GSM, named T-HARM, to capture security changes in dynamic networks;
- Formally define the T-HARM;
- Systematically categorise various network changes;
- Formally define the network changes with respect to the T-HARM;

3.1 Background on the HARM

To address the scalability problem of existing security models [3, 40, 63, 79, 81, 87, 111, 127, 139, 149, 151], Hong and Kim [74] developed a hierarchical GSM. In particular, they developed a three-layer HARM where the reachability

of network subnets is captured at the upper layer, the host reachability information for each subnet is captured in the middle layer (using an AG) and the vulnerability information is captured in the lower layer (using an AT). Hong and Kim used both the AG and the AT in the same model but on a different layer to improve the scalability and the computational complexity of GSMs.

However, the current approaches (including the HARM) do not take into account the various changes that happen in the network for their security analysis. But modern network changes frequently, for example, dynamic networks consist of a varying set of hosts and edges (i.e., the connections between the hosts) over time. Also, each of the hosts can have a varying set of vulnerabilities which an attacker can use to compromise the hosts over the time. As a result of these network changes, the attack vector for the network changes frequently. Therefore, to effectively represent the changing security posture of dynamic networks, GSMs need to adjust to changes when security changes are observed in the networks. Hence, this chapter extends the static HARM with the idea of temporal graphs to model the security changes of dynamic networks.

3.2 System and Attacker Model

The system and the attacker model used to describe the T-HARM are presented in Section 3.2.1 and Section 3.2.2, respectively. Specifically, the system and the attacker models are used to incorporate the dynamic properties of the network (i.e., how the system changes dynamically, and how the attack scenarios are affected as a result). These models will be used in most part of this thesis.

3.2.1 System Model

The network in Figure 3.1 is used as the system model. The network consists of a DMZ and an internal network. The DMZ connects to the Internet via the external firewall which is configured to allow direct connections from the Internet only to the DMZ. The internal network is further divided into two subnets by the internal firewall 1 and firewall 2. The internal firewall 1 only allows traffic from the DMZ to have access to ports necessary for the services in the internal network. In the network, the web servers in the DMZ are allowed to access the Internet while the hosts in the DMZ are allowed access to the application servers in the internal network then to the database server. In specific, a remote user cannot have direct access to the database server, and only the application servers in the internal network can request data from the database server. Further, there are user workstations in the internal network (the number of hosts can vary for the simulation scenarios). In Figure 3.1, the symbol '$->$' is used to indicate the connections from a host or subnet to another (e.g., A can connect ($->$) to B). Table 3.1 shows the OSes and services running on the servers and workstations. It is assumed that each host in the network has at least two vulnerabilities. In the Table, a web server is denoted as WS, application server as AS, Database server as DB and a user workstation as $User_i$ (where $i = 1, 2, ..., n$).

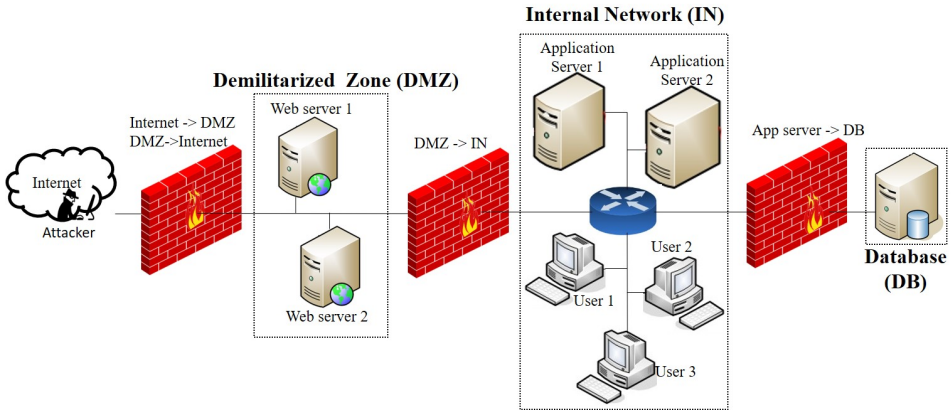


Figure 3.1: Configuration of the network.

Table 3.1: OSes and applications running on hosts.

Host	OS	Service
WS_1	Redhat Enterprise Linux 6	Apache http server 2.4
WS_2	Redhat Enterprise Linux 6	Apache http server 2.4
AS_1	Windows 10	WebLogic server 12.1
AS_2	Redhat Enterprise Linux 6	Apache tomcat 7.0
DB	Windows 10	Oracle database 11g
$User_i$	Redhat Enterprise Linux 6	Mozilla firefox 31.1.0

3.2.2 Attacker Model

Users from the Internet can have access to services in the network. An attacker can easily access network hosts and compromise them remotely. A targeted attack scenario is considered in which an attacker is interested in the DB containing sensitive information. The entry points of the attacker are the web servers. There is only one attacker, and the attacker is located outside of the network (for example, an outside attacker can come from the Internet or a partner network linked to the enterprise network such as customers or vendors). In this model, the attack goal is to escalate privileges within a low privilege account and gain access to administrator rights and further steal sensitive information.

The DB is running the Oracle database that has a forever day vulnerability in its current version. The CVE [115] ID for the vulnerability is CVE-2012-1675. It is often impossible to patch the "forever day" vulnerability as the vendor is unlikely to provide the patch (for example, the service is no longer available or the vendors no longer support that product) and this vulnerability can be remotely exploited without authentication (i.e., without the need for a username and password) thus allowing the attacker to gain the root privilege with full control of the DB. It is assumed that the attacker cannot compromise the target host directly. However, once the attacker successfully compromises a host, the attacker can gain the root privilege of the host and subsequently attack the next host in the network until the target host is reached. Besides,

the attacker must exploit vulnerabilities at the OS and the database level in order to have full control of the target host (i.e., the DB).

3.3 Formalism of T-HARM

The main goal of the T-HARM is to analyse the security of dynamic networks. Specifically, the T-HARM captures the security of network states at varying times by constructing multiple HARMs for each time interval. Moreover, it captures all the security changes onto two layers: the upper and the lower layer. In the upper layer, the temporal hosts' reachability information of the hosts is captured while the changing vulnerabilities information is captured in the lower layer.

3.3.1 Definitions of T-HARM

Given t_i (where $i = 1, 2, \ldots, n$), a discrete time in a time window T, the T-HARM is define as follows.

Definition 1. *T-HARM is a 3-tuple* $T - HARM = (S, H, V)$*, where* $S = \{s_{t_0}, s_{t_1}, \ldots, s_{t_n}\}$ *is a set of HARM for each network state at time* t_i*,* $H = \{h_0, h_1, \ldots\}$ *is a set of all hosts in the network, and* $V = \{v_0, v_1, \ldots\}$ *is a set of all vulnerabilities in the network.* $H_{t_i} \subseteq H$ *is a set of hosts only in the network state at time* t_i*, and* $V_{t_i} \subseteq V$ *is a set of vulnerabilities only in the network state at time* t_i*.*

In addition, the HARM for each discrete time t_i is defined as follows.

Definition 2. *A HARM at time* t_i *is a 3-tuple* $s_{t_i} = (U_{t_i}, L_{t_i}, C_{t_i})$*, where* U_{t_i} *is the upper layer (dynamic AG) that models the set of hosts* H_{t_i}*, and* L_{t_i} *is the lower layer (dynamic ATs) that models the set of vulnerabilities* V_{t_i} *for each host* $h \in H_{t_i}$*, respectively. The mapping between the upper and the lower layers is defined as* $C_{t_i} \subseteq \{(h_j \leftrightarrow at_{t_i,k})\} \forall h_j \in U_{t_i}, at_{t_i,k} \in L_{t_i}$ *(here,* $k = 1, 2, \ldots$ *denotes a distinct attack tree* $at_{t_i,k}$ *in the lower layer).*

The attributes; the set of HARMs S, the set of hosts H, and the set of vulnerabilities V are described as follows:

- Each HARM $s_{t_i} \in S$ has a set of hosts $s_{t_i}^{hosts} \subseteq H_{t_i}$, a set of vulnerabilities $s_{t_i}^{vuls} \subseteq V_{t_i}$, a set of metrics $s_{t_i}^{metrics} \in \{$attack cost, attack risk, ROI, $\ldots\}$, a topology information $s_{t_i}^{topo} \in \{bus, tree, \ldots\}$.

- Each host $h_j \in H_{t_i}$ has a set of adjacent hosts $h_j^{adj} \subseteq H_{t_i}$, a set of vulnerabilities $h_j^{v} \subseteq V_{t_i}$, and a set of security metrics $h_j^{metrics} \in \{$attack cost, attack risk, $ROI, \ldots\}$.

- Each vulnerability $v_k \in V_{t_i}$ has a privilege level that is acquired by the attacker after the vulnerability is successfully exploited $v_k^{privilege} \in \{root$, $user$, ...$\}$ and a set of security metrics $v_k^{metrics} \in \{$attack cost, attack risk, $\ldots\}$.

Definition 3. *A dynamic AG is a directed graph $U_{t_i} = ag_{t_i} = (H_{t_i}, E_{t_i})$ at time t_i, where H_{t_i} is a finite set of hosts and $E_{t_i} \subseteq H_{t_i} \times H_{t_i}$ is a set of edges. Let Z be a sequence of attacker's states which include one or multiple attackers and $z \in Z$ is a sequence of states $z_{t_0}, z_{t_1}, ..., z_{t_n}$, where n is the total number of states, $Z \notin S$ and $Z_{hosts} \cap H_{t_i} = \emptyset$. The representation of the upper layer is given by $H_{t_i} \subseteq S \cup Z$ and $E_{t_i} \subseteq (S \cup Z) \times S$.*

Definition 4. *A dynamic AT is a 5-tuple $at_{t_i,k} = (A_{t_i,k}, B_{t_i,k}, c_{t_i,k}, g_{t_i,k}, root_{t_i,k}), (L_{t_i} = \{at_{t_i,1}, at_{t_i,2}, \ldots at_{t_i,k}, \ldots\})$ at time t_i. Here, $A_{t_i,k} \subseteq V_{t_i}$ is a set of vulnerabilities, $B_{t_i,k} = \{b_{t_i,k}^1, b_{t_i,k}^2, \ldots\}$ is a set of gates, $c_{t_i,k} \subseteq \{b_{t_i,k}^j \rightarrow e_l\} \forall b_{t_i,k}^j \in B_{t_i,k}, e_l \in A_{t_i,k} \cup B_{t_i,k}$ is a mapping of gates to vulnerabilities and other gates, $g_{t_i,k} \subseteq \{b_{t_i,k}^j \rightarrow \{AND, OR\}\}$ specifies the type of each gate, and $root_{t_i,k} \in A_{t_i,k} \cup B_{t_i,k}$ is the root node of the $at_{t_i,k}$.*

The gates $\{AND, OR\}$ have relationships to vulnerabilities and other gates that establish the connection $c_{t_i,k}$ (the vulnerability of a host are combined using AND and OR gates). However, structuring the relationships between the above components of the AT (i.e., gates and vulnerabilities) are outside

the scope of this thesis. The construct of the AT structures can be found in [6, 77, 145], which can be used to generate ATs used here.

Example 1. *The mapping between the upper and lower layer components*: Figure 3.2 (the upper layer) shows T-HARM of the enterprise network when a new host connect to the network. The T-HARM at time t_2 is $s_{t_2} = (U_{t_2}, L_{t_2}, C_{t_2})$, where U_{t_2} and L_{t_2} are the AGs and the set of ATs in the upper and the lower layer at t_2, respectively, and C_{t_2}: $U_{t_2} \rightarrow L_{t_2}$ is a one-to-one mapping of the upper layer U_{t_2} to the corresponding lower layer L_{t_2}.

Example 2. *The Upper Layer Components*: At t_2, the AG in the upper layer is shown in Figure 3.2. The AG is a directed graph $ag_{t_2} = (H_{t_2}, E_{t_2})$, where $H_{t_2} = \{A, WS_1, WS_2, User_1, User_2, User_3, User_4, AS_1, AS_2, DB\}$ and $E_{t_2} = \{(A, WS_1), (A, WS_2), (WS_1, User_1), (WS_1, AS_1), (WS_1, User_2), (WS_1, User_3), (WS_1, User_4), (WS_2, User_1), (WS_2, User_2), (WS_2, User_3), (WS_2, User_4), (WS_2, AS_2), (User_1, AS_1), (User_1, AS_2), (User_2, AS_1), (User_2, AS_2), (User_3, AS_1), (User_3, AS_2), (User_4, AS_1), (User_4, AS_2), (AS_1, DB), (AS_2, DB)\}$.

Example 3. *The Lower Layer Components*: The ATs in the lower layer at t_2 is shown in Figure 3.2 (the lower layer). The set of conditions required to compromise WS_1 at t_2 is given by at_{t_2,WS_1}=(A_{t_2,WS_1}, B_{t_2,WS_1}, c_{t_2,WS_1}, g_{t_2,WS_1}, $root_{t_2,WS_1}$). Where $A_{t_2,WS_1} = \{v_8, v_9\}$ is a set of vulnerabilities for WS_1, $B_{t_2,WS_1} = OR^1_{t_2,WS_1}$, $c_{t_2,WS_1} = \{OR^1_{t_2,WS_1} \rightarrow \{v_8, v_9\}\}$ (i.e., the mapping of gates to vulnerabilities and other gates), $g_{t_2,WS_1} \subseteq \{OR^1_{t_2,WS_1} \rightarrow \{AND, OR\}\}$, and $root_{t_2,WS_1} \in A_{t_2,WS_1} \cup B_{t_2,WS_1}$ is the root node of the at_{t_2,WS_1}.

3.4 Changes in Dynamic Networks

In this section, a categorisation of network changes based on the causes of configuration changes is proposed. Then, the T-HARM definition is extended to include the formalism of the dynamic security changes as well (in Section 3.4.2).

3.4.1 Categorisation of Network Changes

In networks, there are hosts and edges (i.e., links connecting hosts). For each host, there are applications and OS running on it and these components are also with vulnerabilities (i.e., security weaknesses) [105]. The security status of the hosts, edges, applications, OSes and vulnerabilities can be affected by the activities of the users, network administrators and even other events not under the control of the administrators (e.g., software ageing, the discovery of a new vulnerability, *etc*). Hence, the network configuration is changing continuously.

Here, since changes in network configuration can change the security posture of networks [19], the causes of network changes and the possible security changes with respect to a GSM is identified and categorised into two main categories which are; "change in host" and "change in edges (reachability)" (in Table 3.2), respectively. The possible types of security changes are:

- (1) Addition of node (AN)
- (2) Removal of node (RN)
- (3) Addition of edge (AE)
- (4) Removal of edge (RE)
- (5) Addition of vulnerability (AV) and
- (6) Removal of vulnerability (RV)

Further, the relationship between the network changes and the security changes are correlated and they are shown in Table 3.2. For example, the update of a host software can possibly remove existing vulnerability, remove a connection (i.e., a reachable attack path), or remove a node from the security model (if the node has no vulnerability).

Table 3.2: Categorisation of network changes

Enterprise network changes		Possible change(s) in GSM
Categories	Subcategories	
Host	Update software	RV, RE, RN
	Uninstall software	RV, RN, RE
	Install software	AV, AN, AE
	Software turn on or enable	AV, AN, AE
	Software turn off or disable	RV, RN, RE
Edges (reachability)	Firewall rules change (e.g., addition new rule)	AE, RE
	Forwarding table change (by SDN)	AE, RE
	Connection of new host	AN, AE, AV
	Disconnection of existing host	RN, RE, RV
	Host turn on	AN, AE, AV
	Host turn off or failure	RN, RE, RV

3.4.2 Formalism of Security Changes in T-HARM

The changes in security with respect to network changes in the T-HARM are described and formalised as follows:

The addition of a host: The addition of hosts increases the number of host(s) in the network system, which changes both the upper and the lower layers of s_{t_i} in the T-HARM. The definition is given as follows.

Definition 5. *The addition of a host h_j changes the HARM s_{t_i}= (U_{t_i}, L_{t_i}, C_{t_i}) to $s_{t_{i+1}} = (U_{t_{i+1}}, L_{t_{i+1}}, C_{t_{i+1}})$. The HARM upper layer $U_{t_{i+1}} = (H_{t_{i+1}}, E_{t_{i+1}})$ has a new set of hosts $H_{t_{i+1}} = H_{t_i} \cup \{h_j\}$, and a new set of edges $E_{t_{i+1}} = E_{t_i} \cup \{(h_j, h_x)\} \forall h_x \in h_j^{adj}$. The HARM lower layer changes with a new set of attack trees $L_{t_{i+1}} = L_{t_i} \cup \{at_{t_{i+1},k}\} \mid h_j^v = A_{t_{i+1},k}$, where $at_{t_{i+1},k}$ is*

a new attack tree that captures the vulnerabilities of h_j. Lastly, the new mapping between the upper and the lower layers of the HARM changes to $C_{t_{i+1}} = C_{t_i} \cup \{(h_j \leftrightarrow at_{t_{i+1},k})\}$.

The removal of a host: The removal of hosts reduces the number of hosts in the network systems. When this happens, the reachability and vulnerabilities associated with the hosts are removed as well. Thus, the upper and lower layers of the T-HARM are changed. This is formally defined as:

Definition 6. *The removal of a host h_j changes the HARM s_{t_i}= (U_{t_i}, L_{t_i}, C_{t_i}) to $s_{t_{i+1}} = (U_{t_{i+1}}, L_{t_{i+1}}, C_{t_{i+1}})$. The HARM upper layer $U_{t_{i+1}} = (H_{t_{i+1}}, E_{t_{i+1}})$ has a new set of hosts $H_{t_{i+1}} = H_{t_i} - \{h_j\}$, and a new set of edges $E_{t_{i+1}} = E_{t_i} - \{(h_j, h_x)\} \forall h_x \in h_j^{adj}$. The HARM lower layer changes with a new set of attack trees $L_{t_{i+1}} = L_{t_i} - \{at_{t_i,k}\}$, where $h_j \leftrightarrow at_{t_i,k}$. Lastly, the new mapping between the upper and the lower layers of the HARM changes to* $C_{t_{i+1}} = C_{t_i} - \{(h_j \leftrightarrow at_{t_i,k})\}$.

The addition of a vulnerability: Given a new vulnerability v_x, the AT $at_{t_i,k}$ of a host h_j where $h_j \leftrightarrow at_{t_i,k}$ in C_{t_i} in the T-HARM at time t_i is changed when a new vulnerability is found for that host. The lower layer is changed in the HARM, the list of vulnerabilities for the host is updated, and the set of vulnerabilities at a time t_{i+1} is also updated. The definition is given as follows.

Definition 7. *The addition of a vulnerability v_x changes the AT $at_{t_i,k}$ of a host h_j with $h_j \leftrightarrow at_{t_i,k}$ in C_{t_i} and $v_x \in h_j^v \subseteq V_{t_{i+1}}$. This changes $at_{t_i,k}$ to $at_{t_{i+1},k} = (A_{t_{i+1},k}, B_{t_{i+1},k}, c_{t_{i+1},k}, g_{t_{i+1},k}, root_{t_{i+1},k})$, where $A_{t_{i+1},k} = A_{t_i,k} \cup \{v_x\}$ (i.e., v_x is added to the set of vulnerabilities), $B_{t_{i+1},k} = B_{t_i,k} \cup \{b^y_{t_{i+1},k}\}$ $\forall b^y_{t_{i+1},k} \rightarrow e_l \mid e_l \in A_{t_{i+1},k} \cup B_{t_{i+1},k}$ (i.e., new gates are added to connect other vulnerabilities and gates with relation to v_x), $c_{t_{i+1},k} = c_{t_i,k} \cup \{b^y_{t_{i+1},k} \rightarrow e_l\}$ where $e_l \in A_{t_{i+1},k} \cup B_{t_{i+1},k}$ and e_l has a relation to v_x. $g_{t_{i+1},k} = g_{t_i,k}$ (i.e., unchanged set of gate types). Finally, $root_{t_{i+1},k} = \in A_{t_{i+1},k} \cup B_{t_{i+1},k}$ (i.e., may have a new root node based on the relationship of v_x). A list of vulnerabilities is updated to* $V_{t_{i+1}} = V_{t_i} \cup \{v_x\}$.

The removal of a vulnerability: Various event (e.g., applying security countermeasures, uninstalling a vulnerable application, *etc.*) change the lower layer of T-HARM. And as a result, it will need to be updated, and this change is defined as:

Definition 8. *The removal of a vulnerability v_x from a host h_j (where $h_j \leftrightarrow at_{t_i,k}$) will change the AT $at_{t_i,k}$ to $at_{t_{i+1},k} = (A_{t_{i+1},k},\ B_{t_{i+1},k},\ c_{t_{i+1},k},\ g_{t_{i+1},k},\ root_{t_{i+1},k})$, where $A_{t_{i+1},k} = A_{t_i,k} - \{v_x\}$, $B_{t_{i+1},k} = B_{t_i,k} - \{b^y_{t_{i+1},k}\}$ (i.e., if v_x is the only vulnerability associated with the gate), $c_{t_{i+1},k} = c_{t_i,k} - \{b^y_{t_{i+1},k} \rightarrow e_l\}$. $g_{t_{i+1},k} = g_{t_i,k}$ (i.e., unchanged set of gate types). Finally, $root_{t_{i+1},k} = root_{t_i,k}$. A list of vulnerabilities is updated to $V_{t_{i+1}} = V_{t_i} - \{v_x\}$.*

The addition of an edge: An edge is created when there is a connection between hosts. Hence, the set of edges is updated when a new connection is created, and here, only the upper layer of T-HARM has changed. This is defined as:

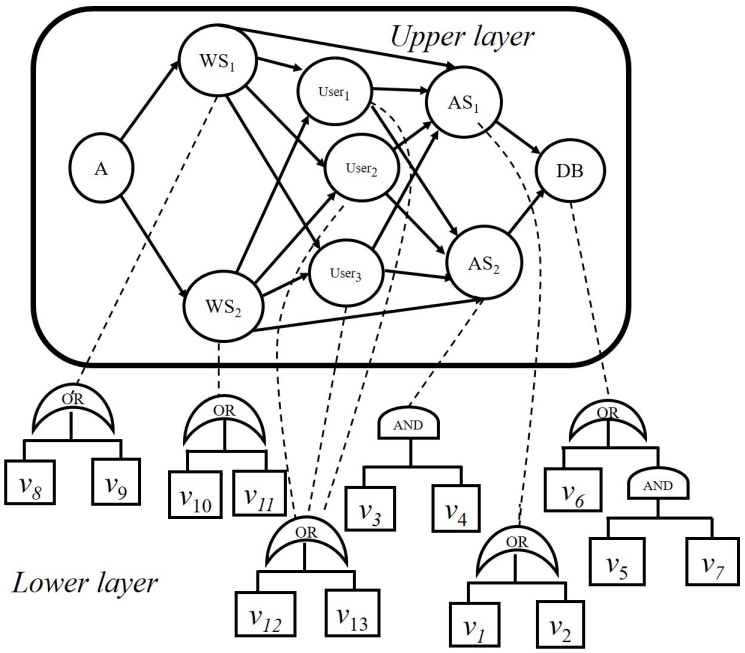
Definition 9. *Given a new connection between hosts h_j and h_m at time t_{i+1}. The HARM s_{t_i} is changed to $s_{t_{i+1}} = (U_{t_{i+1}}, L_{t_{i+1}}, C_{t_{i+1}})$, where the upper layer $U_{t_{i+1}} = (H_{t_{i+1}}, E_{t_{i+1}})$ has a new edge such that $E_{t_{i+1}} = E_{t_i} \cup \{(h_j, h_m)\}$, H_{t_i}=$H_{t_{i+1}}$. Here, the lower layer $L_{t_{i+1}} = L_{t_i}$ and the mapping between the upper layer to the lower layer $C_{t_{i+1}} = C_{t_i}$ is unchanged.*

The removal of an edge: Similarly, an edge is removed from hosts when the reachability between them is disconnected. As a result, only the upper layer of T-HARM is changed accordingly. The removal of edges is defined as follows.

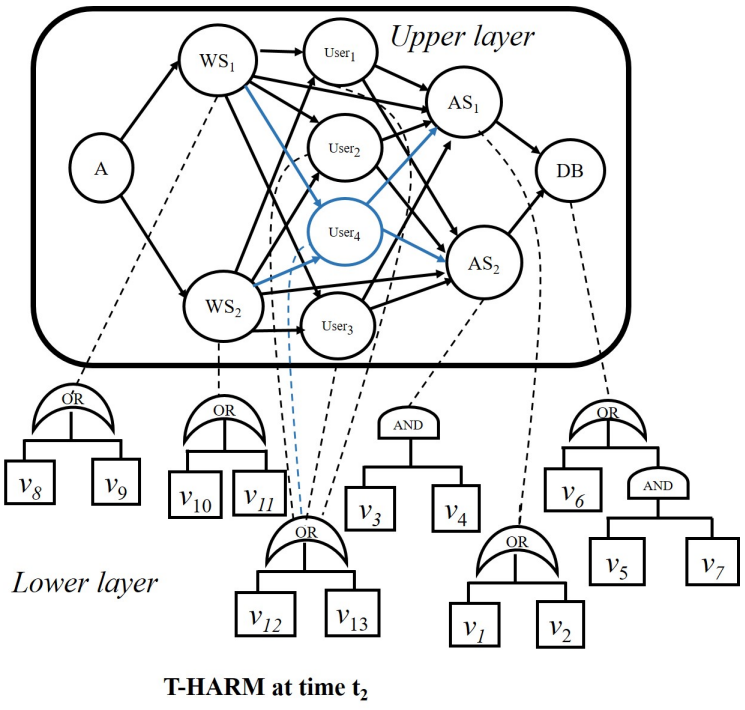
Definition 10. *Given a connection between hosts h_j and h_m. The HARM s_{t_i} is changed to $s_{t_{i+1}} = (U_{t_{i+1}}, L_{t_{i+1}}, C_{t_{i+1}})$, where the upper layer $U_{t_{i+1}} = (H_{t_{i+1}}, E_{t_{i+1}})$ is changed such that $E_{t_{i+1}} = E_{t_i} - \{(h_j, h_m)\}$ and $H_{t_{i+1}} = H_{t_i}$. Here, the lower layer and the mapping between the upper layer to the lower layer is unchanged (i.e., $L_{t_{i+1}} = L_{t_i}$ and $C_{t_{i+1}} = C_{t_i}$), respectively.*

3.4.3 Construction of T-HARM: An Example

The T-HARM is used to capture network changes at different times. A flexible time window can be assumed, so this can be adjusted to different time and interval as desired (e.g., 5 hours or 1 day) thus providing a different view to evaluate the security over time. An example T-HARM is shown in Figure 3.2 for the network shown in Figure 3.1 when a new workstation is connected to the network.



(a) T-HARM at t_1



(b) T-HARM at t_2

Figure 3.2: Example T-HARM when a change is detected (with T = 2)

3.5 Summary

The T-HARM and its formalisms are presented in this chapter. Also, a systematic categorisation of possible security changes with respect to network changes is presented along with its description and formalism. This chapter developed the GSMs and introduced the security changes to be considered in the remaining part of this thesis.

Chapter 4

Dynamic Security Assessments

Many security metrics for assessing cybersecurity have been developed and formalised [34, 79, 114, 123, 126, 130, 136]. While these metrics remain useful in assessing the security of networks, their effectiveness with respect to dynamic changes in the network is still unclear. Therefore, it is important to investigate how different security metrics are affected by changes in the network, in order to identify which ones are suitable or not suitable for dynamic analysis.

First, this chapter describes composite security metrics for the security analysis of networks. Second, it investigates the varying effects of security metrics when changes are observed in the network. This investigation aims to assist network/security administrators with the experimental results to determine the security metric to use when a certain type of changes occurs in a dynamic network. Based on the existing literature, this is the first work to comprehensively investigate the effectiveness of existing security metrics for the assessments of dynamic networks. The main contributions of this chapter are summarised as follows:

- Proposed an approach to combining security metrics;
- Investigate the effect of the various network changes on the existing security metrics over time;
- Conduct a comprehensive security analysis with various changes in T-

HARM;

- Categorise the effectiveness of the security metrics with respect to the security changes.

4.1 Composite Security Metrics

Based on the classification of the current security metrics in Section 2.2.1, an approach to develop *composite security metrics* is proposed. For these metrics, individual metrics are combined to create a new metric (for example, attack impact and attack path metric are combined to form the impact on attack path metric, see Figure 4.1 for more examples). The formulation of the composite metrics is shown for the following only: (i). Impact on attack paths (ii). Risk on attack paths (iii). Probability of attack success on paths.

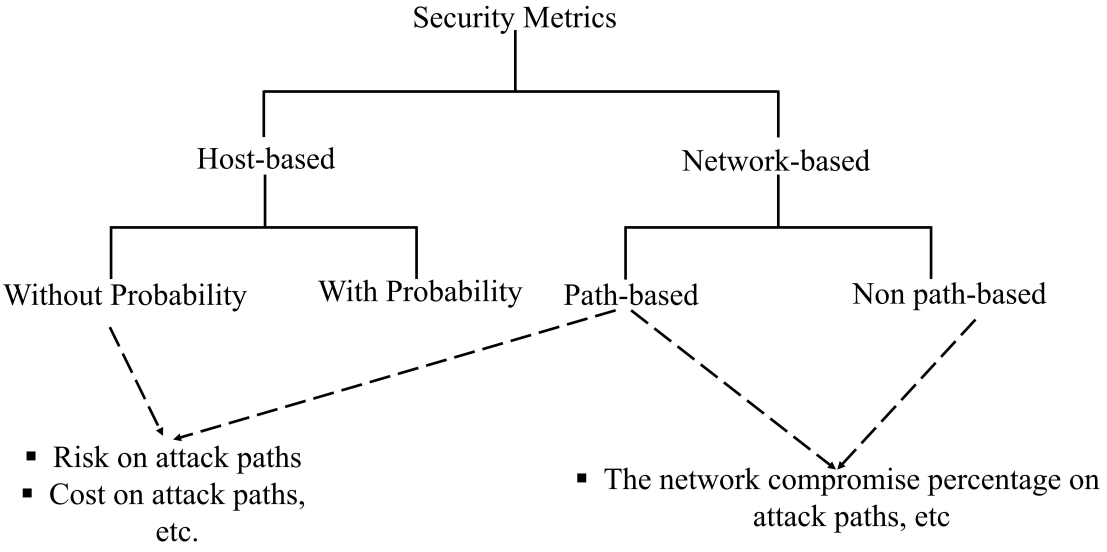


Figure 4.1: Examples of composite security metrics.

4.1.1 Impact on Attack Paths

The native metric (as one of the path-based metrics) used to create the impact of paths is attack paths. Mainly, it combines the attack path metrics

with the impact of each host in the path. The Impact on Attack Paths is defined as the cumulative quantitative measure of potential harm on an attack path. Here, the vulnerability level metric is calculated by Equation (4.1), the host attack impact is calculated by equation (4.2) and the attack-path level metric is calculated by Equation (4.3). The network-level value AIM_{t_i} is then given by Equation (4.4).

$$aim_{b_{t_i}} = \begin{cases} \sum\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} aim_{v_{t_i}}, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = AND} \\ \max\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} aim_{v_{t_i}}, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = OR} \end{cases} \tag{4.1}$$

$$aim^{h}_{t_i} = aim_{root_{t_i}} \tag{4.2}$$

$$aim^{ap_i}_{t_i} = \sum_{h_{t_i} \in ap_i} aim^{h}_{t_i}, \quad ap_i \in AP_{ns_{t_i}} \tag{4.3}$$

$$AIM_{t_i} = \max_{ap_i \in AP_{ns_{t_i}}} aim^{ap_i}_{t_i} \tag{4.4}$$

The impact on path metric can reveal the impact of damage associated with each attack path. A security administrator can use this metric to determine which path to patch first. For instance, hosts in the path with the highest impact value can be considered as the prioritised set of hosts to patch.

4.1.2 Risk on Attack Paths

The Risk on attack paths is defined as the expected value of the impact on an attack path. It is computed as the summation of the product of the probability of attack success pr_h and the amount of damage aim_h h belonging to an attack path ap. In the equation, the vulnerability level risk is calculated by Equation (4.5), the host risk metric is calculated by Equation (4.6) and the attack path level metric is calculated by Equation (4.7). The network-level

value R_{t_i} is then given by Equation (4.8).

$$r_{b_{t_i}} = \begin{cases} \sum\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} pr_{v_{t_i}} \times aim_{v_{t_i}}, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = AND} \\ \max\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} pr_{v_{t_i}} \times aim_{v_{t_i}}, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = OR} \end{cases} \tag{4.5}$$

$$r^h_{t_i} = r_{root_{t_i}} \tag{4.6}$$

$$r^{ap_i}_{t_i} = \sum_{h_{t_i} \in ap_i} pr^h_{t_i} \times aim^h_{t_i}, \quad ap_i \in AP_{ns_{t_i}} \tag{4.7}$$

$$R_{t_i} = \max_{ap_i \in AP_{ns_{t_i}}} r^{ap_i}_{t_i} \tag{4.8}$$

4.1.3 Probability of Attack Success on Paths

The probability of attack success on paths is developed by combining path and probability of attack success. The probability of attack success on paths represents the chances of an attacker successfully reaching the target through an attack path. Equation 4.9 defines the vulnerability level attack success probability, Equation (4.10) defines the host level attack success probability, Equation (4.11) defines the attack path attack success probability. The network-level value Pr_{t_i} is then given by Equation (4.12).

$$pr_{b_{t_i}} = \begin{cases} \prod\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} pr_{v_{t_i}}, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = AND} \\ 1 - \prod\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} (1 - pr_{v_{t_i}}), & \substack{b_{t_i} \in B_{t_i} \\ g(b_{t_i}) = OR} \end{cases} \tag{4.9}$$

$$pr_{h_{t_i}} = pr_{root_{t_i}} \tag{4.10}$$

$$pr^{ap_i}_{t_i} = \prod_{h_{t_i} \in ap_i} pr^h_{t_i}, \quad ap_i \in AP_{ns_{t_i}} \tag{4.11}$$

$$Pr_{t_i} = \max_{ap_i \in AP_{ns_{t_i}}} pr_{t_i}^{ap_i} \tag{4.12}$$

4.2 Evaluating the Effectiveness of Existing Security Metrics for Dynamic Networks

This section investigates the effectiveness of the existing security metrics for the analysis of dynamic networks. The metrics (and their formula) used in this investigations are outlined in Section 4.2.1.

4.2.1 Security Metrics and their Computations

Eleven main security metrics from [33,79,102,126] are evaluated (in addition to the composite metrics). The metrics and their formulas are shown in Table 4.1. For each formula, the attribute time t is introduced so that it can be used in the T-HARM.

Vulnerabilities are collected from a repository NVD [115]) which contains vulnerabilities and their standardised severity score (in real networks, such information is collected using scanners such as Nmap [120], OpenVAS [125], *etc*). These scores are ranging from 0.0 to 10.0, with 10.0 being the most severe level. The vulnerability impact sub score is used as the aim_v and based on the vulnerability CVSS BS [115], values are assigned to the pr_v and ac_v for each of the vulnerabilities.

To evaluate the metrics, T-HARM is used to find all potential attack paths over time. The potential attack paths *ap* are calculated in the upper layer of T-HARM (the potential attack paths and entry point can change over time). The host level metrics $ac_{t_i}^h$, $r_{t_i}^h$, $pr_{t_i}^h$, $aim_{t_i}^h$ and $roa_{t_i}^h$ are calculated from the lower layer of T-HARM. The metrics NAP_{t_i}, MoPL_{t_i}, SDPL_{t_i}, MAPL_{t_i}, NMPL_{t_i} and SAP_{t_i} [79] are calculated in the the upper layer of the T-HARM while the metrics R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i} and PSS_{t_i} are calculated using the host level

metrics in the upper layer.

Table 4.1: Formulae for the security metrics

S/N	Metrics	Formulae
1.	R_{t_i}	$r_{t_i}^{ap_i} = \sum_{h \in ap_i} pr_{t_i}^h \times aim_{t_i}^h, ap_i \in AP_{ns_{t_i}}$
		$R_{t_i} = \max_{ap_i \in AP_{ns_{t_i}}} r_{t_i}^{ap_i}$
2.	AC_{t_i}	$ac_{t_i}^{ap_i} = \sum_{h \in ap_i} ac_{t_i}^h, ap_i \in AP_{ns_{t_i}}$
		$AC_{t_i} = \min_{ap_i \in AP_{ns_{t_i}}} ac_{t_i}^{ap_i}$
3.	Pr_{t_i}	$pr_{t_i}^{ap_i} = \prod_{h \in ap_i} pr_{t_i}^h, ap_i \in AP_{ns_{t_i}}$
		$Pr_{t_i} = \max_{ap_i \in AP_{ns_{t_i}}} pr_{t_i}^{ap_i}$
4.	ROA_{t_i}	$roa_{t_i}^{ap_i} = \sum_{h \in ap_i} \frac{pr_{t_i}^h \times aim_{t_i}^h}{ac_{t_i}^h}, ap_i \in AP_{ns_{t_i}}$
		$ROA_{t_i} = \max_{ap_i \in AP_{ns_{t_i}}} roa_{t_i}^{ap_i}$
5.	SAP_{t_i}	$SAP_{t_i} = \min_{ap_i \in AP_{ns_{t_i}}} \lvert ap_i \rvert$
6.	NAP_{t_i}	$NAP_{t_i} = \lvert AP_{ns_{t_i}} \rvert$
7.	$MAPL_{t_i}$	$MAPL_{t_i} = \frac{\sum_{ap_i \in AP_{ns_{t_i}}} \lvert ap_i \rvert}{NAP_{t_i}}$
8.	$SDPL_{t_i}$	$SDPL_{t_i} = \sqrt{\frac{\sum_{ap_i \in AP_{ns_{t_i}}} (\lvert ap_i \rvert - MAPL)^2}{NAP_{t_i}}}$
9.	$MoPL_{t_i}$	$MoPL_{t_i} = \underset{ap_i \in AP_{ns_{t_i}}}{f} (\lvert ap_i \rvert)$
10.	$NMPL_{t_i}$	$NMPL_{t_i} = \frac{MAPL_{t_i}}{NAP_{t_i}}$
11.	PSS_{t_i}	$PSS_{t_i} = \frac{NSS_{t_i}}{TNH_{t_i}} \times 100$

4.2.2 Effective Patch Management using Prioritised Set of Vulnerabilities

It is important to patch the vulnerabilities that are found on the network in order to protect the organisation's IT assets from cyber-attacks. However, due to some constraints such as budget, time, unavailability of patches, *etc*, it

is sometimes infeasible to patch all the identified vulnerabilities [24]. Hence, the approach called PSV [76] method is used to determine the set of critical vulnerabilities to patch first for the network. A PSV is defined as a set of vulnerabilities which are most important to enhance security. It is possible to use the PSV method using a Top-Down, Bottom-Up or Hybrid approach to manage the vulnerabilities found in the network system. Work [76] has the complete detail of those approaches. The hybrid method is adapted for this chapter, and the description is provided in Section 4.2.2.1.

4.2.2.1 PSV hybrid method

The hybrid method is used to rank vulnerabilities based on values calculated from assigning weights to value of vulnerabilities and hosts, then combining them to get a combined important measures value for each vulnerability. The combined important measures value (CV_v) for each vulnerability is calculated by equation (4.13).

$$CV_v = \alpha NM^h_{v_{name}} + (1 - \alpha)v_{metric} \tag{4.13}$$

Where:

- v_{name} is a vulnerability;
- $NM^h_{v_{name}}$ is the Network Centrality Measure value for a host h containing the vulnerability v_{name};
- v_{metric} is the security metric for the v_{name}.
- $0 \leq \alpha \leq 1$ is a weight value
- A weight value of $\alpha = 0.5$ is reasonable selected and used. However, this value can be adjusted such that the most important factor (e.g., the vulnerability or the well connected host) is giving a higher weight value.

The CVSS BS is used to determine the priority for vulnerabilities, and three NCMs (including degree, closeness and betweenness) to determine the priority of hosts, respectively. For each vulnerability, the importance value of that vulnerability is combined with the importance value of the host using the equation (4.13). The details for the CVSS vulnerabilities and the NCMs computation can be found in [115] and [69], respectively. The importance measures computed for the initial state of the enterprise network are summarised in Table 4.2.

Table 4.2: List of vulnerabilities for the initial network

Host ID	v_{name} ID	CVE-ID	Normalised CVSS BS	$NM^h_{v_{name}}$	CV_v
AS_1	v_1	CVE-2013-0638	1.00	0.3214	0.6607
AS_1	v_2	CVE-2015-0900	0.43	0.3214	0.3757
AS_2	v_3	CVE-2016-0763	0.43	0.3214	0.3757
AS_2	v_4	CVE-2015-0900	0.43	0.3214	0.3757
DB	v_5	CVE-2012-1675	0.75	0.0444	0.3972
DB	v_6	CVE-2013-0900	0.43	0.0444	0.2372
DB	v_7	CVE-2015-6175	0.72	0.0444	0.3822
WS_1	v_8	CVE-2015-3185	0.43	0.6650	0.5475
WS_1	v_9	CVE-2015-5700	0.21	0.6650	0.4375
WS_2	v_{10}	CVE-2015-3185	0.43	0.6650	0.5475
WS_2	v_{11}	CVE-2015-5700	0.21	0.6650	0.4375
$User_i$	v_{12}	CVE-2016-2834	0.88	0.3151	0.5975
$User_i$	v_{13}	CVE-2014-5270	0.19	0.3151	0.2525

4.2.3 Simulation Network and Attacker Model

The enterprise network in Figure 3.1 is used as the initial network state to conduct seven simulations. For the subsequent network states, various network changes are introduced (the changes are listed in Table 4.3), and the processes are described in the various scenarios that they are used below. The following assumptions are made in the simulations:

- dynamic host configuration protocol automatically assigns IP address settings to hosts that are joining the network;

- users can install software on this hosts, and the software may have one or more vulnerability;
- Among other activities, the administrators can perform tasks such as disabling vulnerable hosts, software, *etc.*, and changing of firewall rules;
- there is always at least a type of server that is up and running at any time t in order to guarantee the access of client to the DB (for example, it is ensured that only one of the two web servers (WS_1 and WS_2) is disconnected or removed from the network per time).
- the network states are captured when changes are observed in the network (but in a few scenarios, a fixed change in t between different network states is used).

T-HARM is constructed for the dynamic network using the inputs above and the attacker model specified in Section 3.2.2. Then, several security metrics are calculated in the various scenarios. The simulations focused on investigating the varying effects of security metrics when changes are observed in the network for the following scenarios (such that all the network changes specified in Table 3.2 are captured and analysed): (1) Addition of software vulnerabilities (Section 4.3.1), (2) Addition of new hosts (hosts having vulnerabilities) (Section 4.3.2), (3) Software Update (e.g., patching of vulnerabilities) (Section 4.3.3), (4) Disabling application software (Section 4.3.4), (5) Installation of new application software (Section 4.3.5), (6) Removal of existing hosts (Section 4.3.6), and (7) Change of firewall rules (Section 4.3.7).

Simulation results: Line graphs are used to present the simulation results. In the graphs, the change of time t is presented on the horizontal axis and the normalised metric value on the vertical axis. All the metrics values are normalised (i.e., ranging from 0.0 to 1.0).

4.3 Scenario Descriptions and Results

Experimental analysis via simulations is conducted using the T-HARM for the network changes described in Table 3.2. To achieve this, the network changes with respect to security changes in Table 4.3 are mapped and used for the simulations, accordingly.

Table 4.3: Simulations: security changes with respect to network changes

Changes in security	Causes of configurations change	Related subsection(s)
Addition of vulnerabilities	(1) installation of software	4.3.5
	(2) software turned on or enabled	4.3.5
	(3) addition of new hosts	4.3.2
	(4) discovery of vulnerabilities	4.3.1
Removal of vulnerabilities	(1) update of software	4.3.3
	(2) uninstallation of software	4.3.4
	(3) software turned off or disabled	4.3.4
	(4) removal of hosts	4.3.6
Addition of nodes	(1) addition of hosts	4.3.2
	(2) installation of software	4.3.5
	(3) software turned on or enabled	4.3.5
	(4) host turned on	4.3.2
Removal of nodes	(1) removal of hosts	4.3.6
	(2) uninstallation of software	4.3.4, 4.3.3
	(3) update of software	4.3.3
	(4) software turned off or disabled	4.3.4
Addition of edges	(1) addition of host	4.3.2
	(2) host turn on	4.3.2
	(3) connection of host	4.3.7, 4.3.2
	(4) firewall rules changed	4.3.7
	(5) installation of software	4.3.5
Removal of edges	(1) removal of host	4.3.6
	(2) host turned off or failed	4.3.6
	(3) disconnection of host	4.3.7
	(4) firewall rule changed	4.3.7
	(5) software turned off or disabled	4.3.4

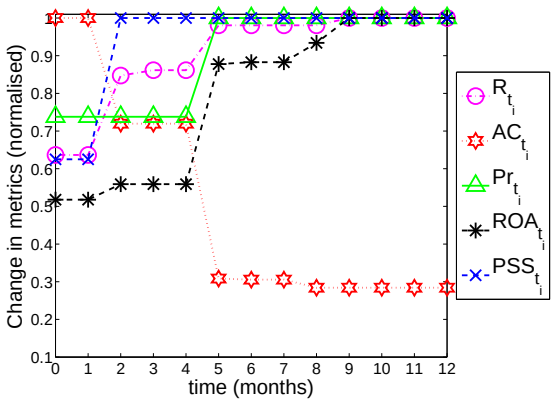
4.3.1 Scenario I: Addition of Vulnerability

Software often has vulnerabilities and these can be discovered (or be emerging) over time [105]. In consequence, the security of hosts in a network system is continuously affected. In this regard, the vulnerabilities of the network states are captured at different time, and it is assumed that the vulnerabilities are not patched between the changes in states. This section aims to capture and investigate how security metrics change when vulnerabilities are discovered over time, and so, it is assumed that the software vendors did not release the patches for the vulnerabilities within those time. Besides, many systems are left unpatched for months and sometimes, even years [147]. In some cases, unknown vulnerabilities (e.g., zero-day vulnerabilities [58]) are impossible to patch. Consequently, this section explores how the existing security metrics change when vulnerabilities are found (announced) and left un-patched (a more detailed description of this scenario is given in [20]).

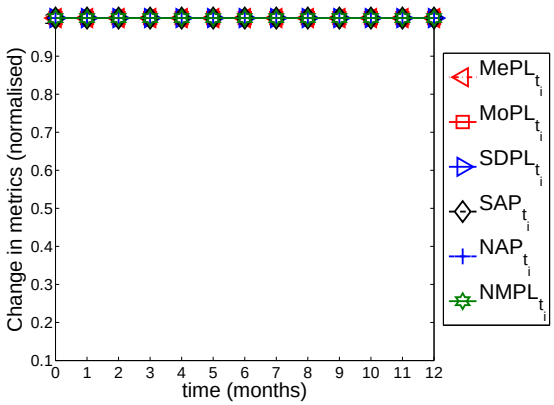
To simulate this, vulnerability data are collected for 12 months (i.e., from April 2015 to March 2016) from the NVD (i.e., for both the OSes and applications summarised in Table 3.1). After that, the collected vulnerabilities are extracted into their respective time of discovery, which is summarised in Table 4.4 and then further, they are used as input (they are used sequentially) into T-HARM (this captures the emergence of the vulnerabilities over time). In this case, it is assumed that the hosts and reachability are not changing. The T-HARM with time window $T = 13$ is used for the analysis and each time t_i is representing a month.

Table 4.4: Summary of the vulnerabilities found for hosts over 12 months

Months	WS_1	WS_2	AS_1	AS_2	DB	$User_i$	Total
Initial	2	2	2	2	3	3×3	17
1						2 ×3	6
2	4	4				6 ×3	26
3	10	10				10 ×3	50
4	1	1				17 ×3	53
5	1	1	10	1	10	1 ×3	26
6	1	1	19	1	19	1 ×3	44
7			6		6		12
8			11		10		21
9	1	1	8		10		20
10	6	6	12		23	1 ×3	50
11			9	7	9		25
12			14		14		28



(a)



(b)

Figure 4.2: Addition of vulnerabilities

Figure 4.2 shows the result of the discovery of vulnerability for the different months. The result show that the metrics R_{t_2}, AC_{t_2} ROA_{t_2} and ROA_{t_2} (i.e., $t = 2$) significantly change at t_2. The reason is, at that point the severity of vulnerabilities on attack paths to the target host has started to become high for each host (which happens as the result of the increase in the number of new vulnerabilities) compared to the earlier network state, thus causing the sharp change in the metric value. Similarly, R_{t_5}, AC_{t_5}, Pr_{t_5} and ROA_{t_5} change significantly and this is for the same reason. On the other hand, the R_{t_9}, AC_{t_9}, ROA_{t_9}, AC_{t_5} and PSS_{t_2} become static at these points because the host level values (i.e., the risk severity value) reach the maximum value (i.e., 10.00 for each of the hosts) and consequently, the network-level security metrics do not change. On the other hand, the other security metrics (i.e., $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$) do not change for all the time as all the hosts in the network regularly have at least one exploitable vulnerability. Hence, it does not change the reachability in the upper layer (i.e., attack paths to the target host) for the entire time window. So, $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$ do not change for all the time; R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i} and PSS_{t_i} continue to deteriorate in their security value. This demonstrates that R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i} and PSS_{t_i} can satisfactory reflect the emergence of vulnerabilities over time.

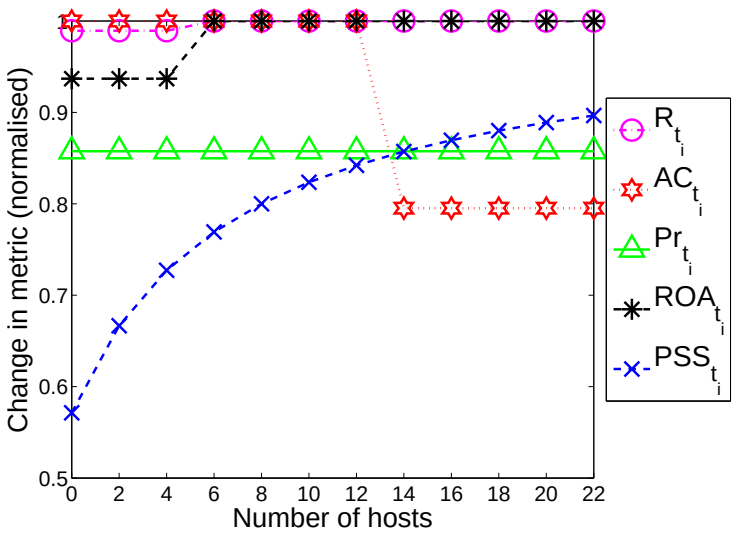
In summary, the results of this scenario showed that R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i} and PSS_{t_i} change in their values accordingly, however as the number of vulnerabilities becomes large for each host, their values become static. Contrarily, the $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$ remain static for all the time.

4.3.2 Scenario II: Addition of Hosts

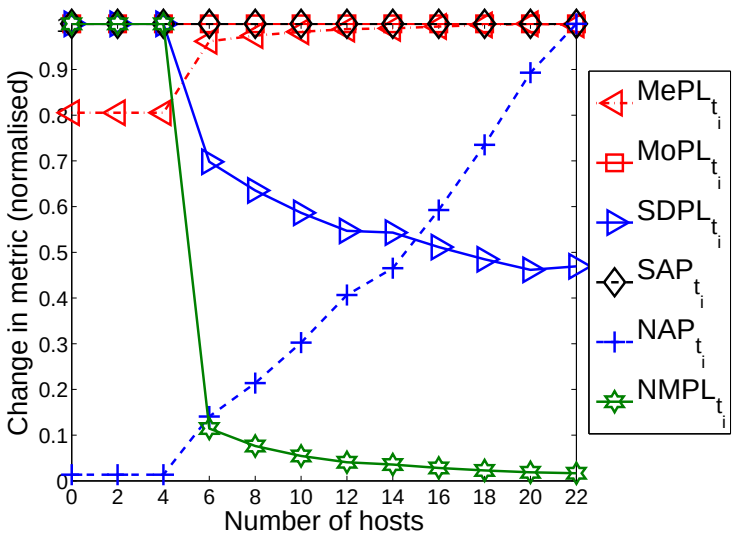
Modern networks are flexible, and as a result, they allow components to be added to the network at various times. Moreover, organisations sometimes increase the size of networks to meet current demands (e.g., by adding new

devices). However, the addition of components can affect the security posture of networks [19]. Hence, this section investigates the effect of the addition of hosts on the existing security metrics.

Here, the addition of hosts to the example network in Figure 3.1 is considered. In the simulation, all the hosts are up and running for all the time. Also, the vulnerabilities listed in Table 4.4 are used for the simulation. Further, the network traffic (for WSs, DB, ASs, and users' workstations) remain as described in Section 3.2.1. However, only the addition of users' workstations is considered. Here, the number of workstations is increased by 20% each time. The results are shown in Figure 4.3.



(a)



(b)

Figure 4.3: Change with respect to addition of hosts

From the result shown in Figure 4.3, the addition of new hosts to the network does not change SAP_{t_i}, MoPL_{t_i} AC_{t_i} and Pr_{t_i} compared to the initial network. However, the metric at R_3 (i.e., at the number of host = 6) and ROA_{t_3} and R_{t_3} and AC_{t_7} (i.e., at the number of host = 14) increase significantly from the previous security state. It is at these two points (and time) that servers are added to the network (i.e., and WS and AS, respectively) thus causing a change

in the metrics value. On the other hand, PSS_{t_i}, $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, NAP_{t_i} and $NMPL_{t_i}$ change progressive for all the time which indicates the decrease in security. Similarly, $MePL_{t_3}$, $MoPL_{t_3}$, $SDPL_{t_3}$, NAP_{t_3} and $NMPL_{t_3}$ indicate significant (sharp) change for the addition of a WS server. Also, it is observed that the SAP_{t_i} does not change because the minimum number of hosts needed along the attack path for an attacker to reach the target remains the same as the initial network configuration. Similarly, the $MoPL_{t_i}$ does not change because the length of attack path that appears the most frequently (for each network state) remains the same as well.

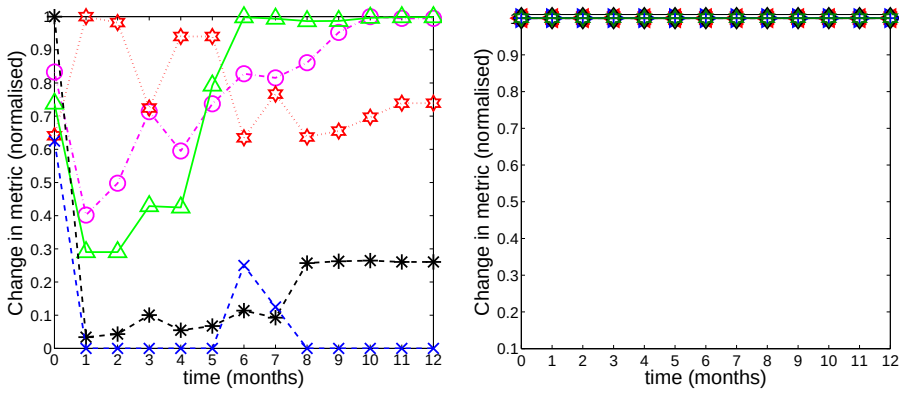
In summary, the results shows that the PSS_{t_i}, $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, NAP_{t_i} and $NMPL_{t_i}$ change significantly. Conversely, R_{t_i}, AC_{t_i} and ROA_{t_i} only show limited change and the SAP_{t_i} and Pr_{t_i} do not change for all the time.

4.3.3 Scenario III: Software Update

Software vendors tend to actively release patches for their software products and then leave it to the customers to decide whether to apply those software corrections or not [42]. The implementation of these updates can remove one or more vulnerabilities from the software and hence, for a networked system (where a cyber-attacker uses this defect to bypass security measures) the removal of these set of vulnerabilities changes the security posture, and the network will need to be re-assessed to determine the security. At this point, it is of interest to investigate what security metrics are changing when software is updated over time.

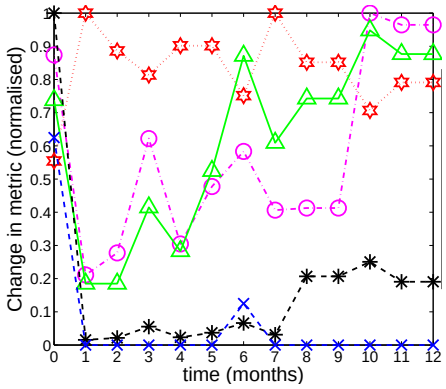
Here, the following assumptions are made: (i) that patches are regularly performed once per month and (ii) that all patches are tested first in a pre-production environment before applying to the network devices (hence, there is no failure during patches). Also, the enterprise network vulnerability information is known for twelve months (as they are collected already from NVD which are shown in scenario 4.3.1). Additionally, since the organisation cannot afford to patch all the vulnerabilities due to cost, time, unavailability

of patches and other security policies, the risk-based PSV using hybrid method is used (from Section 4.2.2.1). Simulations are performed using different PSV values (i.e., 30%, 50% and 70%), however only one PSV value for each time window is used. the results are plotted in Figure 4.4. In particular, the result for the PSV at 30%, 50% and 70% is plotted in Figure 4.4(a) and 4.4(b), 4.4(c) and 4.4(d), 4.4(e) and 4.4(f), respectively.

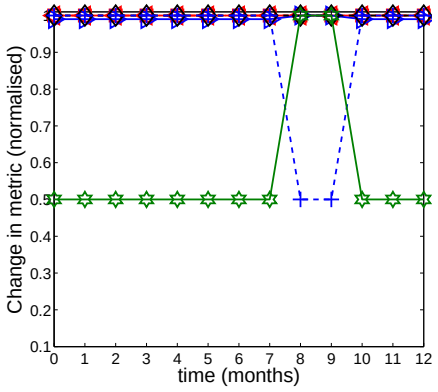


(a) PSV at 30%

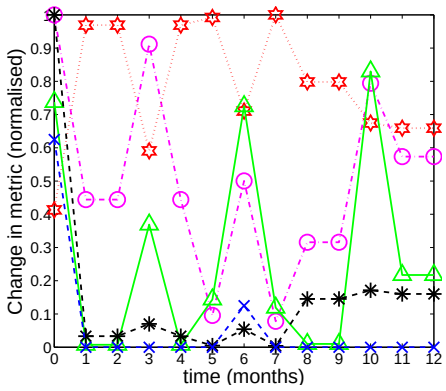
(b) PSV at 30%



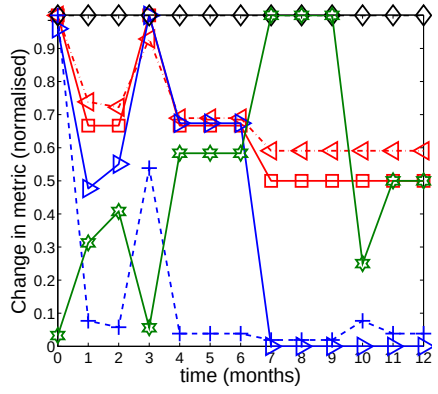
(c) PSV at 50%



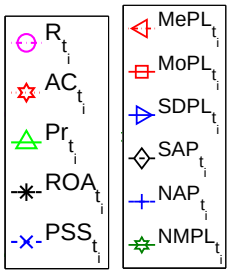
(d) PSV at 50%



(e) PSV at 70%



(f) PSV at 70%

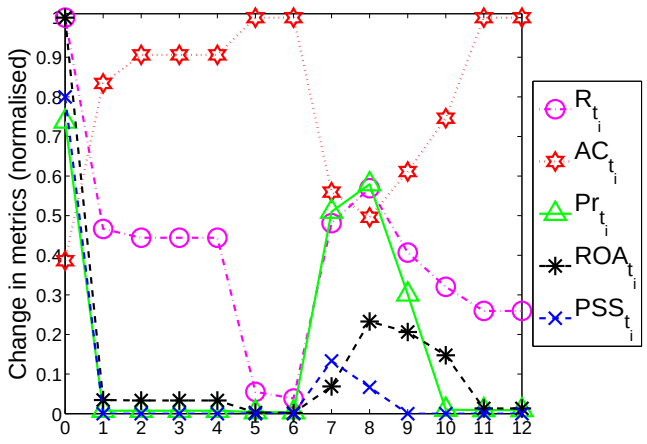


(g) Legend

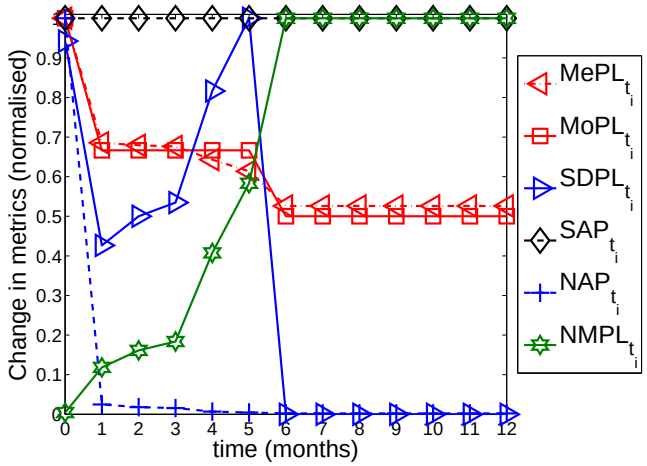
Figure 4.4: Change with respect to emergence and patching of vulnerabilities

In Figure 4.4(a), it is observed that R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i} and PSS_{t_i} change accordingly when vulnerabilities are patched. It is also observed that even when vulnerabilities are patched per month, the security keeps deteriorating over time for the reason that the PSV value used is low compared to the number of vulnerabilities found at each time t. However, the result shows that the regular patching of the vulnerabilities keep the metric PSS_{t_i} very low (since critical vulnerabilities are always patched first). Although, at PSS_{t_6} the value increases because most of the vulnerabilities discovered at this point have high CVSS values (i.e., critical vulnerabilities).

On the other hand, in Figure 4.4(b) SAP_{t_i}, NAP_{t_i}, $MAPL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$ and $NMPL_{t_i}$ do not change for most of the time. Here, it shows that this happened because there is always at least one exploitable vulnerability remaining on each host in the network and hence, the attack paths in the upper layer do not change. Nevertheless, as the PSV value is increased to 50% (as shown in Figure 4.4(c) and 4.4(d)), it result showed that all the metrics in Figure 4.4(c) change continuously while in Figure 4.4(d), only NAP_{t_i} and $NMPL_{t_i}$ that showed a small change (i.e., between month 8 to month 9) however, it became static again during the remaining period. In Figure 4.4(d), the regular patching of vulnerabilities at PSV = 50% was able to remove all the vulnerabilities found on some hosts at month 8 and month 9 (which changes some possible attack paths). Hence the change in NAP_{t_8}, $NMPL_{t_8}$, NAP_{t_9} and $NMPL_{t_9}$ compared to the initial network state. Furthermore, when the PSV value is increased to 70% (in Figure 4.4(e) and 4.4(f)), all metrics show a significant change in their values for all the months except the SAP_{t_i}. The SAP_{t_i} do not change because the minimum number of hosts along the attack path for the attacker to reach the target remain the same as the initial network configuration. This implies that when the values of the PSV are high, all the security metrics will show a significant change in their values (except the SAP_{t_i}).



(a)



(b)

Figure 4.5: Change with respect to emergence and patching of vulnerabilities with different PSV values for month 1 through month 12, respectively

Further, an algorithm based on a security metric is developed to select PSV values that improve the security of networks over time. The algorithm selects different PSV value for each network state based on the number of vulnerabilities that are found for that state (such that the security is never reduced based on a selected metric). In the simulation, the NAP_{t_i} is used as the metric of interest. However, any security metric can be used. The aim is to observe how the security metrics are changing for this case. As a result, simulations are performed using PSV = 60%, 60%, 80%, 60%, 80%, 90%, 30%

, 30%, 70%, 90%, 80% and 80% for month 1 through month 12, respectively (the algorithm (in Algorithm 1) selected these values). The following notations are used in the algorithm:

- PSV: prioritise set of vulnerabilities (calculated in Section 4.2.2.1)
- $s_{t_i}^{psv}$: a PSV value for s_{t_i}
- SW: set of PSV value for a time window ($s_{t_i}^{psv} \in PV$)
- $s_{t_i}^{metric}$: a calculated security metric for s_{t_i}

The Algorithm 1 takes a copy of the simulation network to calculate the PSV value for each network state. First, the first network state is used as the initial network (line 2). For each network states (line 3), the metric NAP is calculated for each of the s_{t_i} (line 4 and 5). Further, the appropriate PSV to use is calculated (line 7 and 8 based on Section 4.2.2.1). In line 8 and 9, the PSV calculated are then patched. For each of the vulnerability (v) patched, the metric ($s_{t_i}^{NAP}$) is calculated (line 10) until the calculated $s_{t_{i+1}}^{NAP}$ is less than the previous network state ($s_{t_{i-1}}^{NAP}$) from S (line 11 and 12) in the set of solutions in SW.

The results are plotted in Figure 4.5. From the results, the NAP_{t_i}, MAPL_{t_i}, MoPL_{t_i}, SDPL_{t_i} and NMPL_{t_i} change progressively and until 'month 6' when there is only an attack path to reach the target host. This is because a 'forever day' vulnerability is used, which is not removed by software update hence, there is always an attack path to reach the target host. Additionally, the results show that the SAP_{t_i} remains static for all the time (this is because the minimum number of hosts along the attack path for the attacker to reach the target remain the same with the initial network.). On the other hand, the R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i}, SDPL_{t_i} and PSS_{t_i} change progressively as the number of paths are progressively reduced over time. However, at R_{t_7}, AC_{t_7}, Pr_{t_7}, ROA_{t_7} and PSS_{t_7}, the metric start deteriorating but later improve again. The manual analysis performed revealed that even when there is only an attack path to reach the

Algorithm 1 Selecting PSV based on NAP

```
Result: SW
s_{t_0} ← initial network
for s_{t_i} ∈ {s_{t_1}, s_{t_2}, ..., s_{t_n}} do
    NAP = |AP|
    s_{t_i}^{NAP} ← NAP
    for V ∈ s_{t_i} do
        s_{t_i}^{psv} ← PSV
        for each patchable v ∈ s_{t_i}^{psv} do
            patch v
            s_{t_{i+1}}^{NAP} ← NAP
            if s_{t_{i+1}}^{NAP} < s_{t_i}^{NAP} and s_{t_{i+1}}^{NAP} <= s_{t_{i-1}}^{NAP} then
                append |s_{t_i}^{psv}| to SW
            end if
        end for
    end for
end for
```

target host, the R_{t_7}, AC_{t_7}, Pr_{t_7}, ROA_{t_7} and PSS_{t_7} increases (i.e., from month 5) because the risk associated with the hosts (i.e., based on the CVSS BS) along the attack paths are high during that period, hence showing the deterioration in the network security from month 7 to month 10 (in Figure 4.5(b)).

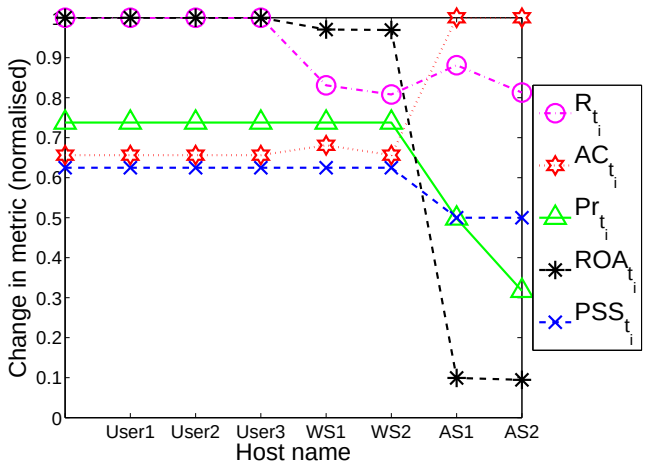
This implies that improving the security of networks based on PSV (i.e., by careful selection of PSV) can improve network security (as seen in Figure 4.5(b)). However, improving the security based on a single metric (e.g., the NAP) may not improve the values of other security metrics (as seen in Figure 4.5(a) compared to Figure 4.5(b)).

In summary, the emergence of vulnerabilities (from the scenario I) and patching of vulnerabilities in this section are combined. The results showed that all the metrics show a significant change in their value (except SAP_{t_i}), when the number of vulnerabilities patched is high.

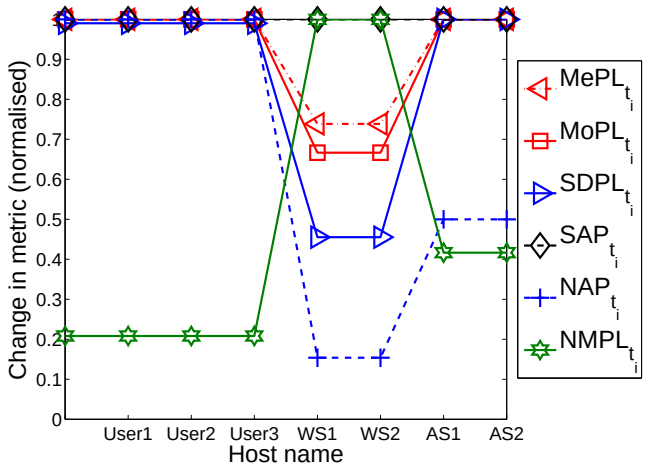
4.3.4 Scenario IV: Disabling Application Software

An unattained vulnerability (e.g., vulnerabilities that the software vendors are no longer supporting the product) can lead to unpredictable outcome and

as such, security administrators need to mitigate the impact of the unattained vulnerabilities by disabling or turning off the service that is associated to the vulnerability [105] in order to avoid exposure to different type of cyber-attack. In this section, the action of how the turning off of a vulnerable application on a host will change the various security metrics in a network system is investigated. The system settings and configurations from section 3.2 are used for this simulation. It is assumed that there is only one vulnerable application that has no security patch per time. Hence, only one application per time is disabled in the simulations. However, the application on the DB is not disabled, and this is to ensure users access to the database. The results are shown in Figure 4.6.



(a)



(b)

Figure 4.6: Disabling a vulnerable application on a host

In Figure 4.6(a) and 4.6(b), the results show that disabling a vulnerable application on the user workstations (i.e., $User_1, User_2$ and $User_3$) does not change any of the security metrics whereas, when the applications on WS_1, WS_2, AS_1 and AS_2 is disabled, the metric NAP_{t_i}, MAPL_{t_i}, MoPL_{t_i}, SDPL_{t_i} and NMPL_{t_i} change accordingly. Similarly, the R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i}, and PSS_{t_i} change as a result of that as well. However, Pr_{t_i} and PSS_{t_i} do not change when the vulnerable application on WS_1 or WS_2 is disabled. On the other hand, SAP_{t_i} does not change for all the time. In the observations, it is found that disabling the vulnerable applications on the servers affected their

availability, hence the significant (sharp) change in the metrics values for most of the time that a server application is disabled.

In summary, it is found that disabling a vulnerable application on a server compared to a user workstation can change the security metrics more significantly, thus improving the security significantly. This reason is that all attack paths to reach the target hosts connect to most of the network servers and therefore when a security measure is applied on any server, most attack paths will be affected as well.

4.3.5 Scenario V: Installation of New Application

An application is usually installed to improve user experiences, but these applications are not without vulnerabilities [105] which can increase the attack surface for a networked system and consequently, change the security posture. This section investigates how security metrics are changing when a new application is installed for the network described in section 3.2. Here, one of the commonly used applications (i.e., Google Chrome) is selected, and then installed on the network hosts one per time. Next, vulnerabilities related to the associated application are collected from the NVD for the simulation network. A list of the vulnerabilities are given in Table 4.5 along with their metric values (i.e., the pr_v, aim_v and ac_v).

Table 4.5: List of vulnerabilities and metrics use for Google Chrome

CVE-ID	CVSS BS	pr_v	aim_v	ac_v
CVE-2015-6790	10.00	1.00	10.00	0.10
CVE-2015-8664	7.50	0.75	6.4	2.50

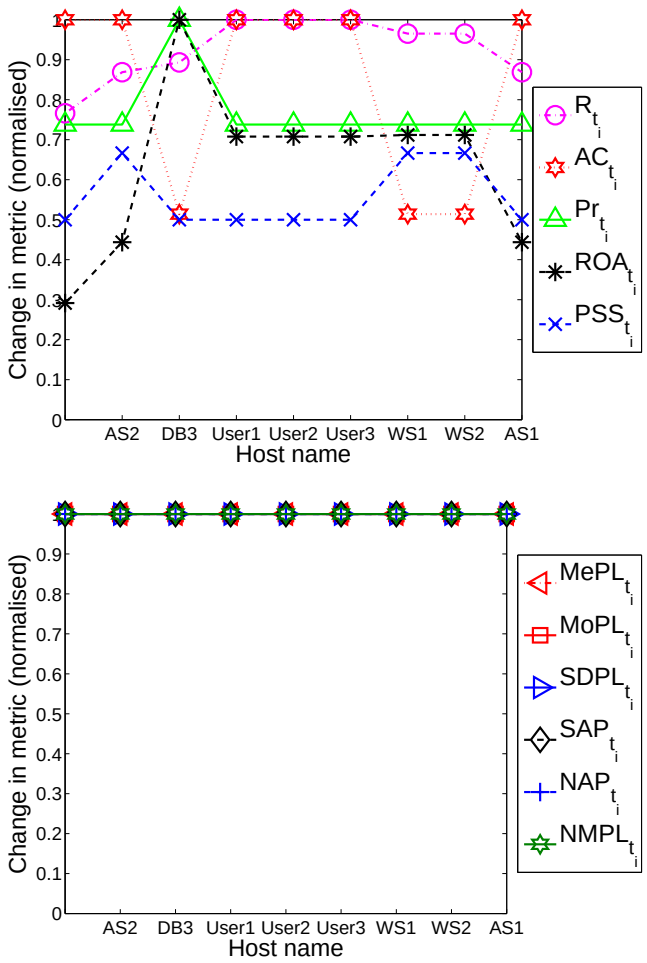


Figure 4.7: Installing an application on a host

The results are plotted in Figure 4.7. It is observed that the metrics - R_{t_i}, AC_{t_i}, ROA_{t_i} and PSS_{t_i} deteriorate in their values for each time that a new application is installed on a host (this is because the installation of the application increases the host's risk value). Contrarily, $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$ do not change for all the time for the reason that all the hosts in the network are regularly having other vulnerabilities. Consequently, the attack paths to the target host do not change for the entire time that a new application is installed. From the results of the simulations, it is found that installing another vulnerability application on the DB affects the R_{t_i}, AC_{t_i}, ROA_{t_i}, Pr_{t_i} and PSS_{t_i} significantly (the security decrease a lot) compared to any other hosts found in the network (with a high chance for

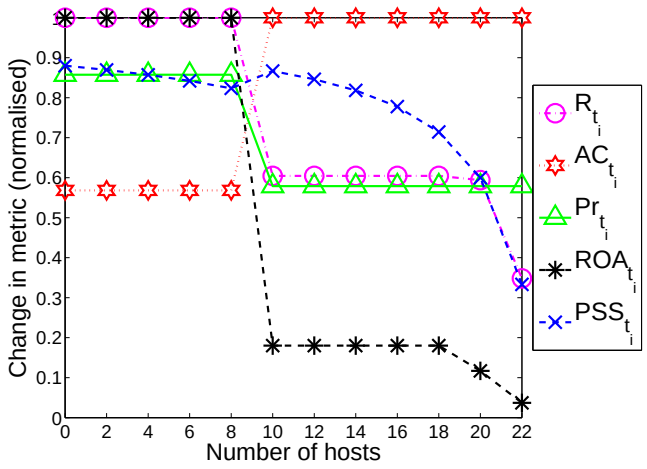
the attacker to attack the target hosts). Similarly, the AC_{t_i} reduces when an application is installed on WS_1 and WS_2 demonstrating that a less effort is required by the attacker to reach the target hosts.

The results in this section showed that the installation of new application on a host does not change $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$. The reason is that there is already an exploitable vulnerability on each of the network hosts (in the upper layer) and thus, all the possible attack paths to reach the target host remain the same compared to the earlier network state. This is consistent for all the scenarios in which this sets of metrics do not change.

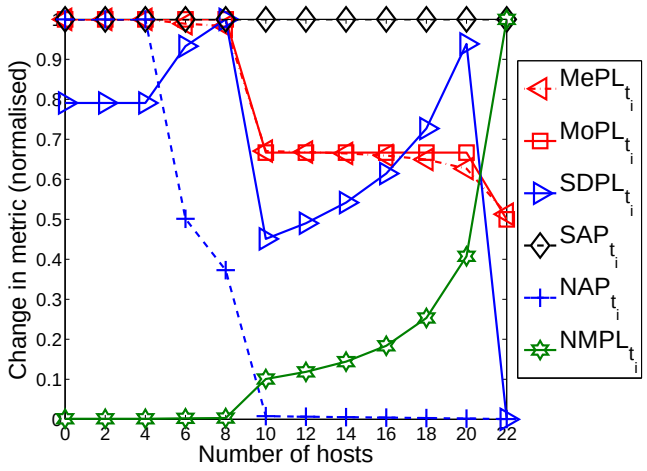
In summary, the results show that the $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_t$ do not change while the others change appropriately with respect to the installation of a new application.

4.3.6 Scenario VI: Removal of Hosts

Modern network components can be removed or disconnected for many reasons (e.g., OS failure, hardware failure, system upgrade, user, *etc*) and as a result, the security posture of the network change. In this scenario, a simulation is performed to investigate how the security changes with the removal of hosts. In particular, an incremental removal of the host is considered over time. However, in the simulation, it is ensured that there is always at least one of each type of servers active (i.e., up and running) for all the time t in order to guarantee the access of a client to the DB. The network in Figure 3.1 is used with an addition of 20 more user workstations.



(a)



(b)

Figure 4.8: Change with respect to removal of hosts

The result for the metrics are plotted and shown in Figure 4.8. In particular, R_{t_i}, AC_{t_i}, ROA_{t_i}, Pr_{t_i} and PSS_{t_i} are plotted in Figure 4.8(a) and the results of $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$ in Figure 4.8(b). From the results, it is observed that the metrics in Figure 4.8(b) change frequently as hosts are removed from the network (showing improvement in security) but the SAP_{t_i} does not change. In Figure 4.8(a), PSS_{t_i} change continuously as hosts are removed. Conversely, R_{t_i}, ROA_{t_i} and Pr_{t_i} change significantly only when the total number of hosts removed is 10. At this point, it is observed that this is because a server (AS_1) which connects most of the hosts to the target host

is removed (the server also happens to have a high vulnerability value), thus causing the sudden sharp change in the security values.

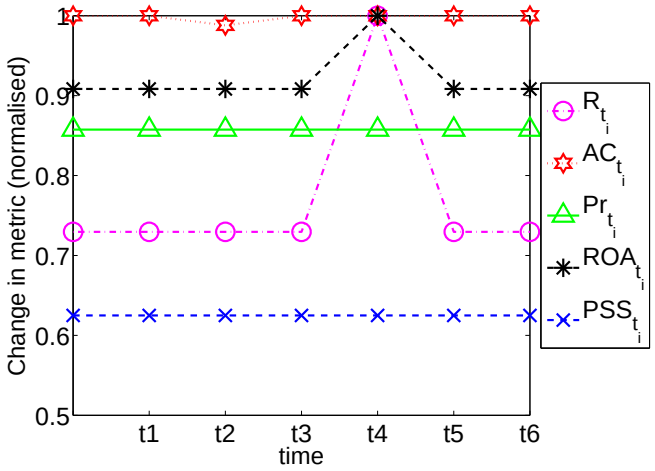
In summary, the results show that PSS_t, MePL_t, MoPL_t, SDPL_{t_i}, NAP_{t_i} and NMPL_{t_i} change in their values when hosts are removed. On the other hand, R_{t_i}, AC_{t_i}, Pr_{t_i} and ROA_{t_i} only begin to change when the number of hosts removed becomes large and also when a server is removed (i.e., at the number of hosts equal to - 10).

4.3.7 Scenario VII: Change of Firewall Rules

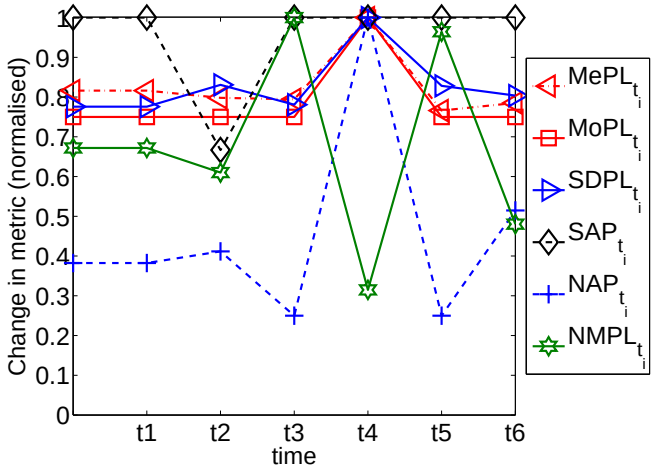
Firewall rules often need to be changed as networks are evolving and new threats are emerging. In accordance with the network changes, firewall rules will need to be changed to provide necessary protection to the network. For the experiments, the initial firewall rules are reasonably modified as in Table 4.6 (such that traffic/connection to the database is not affected).

Table 4.6: Changes of firewall rules.

Time	Source address	Source port	Dest. address	Dest. port	Action (initial)	Action (new)
t_1	$User_i$	*	AS_1	*	Allow	Deny
t_2	WS_1	*	DB	*	Deny	Allow
t_3	$User_i$	*	AS_2	*	Allow	Deny
t_4	$AS1$	*	$User_i$	*	Deny	Allow
t_5	$User_i$	*	WS_2	*	Allow	Deny
t_6	$User_i$	*	DB	*	–	Allow



(a)



(b)

Figure 4.9: Change with respect to firewall rules

The results are shown in Figure 4.9. Here, the initial network settings and configurations are compared to the various firewall rule changes at different time points. The results show that Pr_{t_i} and PSS_{t_i} remain static for all the different changes that were introduced. PSS_{t_i} and Pr_{t_i} do not change because the network vulnerability information does not change from the initial network configurations. R_{t_i} and ROA_{t_i} only show a change at t_4 when a new rule is introduced, and as a result, another attack path emerges which happen to be the most critical thus causing the significant change in R_{t_i} and ROA_{t_i} for that time. Conversely, in Figure 4.9(b), all the metrics show significant changes

with respect to the different security changes accordingly except the SAP. In summary, the MePL_{t_i}, MoPL_{t_i}, SDPL_{t_i}, SAP_{t_i}, NAP_{t_i} and NMPL_{t_i} change accordingly for this network change. R_{t_i}, AC_{t_i} and ROA_{t_i} only show small change and PSS_{t_i} and Pr_{t_i} do not change for the entire time window.

4.3.8 Summary of the Results

The enterprise network in Figure 3.1 is used to investigate the varying effects of security metrics when changes are observed in the network via the T-HARM. The following changes in different scenarios are considered: (1) Addition of software vulnerabilities without patching, (2) Addition of new hosts, (3) Software update (e.g., patching of vulnerabilities), (4) Disabling application software, (5) Installation of new application software, (6) Removal of existing hosts and (7) Change of firewall rules. The results are summarised below.

- Scenario I: Addition of vulnerability: A varying number of vulnerabilities is used for hosts at each time (the number of vulnerabilities for each time is based on the vulnerabilities that are found from NVD for every month). The results of this scenario showed that R_{t_i}, AC_{t_i}, Pr_{t_i}, ROA_{t_i} and PSS_{t_i} change in their values accordingly, however as the number of vulnerabilities becomes large for each host, their values become static. Contrarily, the MePL_{t_i}, MoPL_{t_i}, SDPL_{t_i}, SAP_{t_i}, NAP_{t_i} and NMPL_{t_i} remain static for all the time.

- Scenario II: Addition of hosts: An incremental addition of hosts to the network is considered. From the results, the PSS_{t_i}, MePL_{t_i}, MoPL_{t_i}, SDPL_{t_i}, SAP_{t_i}, NAP_{t_i} and NMPL_{t_i} show significant change continuously. Conversely, R_{t_i}, AC_{t_i} and ROA_{t_i} only show limited change and the SAP_{t_i} and Pr_{t_i} do not change for all the time.

- Scenario III: Software update: The emergence of vulnerabilities (from the scenario I) and patching of vulnerabilities using PSV is combined. In this

scenario, first, a naive approach is used to patch vulnerabilities at PSV = 30%, then 50% and 70%. The results show that the values for R_{t_i}, AC_{t_i}, Pr_{t_i} and ROA_{t_i} significantly change for all the PSV values used and PSS_{t_i} only show small change. While, the $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$ do not change. However, when the PSV value is increased to 50%, NAP_{t_i} and $NMPL_{t_i}$ begin to show small changes in their values and later become static again (i.e., when the number of vulnerabilities becomes large). On the other hand, the $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$ and SAP_{t_i} remain static for all the time. Further, when the PSV is increased to 70%, all the metrics show a significant change in their value (except SAP_{t_i} that remain static). Secondly, a sensitive approach (based on Algorithm 1) is used to determine the PSV to use for the simulations. The results show that all the metrics except SAP_{t_i} changed significantly, in consequence of the PSV used.

- Scenario IV: Disabling application software: Here, an application is disabled on each of the hosts one at the time (except the target host). The results show changes in the security metrics (except SAP_{t_i}) for all disabled application on servers but not on the user's workstation.

- Scenario V: Installation of a software application: Google Chrome is installed on each host per time (the application is with a vulnerability), then an investigation on how the security metrics are changed when new applications are installed on network hosts is performed. The results show that the $MePL_{t_i}$, $MoPL_{t_i}$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_t$ do not change while the others change appropriately.

- Scenario VI: Removal of hosts: For this scenario, an incremental removal of hosts from the network is considered. The results show that PSS_t, $MePL_t$, $MoPL_t$, $SDPL_{t_i}$, SAP_{t_i}, NAP_{t_i} and $NMPL_{t_i}$ change in their values accordingly to the number of hosts removed. On the other hand, R_{t_i}, AC_{t_i}, Pr_{t_i} and ROA_{t_i} only begin to change when the number of hosts

removed becomes large and also when a server is removed (i.e., at the 'number of hosts' equal to- 10).

- Scenario VII: Change of firewall rules: In this scenario, a fixed network configuration is used, while the firewall rules are changed for the different time. MePL_{t_i}, MoPL_{t_i}, SDPL_{t_i}, SAP_{t_i}, NAP_{t_i} and NMPL_{t_i} change accordingly, however, R_{t_i}, AC_{t_i} and ROA_{t_i} only show small change and PSS_{t_i} and Pr_{t_i} do not change for the entire time window.

Conclusions: The results show that the existing security metrics responded to changes in different ways. In specific, the different security metrics can show changes in their values when some categories of changes occur in the network. However, none of the security metrics changes for all the network changes that were observed. Table 4.7 summarised the results into three categories (i.e., significant change, small change and no change). The symbol ✓, † and ✗ is used to indicates a metric that shows significant change, small change and no change, respectively over time. Here, a "significant change" refers to the metric that changes most of the time when there are changes in the network. While "small change" is the metric that change for only few time and finally, the metric that did not change for all the time is referred to as "no change".

Table 4.7: Effects of security metrics with respect to changes in the network

Security metrics	Possible network changes						
	Discovery of Vulnerabilities	Addition of hosts	Update of software	Disabling application	Installing application	Removal of hosts	Add/remove edges or firewall rules
R_{t_i}	✓	†	✓	†	✓	†	†
AC_{t_i}	✓	†	✓	†	✓	†	†
Pr_{t_i}	✓	✗	✓	†	†	†	†
ROA_{t_i}	✓	†	✓	†	✓	†	†
PSS_{t_i}	†	✓	†	†	✓	✓	✗
SAP_{t_i}	✗	✗	✗	✗	✗	✗	✗
NAP_{t_i}	✗	✓	✓	†	✗	✓	✓
$MAPL_{t_i}$	✗	✓	✓	†	✗	✓	✓
$NMPL_{t_i}$	✗	✓	✓	†	✗	✓	✓
$SDPL_{t_i}$	✗	✓	✓	†	✗	✓	✓
$MoPL_{t_i}$	✗	✗	✓	†	✗	✓	✓

4.4 Security Investment Analysis of Dynamic Networks

This section presents the commonly used economic metrics and their computations in the T-HARM. Here, the focus is to automate the analysis of IT security investments, and further show the approach to evaluate the profitability of the security investments for a given period (using the metrics SLE, PLE, BS, CS, ROSI and ROA). The SLE and PLE are defined into three levels (i.e., the host, the attack path(s) and the network levels) while BS, CS and return on security investment into network level.

4.4.1 Single Loss Expectancy

Single loss expectancy [96] is defined as the expected financial loss from a single threat event at time t_i, and it is computed by multiplying AV and exposure factor (EF). The AV is defined as a measure of the cost of purchase, installation, daily operation cost, ownership value, *etc* of an asset while EF is the percentage of loss on the value of an asset. The AV and EF of a host at time t_i is denoted as $AV_{h_{t_i}}$ and $EF_{h_{t_i}}$, respectively. The host level metric in the host level and the attack path level value are calculated in Equation (4.14) and Equation (4.15), respectively. The network level value is calculated by (4.16).

$$SLE_{h_{t_i}} = AV_{h_{t_i}} \times EF_{h_{t_i}} \tag{4.14}$$

$$SLE_{ap} = \sum_{h_{t_i} \in ap_i} SLE_{h_{t_i}}, \quad ap_i \in AP_{ns_{t_i}} \tag{4.15}$$

$$SLE_{t_i} = \sum_{ap_i \in AP_{ns_{t_i}}} SLE_{ap_i} \tag{4.16}$$

4.4.2 Periodic Loss Expectancy

Periodic loss expectancy is based on annual loss expectancy [96]. This is defined as the expected financial loss due to an attack event. It is computed by multiplying the SLE and the attack rate of occurrence for that period (commonly known as ARO [14]. However, it is used as the PRO). The PRO is defined as the likelihood that a risk will occur at a particular time. Here, the PRO values for vulnerabilities in AT are calculated by equation (4.17) (using AND and OR gates). The $PRO_{h_{t_i}}$ and $PLE_{t_i}^{ap}$ values for hosts and attack paths are computed by equation (4.18) and (4.19), respectively. Then, the network level value is calculated by equation (4.20).

$$PRO_{b_{t_i}} = \begin{cases} \prod_{v \in c_{t_i}(b_{t_i})} PRO_v, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = AND} \\ 1 - \prod_{v \in c_{t_i}(b_{t_i})} PRO_v, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = OR} \end{cases} \tag{4.17}$$

$$PRO_{h_{t_i}} = PRO_{root_{t_i}} \tag{4.18}$$

$$PLE_{t_i}^{ap_i} = \sum_{h_{t_i} \in ap_i} SLE_{h_{t_i}} \times PRO_{h_{t_i}}, \quad ap_i \in AP_{ns_{t_i}} \tag{4.19}$$

$$PLE_{t_i} = \sum_{ap_i \in AP_{ns_{t_i}}} PLE_{t_i}^{ap_i} \tag{4.20}$$

4.4.3 Benefit of Security

Benefit of Security [14] is used to quantify the possible benefit of implementing a countermeasure. It is the difference between the loss expectancy without security and the loss expectancy with security. This metric is denoted as BS and compute it by equation (4.21). Here, PLE_{before} and PLE_{after} is the security level before countermeasures and after countermeasures

are applied, respectively.

$$BS_{t_i} = \begin{cases} PLE_{before} - PLE_{after} & \text{if at least a countermeasure is used;} \\ 0 & \text{if no countermeasure} \end{cases} \tag{4.21}$$

4.4.4 Security Cost

Security Cost [15] is the amount of money spent to reach a security level (i.e., a quality of protection). It is calculated by summing up the expenses of security countermeasure for the deployment, maintenance, licensing, acquisition, *etc.* for a time t_i. It is computed by Equation (4.22). Where, cs is an atomic investment cost of a cm and C is the set of all security expenses associated to the cm.

$$SC_{t_i} = \begin{cases} \sum_{cs \in C} cs & \text{if at least a countermeasure is used;} \\ 0 & \text{if no countermeasure} \end{cases} \tag{4.22}$$

4.4.5 Return on Security Investment

Return on security investment is the expected benefit over the SC. It is calculated by Equation (4.23). In this metric, if the value calculated is not zero or a negative number then the investment is economically profitable and justified.

$$ROSI_{t_i} = \begin{cases} \frac{BS_{t_i} - SC_{t_i}}{SC_{t_i}} & \text{if at least a countermeasure is used;} \\ 0 & \text{if no countermeasure} \end{cases} \tag{4.23}$$

4.4.6 Return on Attack

The return on attack [34] is a metric used to quantify the benefit for the attacker when the attacker successfully exploits a vulnerabilities. This metric is calculated using Equation (4.27). The aim_v, ac_v, and pr_v value are calculated for each vulnerability in AT using AND and OR gates by equation (4.24). The host return on attack value (roa_h) is given by equation (4.25), the attack path value is given by equation (4.26) and the network-level value ROA_{t_i} is then given by Equation (4.27).

$$roa_{b_{t_i}} = \begin{cases} \sum\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} \frac{pr_{v_{t_i}} \times aim_{v_{t_i}}}{ac_{v_{t_i}}}, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = AND} \\ \max\limits_{v_{t_i} \in c_{t_i}(b_{t_i})} \frac{pr_{v_{t_i}} \times aim_{v_{t_i}}}{ac_{v_{t_i}}}, & \substack{b_{t_i} \in B_{t_i} \\ g_{t_i}(b_{t_i}) = OR} \end{cases} \tag{4.24}$$

$$roa_{h_{t_i}} = roa_{root} \tag{4.25}$$

$$roa_{t_i}^{ap_i} = \sum_{h_{t_i} \in ap_i} \frac{pr_{t_i}^h \times aim_{t_i}^h}{ac_{t_i}^h}, \quad ap_i \in AP_{ns_{t_i}} \tag{4.26}$$

$$ROA_{t_i} = \sum_{ap_i \in AP_{ns_{t_i}}} roa_{t_i}^{ap_i} \tag{4.27}$$

Economic index: Economic values are assigned to the components (i.e., hosts and vulnerabilities) of the T-HARM, these values are based on the statistical data collected in [14] (the data were collected from the CSI Computer and Security Survey [135] and 2009 Global Security Survey [18]). So, the AV used for information stored on a server is \$11290 (per period), and \$1050 for user workstations and their EF is 0.06. Based on the CVSS exploitability subscore and BS [35], value are assigned to PRO, pr, aim and ac for each vulnerabilities, respectively. The summary of the vulnerabilities metrics is shown in Table 4.8. These values are used along with the economic index to calculate the various economic metrics described in section 4.2.1.

Table 4.8: List of vulnerabilities and their metric

v. ID	h ID	CVE (ID)	pr_v	aim_v	ac_v	PRO_v
v_1	AS_1	2016-0118	0.93	10.00	1.00	1.00
v_2	AS_1	2016-0638	0.75	6.40	5.70	0.64
v_3	AS_2	2015-4022	0.75	7.50	5.70	0.64
v_4	AS_2	2015-5345	0.50	2.90	5.00	0.29
v_5	DB	2012-3132	0.65	6.40	2.50	0.64
v_6	DB	2015-2586	0.43	2.90	5.70	0.29
v_7	WS_1	2015-3247	0.69	10.00	4.10	1.00
v_8	WS_1	2014-8109	0.43	2.90	5.70	0.29
v_9	WS_2	2015-4022	0.75	2.90	3.50	0.64
v_{10}	WS_2	2014-8109	0.43	2.90	5.70	0.29
v_{11}	U_1	2016-0118	0.93	10.00	1.00	1.00
v_{12}	U_1	2016-1946	1.00	10.00	1.00	1.00

4.5 Defence Model

Here, security hardening solution is only applied on critical hosts (i.e., hosts having vulnerabilities with CVSS base score of 8.0 and above as defined in [29]). Three security hardening solutions are incorporated into the T-HARM, but in general, several security hardening can be implemented. However, this depends on the availability of the countermeasure and the network technology been used (for example, using countermeasures such as traffic redirections along with the SDN technology will make the reconfigurations of the network more efficient). Table 4.9 shows the list of proactive security hardening solutions that will be used for different network states. Similar to the work in [14,32], the cost values are assigned to each hardening measure as in Table 4.9 in order to automate the analysis of the security investments.

Table 4.9: List of countermeasures

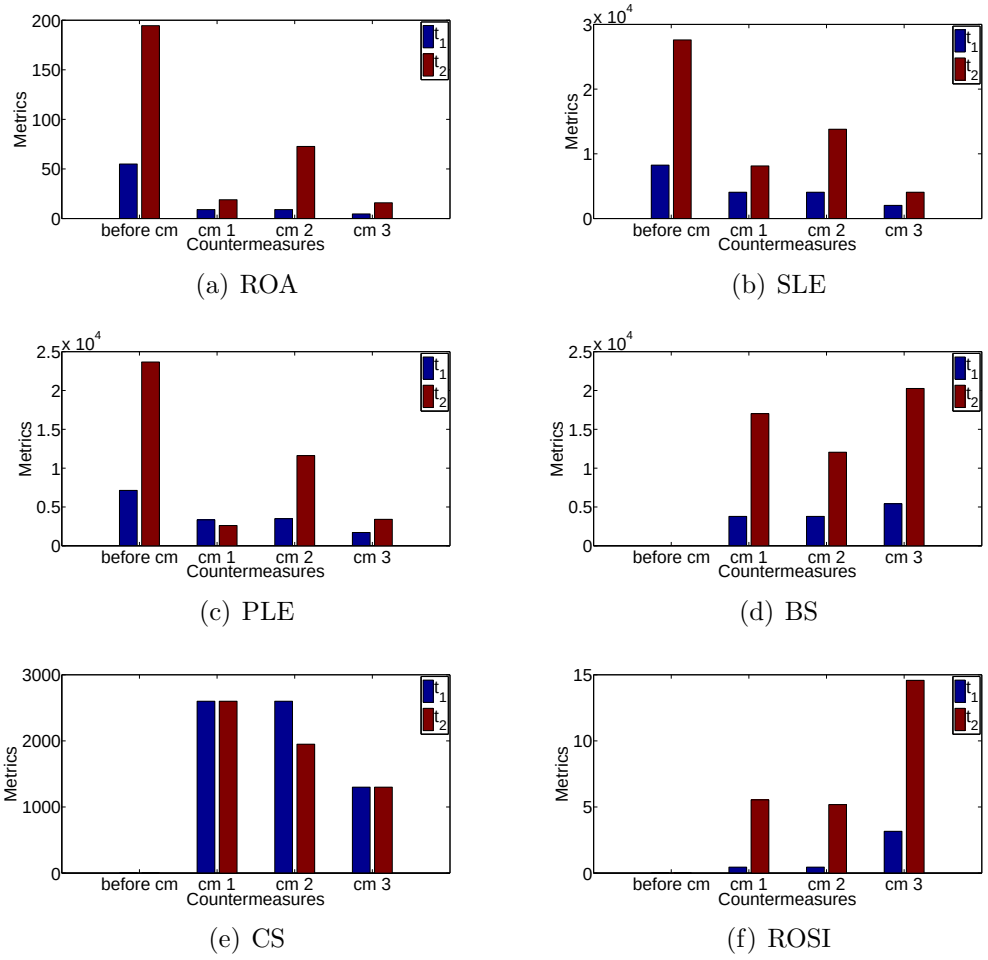
time	cm ID	cm name	cs ($)
t_1	cm_1	Vulnerability patching	1300.00
	cm_2	Traffic redirection	975.00
	cm_3	Host isolation	650.00
t_2	cm_1	Vulnerability patching	1300.00
	cm_2	Traffic redirection	975.00
	cm_3	Host isolation	650.00

4.6 Simulations and Results Analysis

GSMs with economic metrics can be used to automate the analysis of IT investment. This section automates and analyses the profitability of security investments over a period of time via simulations. In the simulations, different economic metrics are computed using the T-HARM. Two network states similar to the one shown in Figure 3.1 is used. However, there are 5 hosts in the first state, which consists of WS_2, AS_1, AS_2, $User_1$ and DB (i.e., the network states at time t_1), and 6 hosts in the second network states which consists of WS_1, WS_2, AS_1, AS_2, $User_1$ and DB (i.e., the network states at time t_2). The metrics, as well as their computations, are shown in Section 4.4. Also, the countermeasures described in section 4.5 are used as the defence mechanisms.

Additionally, for all the scenarios the vulnerabilities that are found for the OSes and applications in Table 3.1 are used. For the vulnerabilities, related data are collected from the NVD [118] (the list of the vulnerabilities is found in Table 4.8.

The T-HARM for the different network states is constructed via simulations, using the reachability information of the example network and the vulnerabilities. The simulations are performed in two scenarios; Scenario I and Scenario II. The former scenario aims to demonstrate how T-HARM is used to evaluate the profitability of IT investments given different network states (i.e., for a period of time). The latter one shows the selection of the best countermeasure in the different network states.



(a) ROA (b) SLE

(c) PLE (d) BS

(e) CS (f) ROSI

Figure 4.10: The use of several countermeasures when critical vulnerabilities are found

4.6.1 Scenario I

The Scenario I focussed on demonstrating how to use T-HARM to evaluate the profitability of IT investments for dynamic networks. In the beginning, the T-HARM for the example network is constructed using the aforementioned inputs and the attacker model specified in Section 3.2.2. Then, several countermeasures are used to restrict the activities of the attacker on the network. In particular, the patching of critical vulnerabilities (cm_1), traffic redirection (cm_2) and the isolation of vulnerable host (cm_3) are used. For each of the hardening measure used, the following metrics are calculated: (i) ROA (ii) SLE (iii) PLE (iv) BS (v) CS and (vi) ROSI. However, it must

be noted that before applying any of the hardening measures, the different metrics are calculated first (and the results are shown with 'before cm'). Then, one hardening measure is used per time, and the results are shown using the hardening measures' (countermeasures') names per time in graphs.

Figure 4.10 shows the results for the simulations. Figure 4.10(a) shows the results for ROA. The ROA shows the attackers' expected gain when he is able to compromise the target hosts. From the graph, the attacker has the most gain if no countermeasure(s) is used for both of the network states (i.e., t_1 and t_2). Similarly, the results show that the attacker will be having more gain if he compromise the target at t_2 compared to t_1 (i.e., for 'before cm', cm_1, cm_2 and cm_3). From the defenders' perspective, using cm_1 and cm_2 at t_1 produce the same results hence, either of them has the same effects in reducing the attackers gain. Further, it is observed that using cm_3 will optimally reduce the attacker gain the most while using cm_1 will allow the attacker to have more gain compared to the other countermeasures.

Figure 4.10(b) presents the results for the SLE. The results show the expected financial loss in consequence of a single attack event. From the results, it is observed that both states have varying SLE value. However, the SLE value for the before countermeasures is higher. Conversely, when the various hardening measures are used, the result shows that the SLE values decrease for both t_1 and t_2 states (with cm_3 being the best for both states). In Figure 4.10(c), the results show the expected financial loss taking into account multiple states (i.e., the period a countermeasure is used compared to its previous network state). For this metric, similar results are observed for the SLE. However, for the PLE the use of cm_3 and cm_1 can reduce the PLE the most at t_1 and t_2, respectively.

Subsequently, the results for 'before cm' is zero in Figure 4.10(d), 4.10(e) and 4.10(f). This is for the reason that, there is no countermeasure use at that points. However, for the other points when countermeasure is used, the BS, CS, and the ROSI are improved compared to former. In addition, at t_1,

cm_1 and cm_2 have the same BS for the defender while cm_3 is the having the maximum benefit for the defender. At t_2, all the countermeasures have varying values with cm_3 returning the maximum benefit for the defender also, then followed by cm_1 and cm_2, respectively.

In Figure 4.10(e), cm_1 and cm_3 have the same CS for t_1 while at t_2, they both have varying values. However, the cm_3 is having the same CS for both states (and it is the minimal CS for the defender). Similarly, in Figure 4.10(f), using either cm_1 or cm_2 can give the defender a similar ROSI value for both states. In summary, it is observed observe that different network states can have varying optimal countermeasures based on the different metrics.

4.6.2 Scenario II

Scenario II automates the analysis of the optimal countermeasures at different time points given a metric. In Algorithm 2, the selection of the optimal countermeasure (for T-HARM) from a set of countermeasures per time is described. Here, only ROSI is used (this is to capture the cost and benefits for the defender perspective). The Algorithm 2 is used for this simulations. The algorithm presents how to select the optimal countermeasure from a set of countermeasures. The input in the algorithm is a set of network states NS, a set of countermeasures, and a set of vulnerabilities. First, the algorithm starts by applying each countermeasure to the set of critical vulnerability found on every host. Then, the ROSI is calculated for each of the countermeasures used. Subsequently, the optimal countermeasure is selected based on the ROSI. This process is done for all network state ns_{t_i} belonging to the set of states NS, and finally, the set of optimal solutions is returned.

The results for this simulation are shown in Table 4.10. And based on the algorithm, the optimal solution is cm_3 with ROSI of 3.16 and 14.58 at t_1 and t_2, respectively. Therefore, a conclusion can be made that, it is financially justified to use cm_3 compared to cm_1 and cm_2 for the network.

Algorithm 2 : Selecting optimal countermeasure based on ROSI

```
1: procedure OPTIMAL COUNTERMEASURES
2:     solution → {}
3:     compute ROSI_{t_i} before cm ∀cm_i ∈ {cm_1, cm_2, ...}
4:     for ns_{t_i} ∈ NS do
5:         for all cm_i ∈ {cm_1, cm_2, ...} do
6:             for all critical v ∈ V_{ns_{t_i}} do
7:                 apply cm_i on hosts containing the v
8:                 compute new ROSI_{t_i}
9:                 if new ROSI_{t_i} > ROSI_{t_i} then
10:                    ROSI_{t_i} = new ROSI_{t_i}
11:                    ns_{t_i}^{cm_i} = cm_i
12:                end if
13:                add the critical set v to ns_{t_i}
14:            end for
15:        end for
16:        solution ← ns_{t_i}^{cm_i}
17:    end for
18:    return solution
19: end procedure
20:
21: procedure COMPUTE ROSI(ns_{t_i})
22:    compute benefit of security (BS_{t_i})
23:    compute cost of security (CS_{t_i})
24:    ROSI_{t_i} ← ((BS_{t_i} − CS_{t_i})/CS_{t_i})
25:    return ROSI_{t_i}
26: end procedure
```

Table 4.10: Optimal ROSI

time	Analysis			
	No countermeasure	cm_1	cm_2	cm_3
t_1	0.0	0.45	0.45	**3.16**
t_2	0.0	5.54	5.18	**14.58**

4.7 Summary

This chapter presented a methodology to developing composite security metrics. Further, it evaluates the effectiveness of the existing security metrics for the analysis of dynamic networks via T-HARM. Finally, it presents an approach to automate the analysis of IT investment for dynamic networks using the T-HARM as well. Besides, an approach to automate the analysis of

IT security investments, and the approach to exhaustively compute the optimal security investment (from a given set of hardening measure based on a metric ROSI) for every network states is demonstrated.

Chapter 5

Time-Independent HARM

There are three main approaches to capture changes using the GSM for the dynamic networks, which are time-driven, event-driven or user-driven. In the case of the time-driven approach, the GSM is constructed at predefined times. In case of the event-driven approach, the GSM is constructed when changes have been detected. In the case of the user-driven approach, a user decides which times the GSM is constructed. These approaches can be used to generate multiple GSM snapshots (e.g., the temporal GSMs), with each snapshot with different security properties for that particular network state within a given time window [19]. However, the existing modelling approaches lack methods and techniques to represent the overall security posture of dynamic networks using a representative GSM or metric value.

In order to have an overall overview of the security of dynamic networks, one must take into account all observable attributes of dynamic networks, which includes multiple network states, the duration of each state and the visibility of components over time.

In this chapter, TI-HARM is proposed to present the overall overview of the security of dynamic networks. The idea is to capture dynamic network states at various times, and then aggregate them taking into account the attributes of the dynamic network. The difference between the temporal GSM and the time-independent GSM is, the temporal GSM models the security states of

the dynamic networks onto multiple GSM at every time t while the time-independent GSM (i.e., TI-HARM) models the security of dynamic networks onto a single GSM (regardless of time and states). The TI-HARM not only assess the security of each network state, but also identify and assess all potential attack paths in the multiple network states, as well as attack events happening over multiple network states (to one GSM). The approach used in this chapter aggregates network states for security modelling and analysis for the dynamic network taking into account various dynamic attributes. The main contributions of this chapter are as follows:

- Develop a time-independent GSM by incorporating multiple network states and their dynamic attributes;
- Formally define TI-HARM;
- Propose a security rating system based on weight optimisation algorithm using the TI-HARM;
- Demonstrate the feasibility of the approach in experimental analysis via simulations.

5.1 Network and Attacker Model

To demonstrate this approach, a three-tier enterprise network (i.e., consisting of DMZ, subnets, firewall, web server which is accessible from the public Internet, *etc*) and attacker model which is similar to the one in Figure 3.1 and in Figure 3.2.2 is used, respectively. The initial network consists of eight hosts located in three subnets; DMZ, internal network and the Database (DB) subnet. The subnets are divided by firewalls which control access from one subnet to another. However, the machines in the DMZ passively receive all service requests from the Internet then respond appropriately. Here, it is assumed that the machine names do not change for the period considered. In

Figure 5.1, the topologies for the network captured when changes are observed in the network (i.e., event-driven approach) are shown. The descriptions of the topologies are given as follows; (a) ns_0 topology: The initial network topology with a state duration = 2 mins. (b) ns_1 topology: The connection between WS_1 and U_3 is removed, and the state duration = 4 mins. (c) ns_2 topology: Host U_3 is removed from the network as well as its edges, and the state duration = 4 mins. (d) ns_3 topology: Host U_4 is added to the network, and the state duration = 5 mins. (e) ns_4 topology: Edge between WS_1 and U_2 is added to the network, and state duration = 4 mins. (f) ns_5 topology: Hosts WS_2 is removed from the network, and state duration = 5 mins. The different states have the vulnerabilities listed in Table 5.1.

Table 5.1: List of vulnerabilities for the example network along with their metrics

v ID	pr_v	aim_v
v_1	0.43	5.50
v_2	1.00	10.00
v_3	0.75	7.00
v_4	0.43	5.50
v_5	0.72	10.00
v_6	0.43	4.00
v_7	0.90	9.00
v_8	0.50	5.00
v_9	0.20	2.00
v_{10}	0.88	8.00
v_{11}	0.43	6.00

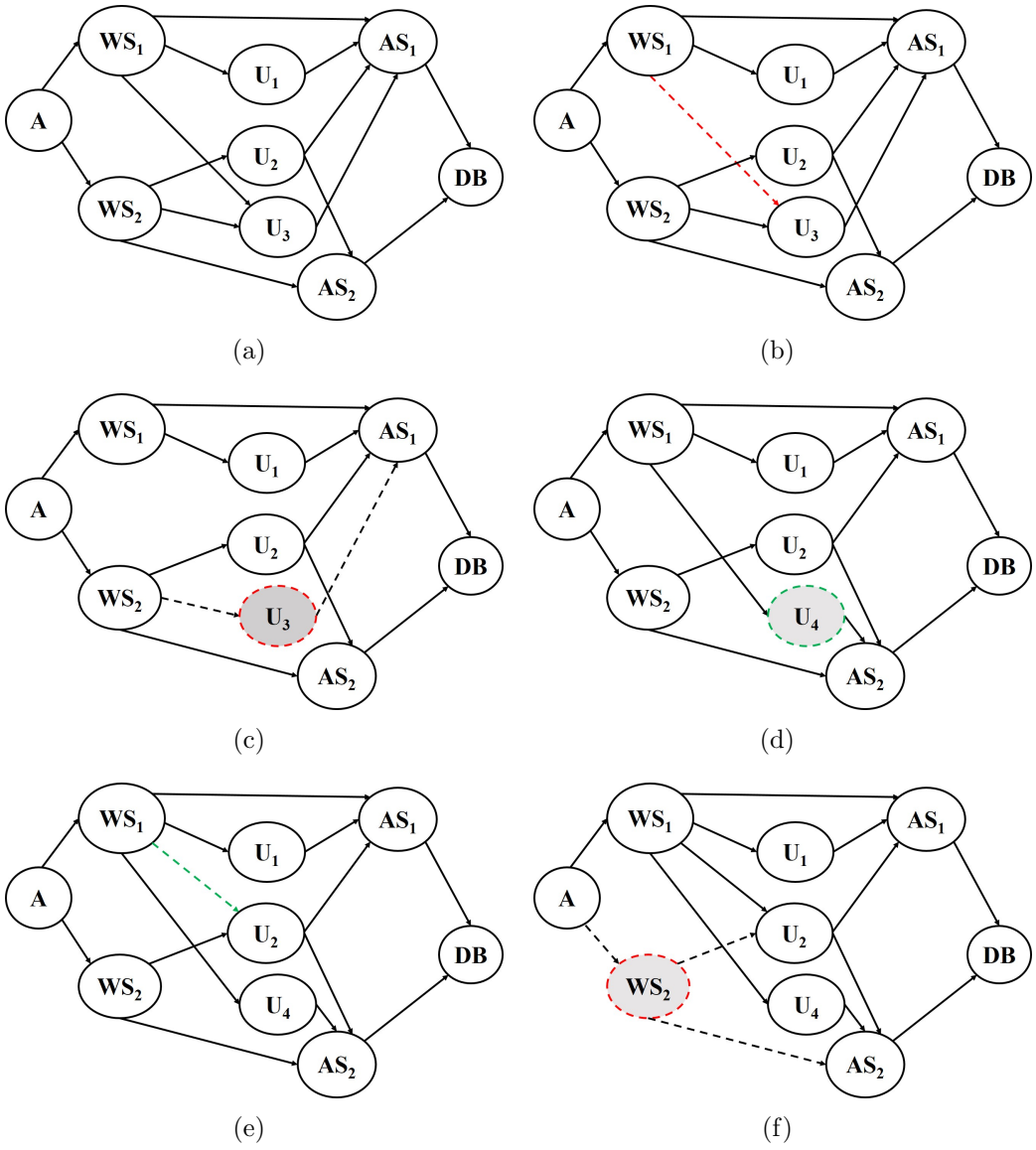


Figure 5.1: Topology configurations for the network with pre-defined changes that are captured at different time. The time window T = 24 min.

5.2 The Proposed Approach

The main idea of the TI-HARM is to model the security of dynamic networks by aggregating the security components of multiple states to form a single GSM. By doing so, the model will be able to capture the possible network components observed in different network states, and thus modelling all possible attack scenarios including ones carried out in multiple network

states.

In this section, the description and the construction of the TI-HARM for the analysis of dynamic networks are provided. The following network properties are taken into account; multiple network states, time duration of states and the visibility of network components in the states to construct the TI-HARM. Specifically, the changes associated with hosts and their reachability information in multiple states are considered. This is because the structure of the network system (i.e., the hosts reachability) is important for some type of progressive attacks (e.g., sequential attacks) [72].

In the TI-HARM, the components have weight values based on their visibility over time (where a component that appears more frequently will have a higher weight value). This approach can allow network administrators to perform other security analysis on network components with different visibilities. For example, more static network components are exposed to the attackers, allowing them to discover vulnerabilities and plan an attack that would still be viable in time. For this fact, the network administrator can use the TI-HARM to discover such static components in order to mitigate such attacks.

The calculations for the weight value is formulated in equation (5.1). The TI-HARM is described in Section 5.2.1. Then, in Section 5.2.2, the construction of the TI-HARM with different weight values is shown for the network states in Figure 5.1.

$$nc_j^{\alpha} = \left(\frac{OC_{nc_j}}{|NS|} \times \frac{\sum_{i=0}^{|NS|} t(nc_j)}{T} \right) \times 100 \tag{5.1}$$

5.2.1 Formalism of TI-HARM

In this section, the descriptions and formalism of TI-HARM is presented. The TI-HARM is described in terms of H, E and V as follows:

- Each host $h_i \in H$ has a weight value h_i^{α} that is calculated based on the

visibility of the host in the network states (such that $0 \leq \ h_i^{\alpha} \leq 100$), a set of weighted adjacent hosts $h_i^{adj} \subseteq H$, a host type $h_i^{type} \in \{$web server, app server, user workstation$\}$, a set of vulnerabilities $h_i^{v} \subseteq V$, and a set of security metrics $h_i^{metrics} \in \{$attack cost, attack risk, $ROSI$, ...$\}$.

- Each edge $e_i \in E$ has a weight value e_i^{α} that is calculated based on its visibility in the network states as well (with $0 \leq e_i^{\alpha} \leq 100$).

- Each vulnerability $v \in V$ has a privilege level that is acquired by the attacker after the vulnerability is successfully exploited $v_{privilege} \in \{root$, $user$, ...$\}$ and a set of security metrics $v_{metrics} \in \{$attack cost, attack risk, ...$\}$.

The TI-HARM is described as two layered GSM; the upper layer and the lower layer. The upper layer captures the temporal hosts' reachability information and the attacker's entry points (using AG) while the lower layer captures the vulnerability information of each hosts using ATs. The TI-HARM is formally defined as follows.

Definition 11. *The TI-HARM is a 4-tuple* $TI - HARM = (U, L, C, w)$ *which is constructed based on the calculated weight values of network states components that are equal or below the weight value threshold* w *(the calculation of the weight value is shown in Equation(5.1)). Here,* U *is the upper layer (AG) that models the set of hosts* H *and their reachability information, and* L *is the lower layer (ATs) that models the set of vulnerabilities* V *for each host* $h_i \in H$*, respectively. The mapping between the upper and the lower layers is defined as* $C \subseteq \{(h_i \leftrightarrow AT)\} \forall h_i \in U, AT \in L$.

Next, the upper layer and the lower layer are defined in Definition (12) and Definition (13), respectively.

Definition 12. *The upper layer of the TI-HARM is a 3-tuple* (H, E, w)*, where* H *is a finite set of weighted hosts in the upper layer where* $h_i \in H$ *and* $h_i^{\alpha} \leq w$,

$E \subseteq H \times H$ is a set of weighted edges where $e_i \in E$ and $e_i^{\alpha} \leq w$, and w is the calculated weight threshold value.

Definition 13. *The lower layer of the TI-HARM is a set of ATs. Here, AT is a 5-tuple AT=(A, B, c, g, $root$), where $A \subseteq V$ is a set of vulnerabilities, $B = \{b^1, b^2, \ldots\}$ is a set of gates, $c \subseteq \{b^j \rightarrow e_l\} \forall b^j \in B, e_l \in A \cup B$ is a mapping of gates to vulnerabilities and other gates, $g \subseteq \{b^j \rightarrow \{AND, OR\}\}$ specifies the type of each gate, and $root \in A \cup B$ is the root node of the AT.*

5.2.2 Constructing TI-HARM

To fully understand the security of a dynamic network, it is important to take into account changes in the networks (for an effective security analysis). Therefore, an approach that takes into account changes associated with hosts, their connections and their duration is developed. The approach (i.e., the construction of the TI-HARM) is described using Algorithm 3, Algorithm 4 and Algorithm 5. In particular, Algorithm 3 and Algorithm 4 show the calculations of weight values for the hosts and edges, respectively. Algorithm 5 show the construction of the TI-HARM. An example network is used to describe the construction of the TI-HARM. In specific, the network topologies in Figure 7.1 are used, and the equation 5.1 is used to calculate the weight value for each components.

Algorithm 3 Algorithm for computing hosts' weight value

1: **procedure** $Weight\_Hosts(NS)$
2: $H \rightarrow \{\}$
3: **for all** $ns_i \in NS$ **do**
4: $H = H \cup \{h_i, \forall h_i \in ns_i\}$
5: **end for**
6: **for** *each* $h_i \in H$ **do**
7: $nc_{h_i}^{\alpha} = (OC_{nc_{h_i}}/|NS|) \times (\sum_{i=0}^{|NS|} t(nc_{h_i})/T) \times 100$
8: $h_i^{\alpha} \leftarrow nc_{h_i}^{\alpha}$
9: **end for**
10: **end procedure**

Table 5.2: The calculated weight values for hosts

Host name (nc_j)	AS_1	AS_2	WS_1	WS_2	U_1	U_2	U_3	U_4	DB
OC_{nc_j}	6	6	6	5	6	6	2	3	6
$\sum_{i=0}^{\lvert NS\rvert} t(nc_j)$	24	24	24	19	24	24	6	14	24
$\frac{OC_{nc_j}}{\lvert NS\rvert}$	1.00	1.00	1.00	0.83	1.00	1.00	0.33	0.50	1.00
$\frac{\sum_{i=0}^{\lvert NS\rvert} t(nc_j)}{T}$	1.00	1.00	1.00	0.79	1.00	1.00	0.25	0.58	1.00
$\left(\frac{OC_{nc_j}}{\lvert NS\rvert} \times \frac{\sum_{i=0}^{\lvert NS\rvert} t(nc_j)}{T}\right) \times 100$	100	100	100	66	100	100	8.33	29	100

Algorithm 4 Algorithm for computing edges' weight value

```
1: procedure Weight_Edges(NS)
2:     E → {}
3:     for all ns_i ∈ NS do
4:         for each h_i ∈ s_i do
5:             eN= Get_set_of_edges_for_a_node(h_i)
6:             for each e_i ∈ eN do
7:                 if e_i not in E then
8:                     add e_i to E
9:                 end if
10:            end for
11:        end for
12:    end for
13:    for each e_i ∈ E do
14:        nc^α_{e_i} = (OC_{nc_{e_i}}/|NS|) × (Σ_{i=0}^{|NS|} t(nc_{e_i})/T) × 100
15:        e^α_i ← nc^α_{e_i}
16:    end for
17: end procedure
```

Table 5.2 and Table 5.3 show the detailed calculations for the hosts and edges from the network topologies, respectively. The weight value shows how each component appears in the network states for the time window (i.e., T=24 mins). In Figure (5.2), the construction of the TI-HARM (using different weight values) for states (in Figure 7.1) is demonstrated. Specifically, Figure 5.2(a) show the TI-HARM with $w = 0.0\%$. This shows the extreme cases where the TI-HARM captures all the observed components from all network states. In this case, it can be said that all the possible attack scenarios are well captured. Figure 5.2(b) captures only network component that are visible for half of the entire time window (i.e., $w = 50.0\%$). Figure 5.2(c) captures the network

Table 5.3: The calculated weight values for edges

Edges (nc_j)	OC_{nc_j}	$\sum_{i=0}^{\lvert NS\rvert} t(nc_j)$	$\frac{OC_{nc_j}}{\lvert NS\rvert}$	$\frac{\sum_{i=0}^{\lvert NS\rvert} t(nc_j)}{T}$	$\left(\frac{OC_{nc_j}}{\lvert NS\rvert} \times \frac{\sum_{i=0}^{\lvert NS\rvert} t(nc_j)}{T}\right) \times 100$
(U_1, AS_1)	6	24	1.00	1.00	100
$(WS_2, AS2)$	5	19	0.83	0.79	65.97
$(U_4, AS2)$	3	14	0.50	0.58	29.16
(WS_1, U_1)	6	24	1.00	1.00	100
(WS_2, U_3)	2	6	0.33	0.25	8.33
$(U3, AS_1)$	2	6	0.33	0.25	8.33
$(WS_2, U2)$	5	19	0.83	0.79	65.97
$(U2, AS_1)$	6	24	1.00	1.00	100
$(U2, AS2)$	6	24	1.00	1.00	100
(AS_1, DB)	6	24	1.00	1.00	100
(AS_2, DB)	6	24	1.00	1.00	100
(WS_1, AS_1)	6	24	1.00	1.00	100
$(WS_1, U2)$	2	9	0.33	0.38	12.54
$(WS_1, U3)$	1	2	0.16	0.08	1.33
$(WS_1, U4)$	3	14	0.50	0.58	29.26

Algorithm 5 Algorithm to construct the TI-HARM

1: **procedure** $Construct\_TI\_HARM(NS,\ w)$
2: AT_{h_i} is the AT for the host (h_i)
3: $U \rightarrow \{\}$
4: $L \rightarrow \{\}$
5: $TI\_HARM = (U, L, C)$
6: **for** *each* h_i *in* $Weight\_Hosts(NS)$ **do**
7: **if** $nc^{\alpha}_{h_i} \leq w$ **then**
8: add h_i to U
9: **end if**
10: **end for**
11: **for** *each* e_i *in* $Weight\_Edges(NS)$ **do**
12: **if** $nc^{\alpha}_{e_i} \leq w$ **then**
13: **if** $(\forall h_i \in$ tuple $(e_i))$ *exists* in the U **then**
14: add e_i to U
15: **end if**
16: **end if**
17: **end for**
18: **for all** $h_i \in U$ **do**
19: $L \leftarrow Get\_AT(h_i)$ such that $C \subseteq \{(h_i \leftrightarrow AT_{h_i})\}$ and $AT_{h_i} \in L$
20: **end for**
21: **end procedure**

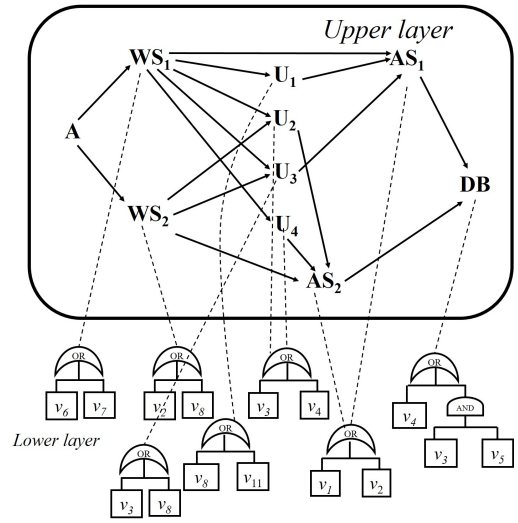
components that are visible for all the times in the states (i.e., the components that have a weight value of 100%. This is also the other extreme where only the most persistent components for the entire time window are captured).

5.2.3 Security Metrics Calculations

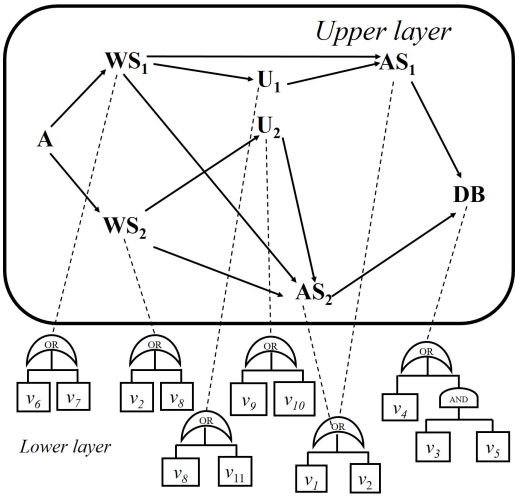
In the TI-HARM, several security metrics can be implemented to analyse the security of dynamic networks. However, in this section, only the following are used; (i) Risk on attack paths (ii) Probability of attack success on paths and (iii) Number of attack paths. The calculation details for those metrics can be found in Chapter 4.

5.2.4 Determining the Minimum Weight Threshold to use for TI-HARM

Depending on the configurations and operational requirements of networks, attack scenarios vary vastly. For example, a dynamic network with minimal change over time would present similar weaknesses and vulnerabilities more persistently in comparison to a dynamic network with many components changing more frequently. Therefore, there is no single value of the weight value to be used with the TI-HARM that can be used globally, rather more adaptive means of choosing the weight value is needed. This is important as choosing a wrong weight value may result in misleading security analysis if the core network components forming the attack scenarios are not captured and modelled. To address this problem, a MWT algorithm shown in Algorithm 6 is developed. The algorithm computes the weight value that guarantees at least one attack path is present. By doing so, it can carry out security analysis taking into account the most persistent network components (i.e., network components that appears the most across the network states). In the algorithm, $r\_threshold$ and $step\_intv$ is used to represent the required threshold and for the interval in which the weight value is adjusted, respectively.



(a)



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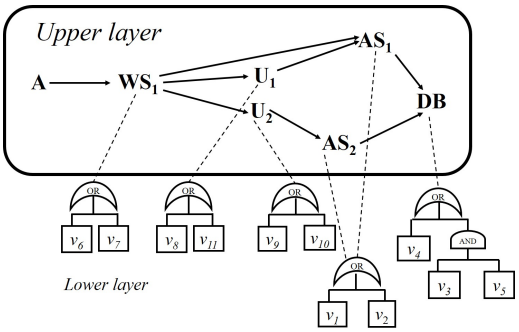


(c)

Figure 5.2: TI-HARM (a) TI-HARM with $w = 0.0\%$ (i.e., all the appearance of components), (b) TI-HARM with $w = 50\%$, and (c) TI-HARM with $w = 100\%$

Algorithm 6 Minimum weight threshold computation

```
1: procedure Cal_min_value(S, step_intv, r_threshold)
2:     set w = 0.0
3:     minimum_w→ w
4:     while w ≤ 100 do
5:         TI_HARM = TI_HARM(S, w)
6:         if attack paths exist in TI_HARM then
7:             increment w by the step_intv
8:         else
9:             minimum_w ← w − step_intv
10:            break
11:        end if
12:        break
13:    end while
14:    TI_HARM = TI_HARM(S, 0.0)
15:    New TI_HARM = New TI_HARM(S, minimum_w)
16:    risk = CALCULATE RISK(TI-HARM)
17:    new risk = CALCULATE RISK(New TI_HARM)
18:    threshold ← (risk - new risk)/risk
19:    while threshold < r_threshold do
20:        reduce minimum_w by the step_intv
21:        threshold ← calculate new threshold for minimum_w
22:    end while
23:    return minimum_w
24: end procedure
25:
26: procedure CALCULATE RISK(GSM)
27:    Compute all possible attack paths of GSM (paths)
28:    max_risk → 0
29:    for all path in paths do
30:        new risk ← sum of risk in path
31:        if new risk > max_risk then
32:            max_risk=new risk
33:        end if
34:    end for
35:    return max_risk
36: end procedure
```

5.2.5 Security Rating System

Using the MWT algorithm shown in Algorithm 6, a security rating system is defined for the dynamic networks. The advantage of dynamic networks compared to the traditional static networks is the ability to implement

advanced security mechanisms such as MTD to continuously change the attack surface. Therefore, if an attack path is identified and that attack path is visible for a long duration (i.e., appears in many network states), then such network yields a similar security concern as of a static network. Assuming that all vulnerabilities are equally damaging to the network, it is more secure to change the network components more frequently. The MWT algorithm can be used to determine the dynamicity of networks (i.e., how much changes are observed through different network states). Equation (5.2) shows the SRS score calculation. In the calculation, *Risk* is used to denote the calculated risk for $w = 0.0\%$, (i.e., for all appearance) and *New Risk* to denote the risk calculated using the MWT value in the TI-HARM. The metric Risk on attack paths (here used as *Risk*) is calculated by Equation (4.8).

$$SRS = (Risk - New\ Risk)/Risk \tag{5.2}$$

Figure 5.3 shows the meaning of the threshold value calculated. The SRS aims to provide the overview of security for network systems. From the figure, the SRS value shows the overview of the security for a weight value use (i.e., how the number of the vulnerable component are captured by the security model based on risk). When the threshold is 0.0, it means that all the persistent network component have been well captured by the weight value (this will give a better analysis). Conversely, when the threshold value begins to move towards 1.0, it shows that the level of the coverage is decreasing (with 1.0 as the most critical threshold to allow). In this case, using a weight value with a threshold value towards 1.0 will lead to a misleading security analysis (because only a few important hosts are being considered for analysis). In Section 5.3.4, the simulation networks is used to demonstrate the algorithm as well as the interpretation for the threshold values in Figure 5.3. Also, the calculation of the SRS is demonstrated as follows.

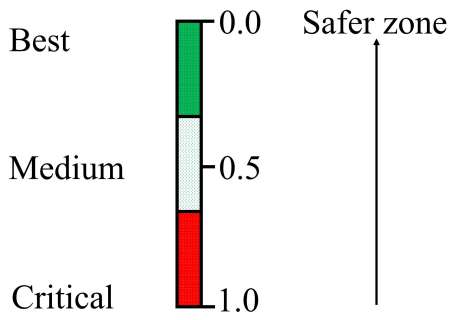


Figure 5.3: Interpreting the SRS value

Risk on attack paths: This is calculated by Equation (4.8). The calculations are shown in Table 5.4 and Table 5.5 for $w = 0.0\%$, and $w = 100\%$, respectively. From the calculations, the Risk for for $w = 0.0\%$, and $w = 100\%$ is 39.78 and 38.27, respectively.

Table 5.4: Risk on attack paths for $w = 0.0\%$

ID	Paths	Risk
ap_1	A, WS1, AS1, DB	31.03
ap_2	A, WS1, U1, AS1, DB	35.32
ap_3	A, WS1, U2, AS2, DB	38.27
ap_4	A, WS1, U3, AS1, DB	37.15
ap_5	A, WS1, U4, AS2, DB	38.27
ap_6	A, WS2, U2, AS2, DB	**39.78**
ap_7	A, WS2, U3, AS1, DB	38.67
ap_8	A, WS2, AS2, DB	32.54

Table 5.4 and Table 5.5 shows the calculations of the $RISK$, while the SRS is calculated by Equation (5.2) as:

$$SRS = (39.78 - 38.27)/39.78$$
$$= 0.04$$

Based on Figure 5.3, it can be concluded that the TI-HARM with $w = 100\%$ has captured the core network components that were visible for a long duration

in states since the SRS value is very close to the safe zone.

Table 5.5: Risk on attack paths for $w = 100.0\%$

ID	Paths	Risk
ap_1	A, WS1, AS1, DB	31.03
ap_2	A, WS1, U1, AS1, DB	35.32
ap_3	A, WS1, U2, AS2, DB	**38.27**

5.3 Simulations and Results

Experimental analysis via simulations is performed to demonstrate the proposed model. Also, the appropriate weight value (for hosts and edges) to use (for different network models) given multiple states, network components and their duration are investigated. To generalise, two dynamic network models (similar to Bopche and Mehtre [19]) are simulated; (i) External - DMZ - Internal network (E - D - I network) and (ii) External - Internal network (E - I network), these may include a subset of other complex network topology within each subnet. The descriptions for the networks are giving in Section 5.3.1. In Section 5.3.2, the simulations settings are described, and in Section 5.3.3 the results are presented.

5.3.1 Scenario Description and Simulation Networks

In this section, a campus network is assumed and simulated, in which the network is open to a large number of users and so contains several workstations. It is assumed that the network allows workstations to join the network without security scanning and that, dynamic host configuration protocol is used to automatically assign IP address settings to the hosts that are joining (for instance, BYOD). Further, the network users are allowed to install software on their workstations, and this software may have one or more vulnerability. Hence, this may provide platforms for the attackers to hack into the network

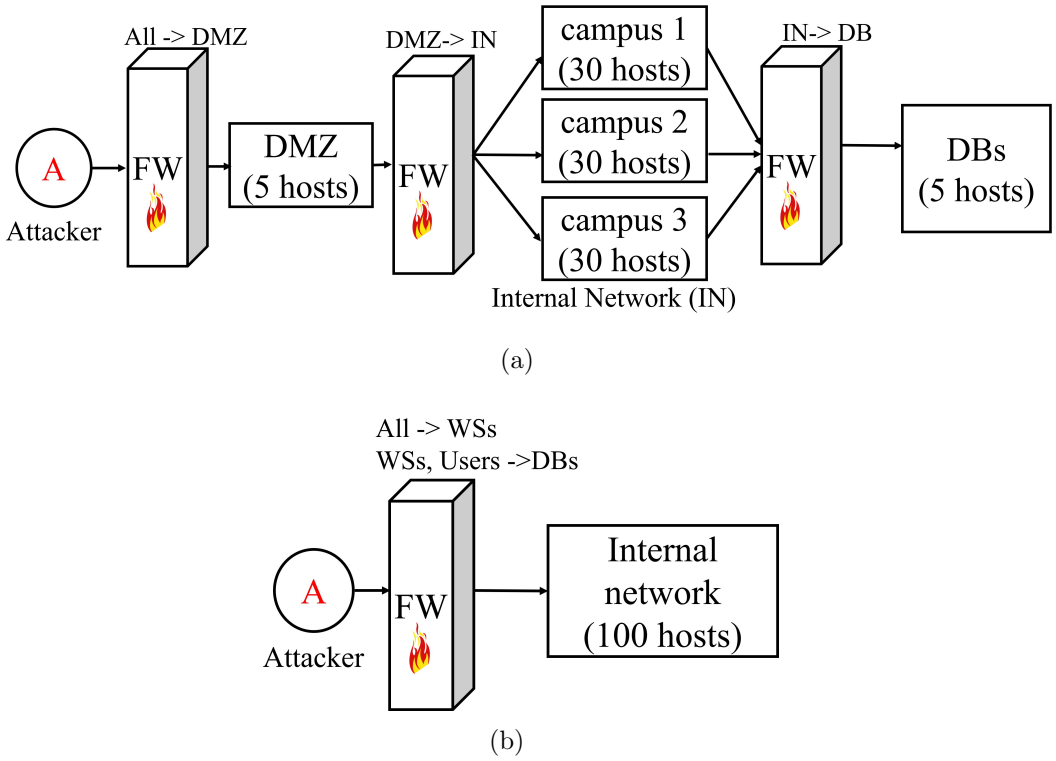


Figure 5.4: The initial network use in simulations: (a) E - D - I network, and (b) E - I network.

then have control over sensitive resources.The description of the two network models used is described as follows.

E-D-I network: The network is shown in Figure 5.4(a). The network is divided into a DMZ and internal network with the attacker located on the external network. The internal network consists of three campuses and the database subnet. The subnets are separated by firewalls which control access to resources found on each of the subnets. The DMZ subnet only allows external users to have access to the web server before having access to the Database. Further, the hosts in the internal network are allowed to send packets to other hosts within the internal network. The outside attacker is an authorised user who does not have permission to access sensitive data on the database. Here, the attack goal is for the attacker to escalate privileges from users' to administrator' privilege then steal sensitive data. It is assumed that the attacker cannot reach the Database directly. However, once an attacker

connects to the network through the web servers, the attacker can easily obtain information about the network topology and vulnerabilities using tools such as Nmap and OpenVAS.

E-I network: The network is shown Figure 5.4(b). The network consists of only a firewall which controls access to the internal network. However, hosts in the internal network are able to send packets to other hosts within the internal network. It is assumed that the attacker is located on the external network and therefore the attacker is able to reach only a few hosts (i.e., the web servers) however, the attacker can reach other hosts once he reaches the web server. Similarly, the attack goal here is to escalate privilege to administrators' then compromise the database.

5.3.2 Simulation Settings for the Network Models

The networks in Section 5.3.1 is used as the initial network state to conduct several simulations. The initial number of hosts used for the simulation is 100. It is assumed that each host has an OS with a vulnerability as shown in Table 5.6 (this are randomly assigned to the hosts). The following network changes are introduced to the states, which are; (a) additions of host, (b) removal of existing host, (c) additions of connection, and (d) removal of existing connection, with each state has a combination of the network changes (e.g., a state can have the combination of the changes {a,b,c,d} or {a, a, a, a}, *etc*). Thus, each state has a varying number of hosts and edges. In addition, each state has a time duration (i.e., the duration before the next network state is captured). In this simulation, a random time duration is assigned to the states ranging from 1 to 5 minutes. Also, ten (10) network states for every time window (T) is simulated and used.

Table 5.6: The hosts OSes and their vulnerability information used

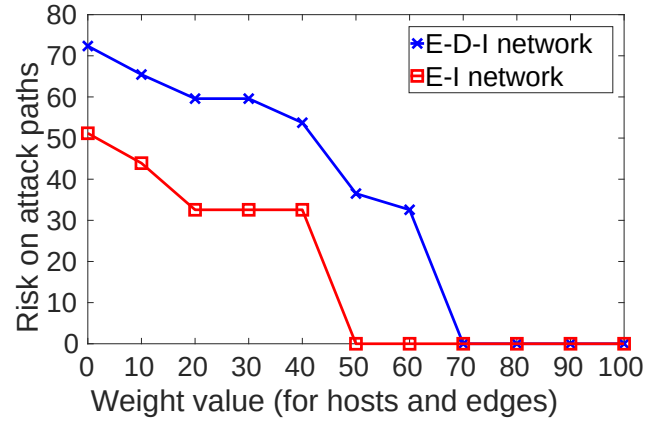
OS	CVE ID	CVSS BS
Windows 10	CVE-2017-8589	10.00
Redhat Enterprise Linux	CVE-2017-9953	5.00
Windows 8	CVE-2017-8464	9.30
Ubuntu	CVE-2015-5479	4.30

5.3.3 Results and Analysis

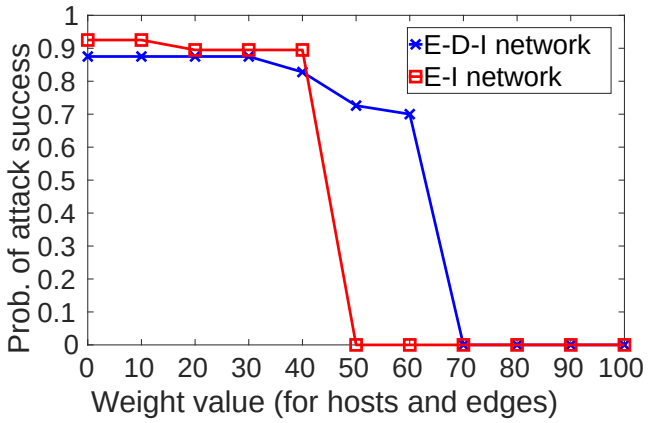
This section describes the results obtained for the settings in Section 5.3.1 and Section 5.3.2. The simulation covers the following factors in different scenarios; (1) Varying weight values (2) Varying the number of network states and (3) Varying the number of vulnerabilities.

Scenario I: Varying the weight value

In the TI-HARM, various weight values can be used to construct the TI-HARM and analyse the security of network states. The effect of changing the weight values on the aforementioned network models is evaluated. As shown by the results in Figure 5.5, irrespective of the network model used, increasing the weight value reduces the value of the security metrics. This is because increasing the weight value decreases the number of core components being modelled. Additionally, the changes in the security metrics indicate that the hosts and edges have varying weight value (they are very dynamic) when multiple states are taking into account. Also, it is observed that when there are more persistent hosts and edges in the states, increasing the weight value do not affect the value of the security metrics for some range of weight values (this is shown at weight value 20% to 40% for the E-I network except the number of attack paths). Also, the observations showed that, from 70.0% to 100.0% and 50.0% to 100.0% for E-D-I network and E-I network respectively, there is no attack path from the attacker to the target host because the weights for the edges (that is connecting the attacker to the target) are all less than 70% and 50%, respectively. This means that no edge was visible for 70% and 50% (or above) from the states, respectively.



(a)



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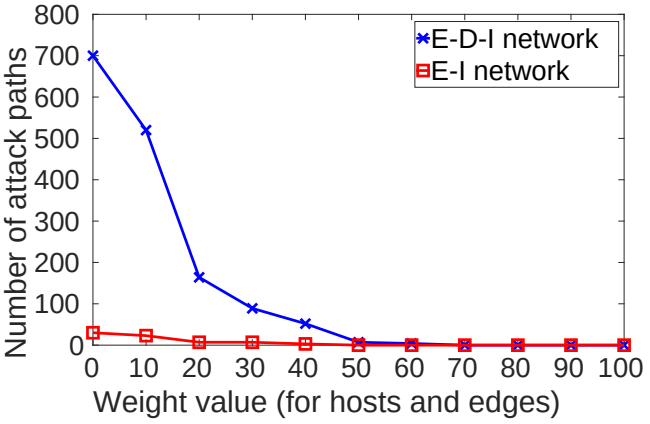


(c)

Figure 5.5: The effect of increasing weight value on different network model

In summary, using lower weight value covers more network hosts and show more attack scenarios. While increasing the weight value will progressively

reduce the number of hosts and edges and will model only the more persistent components.

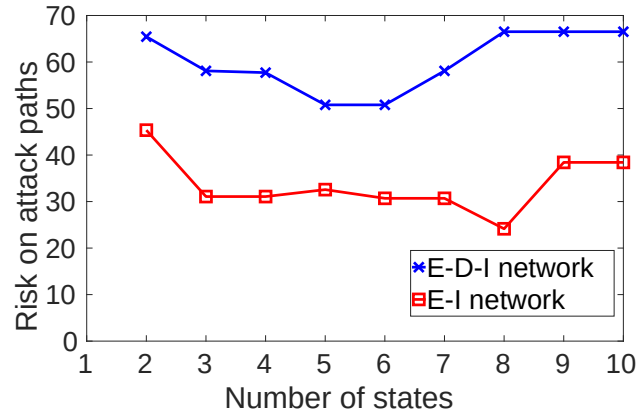
Scenario II: Varying the number of states

The TI-HARM can model multiple network states with various security property. For this simulation, the number of network states captured is varied (ranging from two to ten states, with each state having various changes). The network and settings in Section 5.3.1 and Section 5.3.2 is used. The weight value $w = 40.0\%$ is carefully used for all the network states in order to ensure that the paths from the attacker to the target hosts is not completely lost for both network models. Here, an investigation is performed on how the number of states captured may affect the value of metrics for the given weight value. Figure 5.6 shows the results, given weight ($w = 40.0\%$).

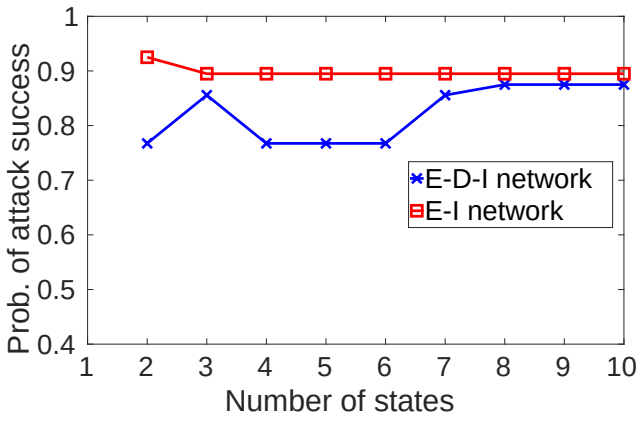
The results show that increasing the number of network states will continuously change the representation of security posture even when the weight value is kept constant for all cases (this is evident by the changes shown by the security metric values in Figure 5.6). Also, it is observed that as the number of states considered increases, the weight for the network components reduces (this is shown by the security metric values when the following number of states is used; 2 to 8 states and state 2 to 6 states for E-I network and E-I-D network, respectively). Further, it is observed that in Figure 5.6(c) there is a dramatic change in the number of attack scenarios from using 2 states to 3 states. This could be because most of the components are only visible in 1 of the 3 states or they are having a short time duration in the states (thus, their weight values are less than 40%). In this case, using a small number of states may not fully show the changes in the TI-HARM.

Scenario III: Varying the number of vulnerabilities

In this section, the number of hosts vulnerabilities are varied for the simulation networks in section 5.3.1. The aim is to investigate how the number of vulnerabilities affects the security analysis when a given weight value is



(a)



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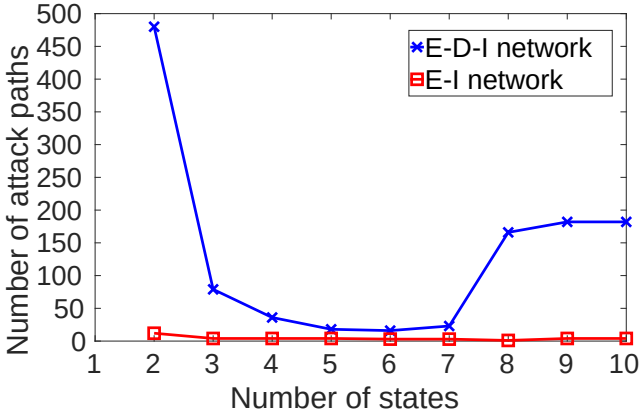
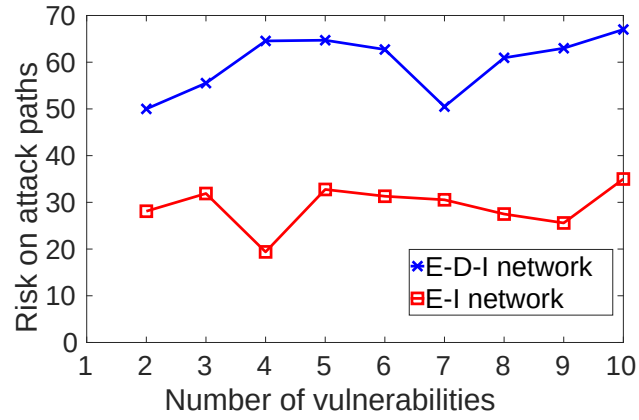


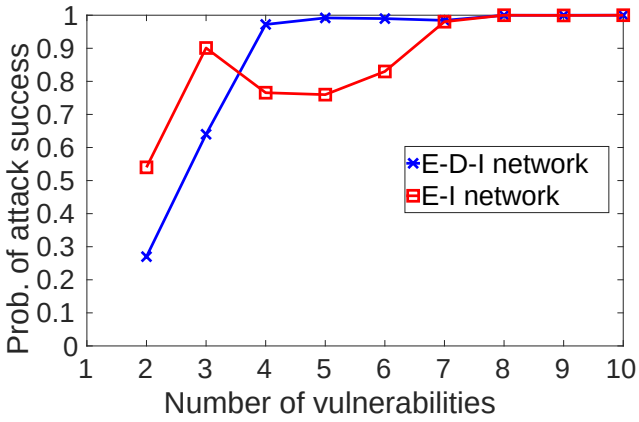
(c)

Figure 5.6: The effect of varying the number of states

considered. Similarly, the weight value used for the ten network states in the TI-HARM is $w = 40.0\%$. In the simulations, the vulnerabilities are randomly



(a)



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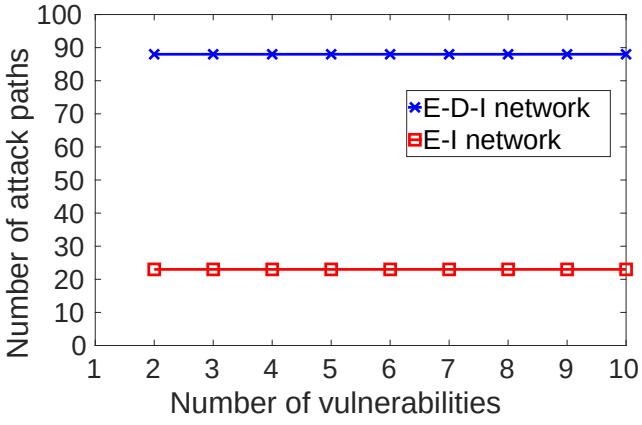


(c)

Figure 5.7: The effect of varying the number of vulnerabilities

assigned to the hosts. However, hosts in the same subnet (e.g., hosts in the web server subnet) have the same type of vulnerabilities and risk values. In

addition, the set of vulnerabilities found in network states for the same time window (T) may vary because the vulnerabilities are randomly assigned.

Figure 5.7 shows the results. In Figures 5.7(a) and 5.7(b), the metrics show similar effect. Here, regardless of the network model and number of vulnerabilities found on hosts, the metrics show different values for the same weight factor. However, in Figure 5.7(c), the metric did not change for all time that vulnerabilities are added to the states. This is because a two-layer security model is used, where attack paths are captures in the upper layer and the vulnerabilities information is captured in the lower layer. Moreover, since the network hosts already have one exploitable vulnerability each, that has already created attack paths for the hosts in the upper layer. As a result, adding more vulnerabilities on the hosts do not affect the number of possible attack paths (because every attack path is already represented).

5.3.4 Computing the Minimal Weight Value to Use

Using high weight value may sometimes result in complete loss of attack paths to the target hosts. This happens when connections (edges) from the attacker to the target host are not the same connections in the network states persistently (as a result of firewall rules changing, shuffle in MTD [73], users disconnecting and joining, *etc*). Hence, it is important to find an approach to determine the minimum weight threshold with non zero attack paths for the TI-HARM. In this section, the proposed algorithm in Algorithm 6 is used to compute the minimum weight value. Further, Figure 5.3 is used to explain the results.

The networks and settings presented in Scenario I (Section 5.3.3) is used for the simulations. Also, the simulation is run many times until a threshold less than 0.4 is found (which is close to the 'best' threshold value), and the step interval is set to 10 (here, a user can specify a desired threshold to allow). The result of this simulation is presented in Table 5.7. Using the algorithm, the minimum 'safe' weight value to use is $w = 30.0\%$ and $w = 40.0\%$ for E-D-I

and E-I network, respectively.

Table 5.7: Weight value based on a given threshold

Network model	initial		SRS	final	
	threshold	$w(\%)$		threshold	$w(\%)$
E-D-I	0.55	60.00	Medium	0.26	30.00
E-I	0.36	40.00	Safer zone	-	-

5.4 Discussions

In this section, an approach for a comprehensive security analysis taking into account several factors of multiple network states is developed. Experimental analysis via simulations is used to demonstrate the applicability of the proposed model. The results, findings and limitations are discussed below.

Comparing the TI-HARM with temporal GSM:
TI-HARM is proposed to comprehensively assess the security of the dynamic network. The security model takes into account network states, the duration of components in the states and their visibility over time. In particular, the captured network states are aggregated. By doing so, the TI-HARM is able to model all the possible network states components and also, it is able to calculate metrics that represents the security of the overall network states. As anticipated, the results showed that the proposed approach provides more comprehensive analysis because all important network components are well captured (i.e., against a GSM that can capture only a single network state, which ignores other components joining the network afterwards). Also, it is observed that the approach is able to capture all the possible attack scenario that may happen for a period of time.

Using weight values for the TI-HARM: A more static network component provides more time (or advantage) for an attacker to easily

study and find potential system vulnerabilities, then exploit them in order to penetrate through valuable network assets and steal sensitive information [163]. These analysis results show that increasing the weight value in the TI-HARM can generate a security model with the most persistent network components. Thus, the TI-HARM can generate important components for security assessments.

Security evaluations: The security analysis performed have shown that several existing security metrics (e.g, system risk, the probability of attack success) can be computed via TI-HARM. However, they may be some overhead in the calculations of the metric for large size network when smaller weight value (e.g., $w = 0.0\%$) is used to construct the TI-HARM. So, there is a need to find a method to reduce the overhead of using the smaller weight values in the future work.

5.5 Summary

The properties of dynamic networks make it technically challenging to carry out a security analysis, where there is a lack of methods and techniques to capture different security posture when the network changes. In this chapter, TI-HARM is developed to comprehensively model and analyse the security of changing networks by taking into account multiple network states, their duration and the visibility of components in the states. Further, the effect of using different weight threshold to construct the TI-HARM is investigated. Then, an algorithm for determining the MWT to use in order to prevent misleading security analysis when using the TI-HARM is developed. The analysis showed that TI-HARM could model and analyse the overall security of changing networks which were not possible using existing GSM.

Chapter 6

Metrics for Assessing the Security of Dynamic Networks

To get an accurate assessment of network security, security metrics are necessary to quantify the level of the security. However, it is a challenging task to quantify the security of modern networks due to the unpredictable network and security posture changes at different times. Therefore, a systematic approach is needed to quantitatively assess the security posture of dynamic networks. There are many quantitative security metrics that are used with traditional GSMs such as AG, to assess the security posture of the network [2, 15, 19, 33, 48, 79, 108, 114, 127, 137]. However, these approaches assumed the network of static nature. As such, changes made due to networking functionalities (e.g., firewall rule change, host joining, host migration in the cloud [37], *etc.*) changes the security posture and the security information, which are not captured using the traditional GSMs and metrics.

In this chapter, T-HARM and TI-HARM are used to address the aforementioned problems by developing a new set of security metrics to assess the security of dynamic networks. First, all the possible security changes that will be measured are identified (i.e., based on characteristics of the dynamic network and their relations to system risk). Next, formulas are built to capture every change in the network states under consideration. Furthermore, the

security metrics are grouped according to their functionalities and what they can capture or represent. Examples and simulations are used to demonstrate the proposed security metrics. The main contributions in this chapter are summarised as follows.

- Categorise the metrics for assessing the security of dynamic networks;
- Develop a new set of metrics to measure different aspects of the security of dynamic networks;
- Demonstrate the applicability of the new security metrics.

6.1 Metrics for Assessing Dynamic Networks

There is a lack of approach to quantitatively assess the security of dynamic networks [19]. As a result, two groups of security metrics for the analysis of dynamic networks are developed; (1) Dynamic metrics (2) Stateless metrics. The dynamic security metrics capture and assess the changing security posture of networks when the network components change over time. On the other hand, the stateless metrics provide the overview of the security posture of the dynamic network for a given time window. Figure 6.1 shows the different groups of the the metrics for the assessment of dynamic networks, and Section 6.1.1 (Dynamic metrics) and Section 6.1.2 (Stateless metrics) explains the different groups. Since the proposed metrics are grouped and modularised, this approach provides flexibility to add/modify/remove metrics as necessary.

6.1.1 Dynamic Metrics

Existing security metrics lack the capabilities to represent the changes in the security posture of networks as the network components change over time. It is of paramount importance to understand the changing security posture in order to provide effective security solutions. To address this issue, attack

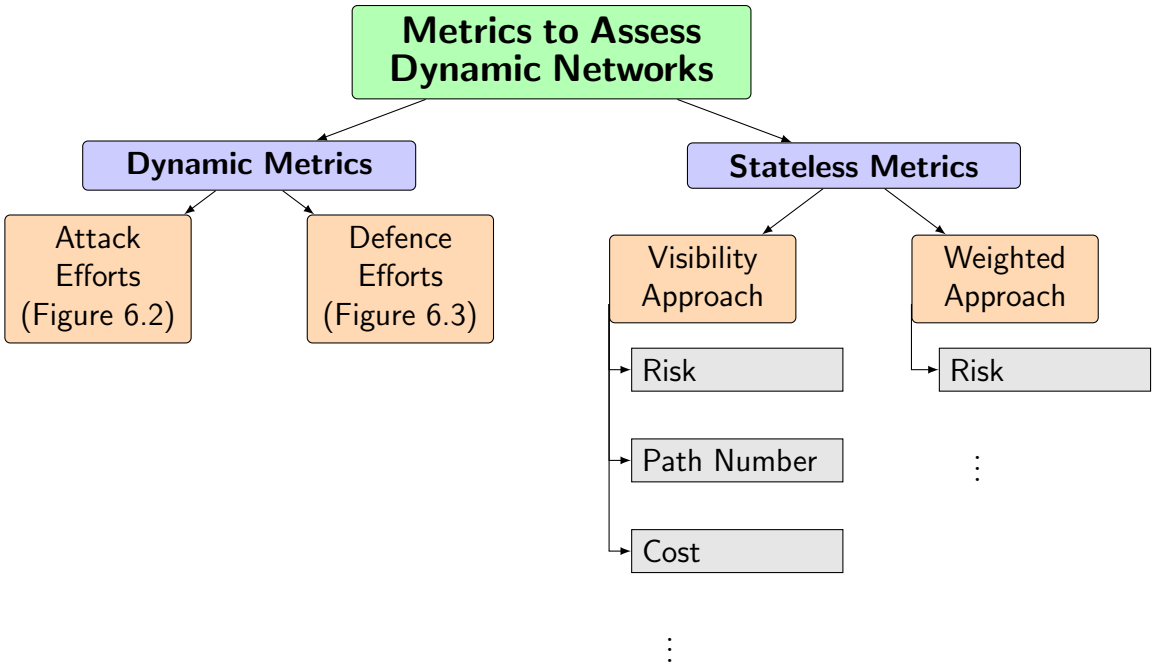


Figure 6.1: Metrics for assessing dynamic networks

and defence efforts are taken into account to develop a set of new security metrics to capture the effects security changes with respect to changes in the network using the T-HARM. First, Section 6.1.1.4 presents the attack efforts metrics, and Section 6.1.1.5 presents the defence efforts metrics. Lastly, the quantification of these metrics is shown in Section 6.1.3. In the following, the new dynamic security metrics are presented.

6.1.1.1 Attack and Defence Efforts Metrics

There are different efforts made by attackers and defenders depending on the imposed threat to the system. The attack and defence efforts are presented in this section, which is used to develop new security metrics for assessing the security of dynamic networks. First, the attack efforts is classified in Section 6.1.1.2, followed by the classification of defense efforts in Section 6.1.1.3.

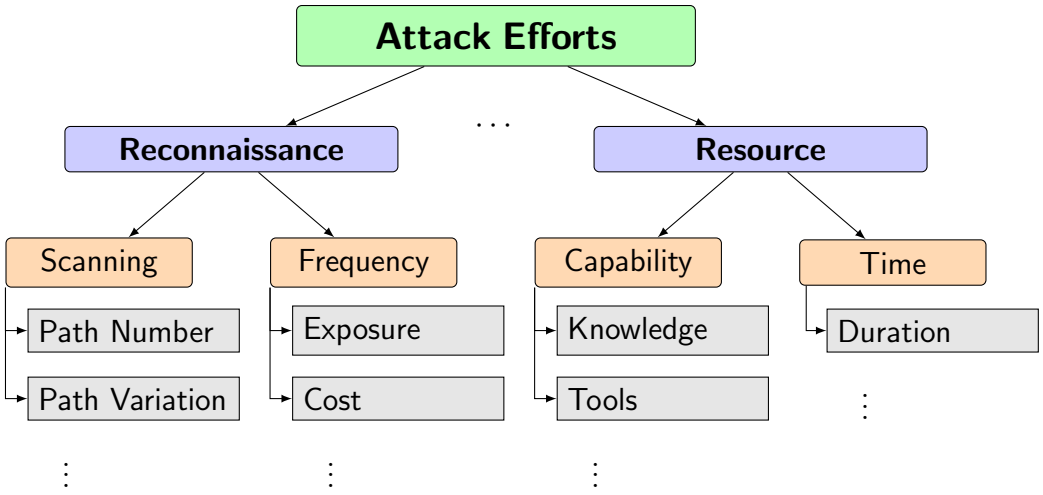


Figure 6.2: Categorising attack efforts

6.1.1.2 Categorisation of Attack Efforts

Attack efforts vary depending on the complexity of the attack scenario, which is dependent on the security characteristics of the network configuration. Hence, identifying security characteristics of the network configuration can be used to evaluate the attack efforts. Here, the security characteristics of dynamic networks are specify by the changes made in the network configuration (see Table 3.2) which can be as a result of users' activities (e.g., installations of applications) or security administrator' activities (e.g., apply defence mechanisms), *etc.* Figure 6.2 shows the categorisation of attack efforts. It shows two subcategories of the attack efforts, based on *Reconnaissance* and *Resource*. Reconnaissance is an action taken by the attacker to gather information. This is further divided into *Scanning* and *Frequency*, where *Scanning* observes the network configurations, and *Frequency* specifies the amount of scanning. *Resource* specifies the properties of the attacker, which divides into *Capability* and *Time*. *Capability* specifies the ability of the attacker (e.g., knowledge of attacks, tool availability, *etc.*), and *Time* specifies how much time would be/has taken for the cyberattack. New dynamic security metrics are proposed to capture those attack efforts in Section 6.1.1.4.

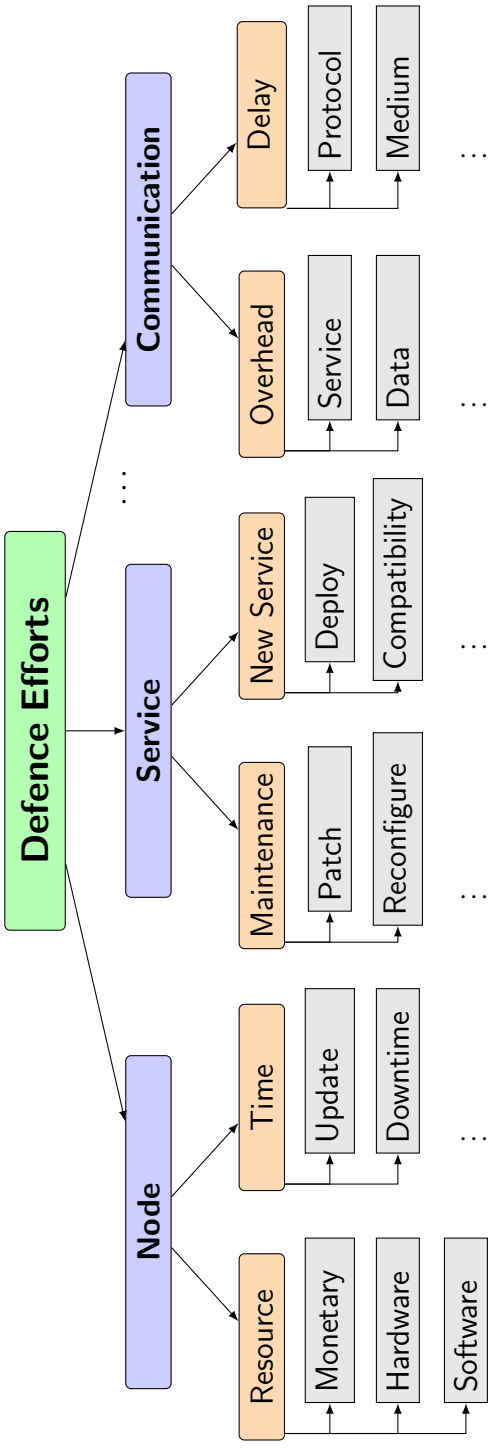


Figure 6.3: Categorising defence efforts

6.1.1.3 Categorisation of Defence Efforts

The deployment of security measures on the network changes the security posture as well. As a result, the security administrator needs to consider the cost that is associated with such a deployment. The defender's efforts made when deploying security measure for modern networks is considered. Figure 6.3 shows the categorisation of defence efforts. It shows three subcategories on the basis of network components; network nodes, services, and communications. The deployment of security measures (e.g., security update) can change the security information of *Nodes* (e.g., hosts), and besides this require time and resources to do so. *Services* form a platform for interaction (e.g., applications), which requires the adoption and deployment of new services and maintenance. This can be changed using some security measures such as hosts migration. *Communications* (e.g., connections between network nodes) can be changed by modifying the firewall rules, *etc.* Similarly, with attack efforts, new dynamic security metrics capturing each subcategory of defence efforts are presented in Section 6.1.1.5.

6.1.1.4 Attack Efforts Metrics

This security metrics aim to capture the change in security posture as the network configurations and attack vector changes. One aspect of the attack vector is the attack paths. By observing the changes to attack paths, the increase in the attack effort can be evaluated.

Scanning: Path Number

This metric is used to show the exposure of the dynamic network states to attack. The network security can negatively be affected when there is an increasing number of attack paths, as it reveals more choices to be taken by the attacker when the scanning is carried out. Therefore, changes in the number of attack paths when network changes occur need to be taken into account

in order to understand the changes in the security of the network in terms of possible paths to reach the target. Equation (6.1) shows the proportion of attack paths increased. If the number of attack paths stays the same, then it equates to value 0. However, if the previous network state had no attack paths, then it equates to 1.

$$\frac{|AP_{ns_{t_i}}| - |AP_{ns_{t_{i-1}}}|}{|AP_{ns_{t_i}}|} \tag{6.1}$$

Now consider a reduced number of attack paths in the current network state. Assuming that the attack efforts stay the same (i.e., there is no advantage), then the security metric can be calculated as shown in equation (6.2).

$$\frac{max(|AP_{ns_{t_i}}| - |AP_{ns_{t_{i-1}}}|, 0)}{|AP_{ns_{t_i}}|} \tag{6.2}$$

The difference between the number of attack paths for all network states is computed and then normalised. Equation (6.3) shows the computation of APN metric that measures the differences between the numbers of attack paths for all network states. The APN metric does not need an arbitrary assignment of values, and it is calculated only based on the observed number of attack paths from all network states NS.

$$APN = \frac{\sum_{i=1}^{|NS|} \frac{max(|AP_{ns_{t_i}}| - |AP_{ns_{t_{i-1}}}|, 0)}{|AP_{ns_{t_i}}|}}{|NS| - 1} \tag{6.3}$$

Frequency: Exposure

The duration of attack path exposure for dynamic networks can be calculated. It is assumed that the attacker is likely to prepare and launch an attack successfully if the exposure of an attack path is long enough (e.g.,

the attack lifetime described in [53]). Hence, the duration of an attack path should be minimised to enhance security. However, estimating the amount of time needed for the attacker to prepare and launch an attack is difficult. Hence, the best case is to minimise the duration of an attack path exposure. That is, the goal of the metric is to compute the duration of each attack path exposed. The function $t(ap_i)$ is used to compute the attack path exposure as shown in equation (6.4), which is normalised by the number of attack paths and the total number of network states.

$$APE = \frac{\sum_{i=0}^{|NS|} t(ap_j)}{|AP| \times \sum_{i=1}^{|NS|} t(ns_{t_i})} \forall ap_j \in AP_{ns_{t_i}} \tag{6.4}$$

For the APE metric, if the initial set of attack paths are exposed in all the network states without any new attack paths, then the APE value tends toward one. Hence, it is better to achieve a lower value of APE which represents that an attack path is only exposed in one network state.

Capability: Knowledge

Costs are one of the important decision constraints for both attackers and defenders. Here, the cost of an attack is estimated based on the difficulty of exploiting vulnerabilities using the CVSS, particularly the exploitability score (from the Base Equation of the CVSS) that determines the difficulty of exploiting the vulnerability (i.e., the knowledge of the attacker will determine the ability to exploit vulnerabilities with lower exploitability scores etc). The CVSS version 2 is used, as many of the legacy vulnerabilities do not have version 3 available yet, but new vulnerabilities still have version 2 available, which is more practical (both versions have the exploitability (sub) score which is used in this subsection). However, other means of cost metrics can be used to further categorise the knowledge category of the attacker efforts in addition to the CVSS exploitability scores.

The attack cost associated with exploiting vulnerability can be calculated by taking into account all possible attack paths. Then, the exploitability of each attack path becomes the cumulative product of all the vulnerabilities required. The attack cost of exploitation for a state, $AC_{ns_{t_i}}$, is shown in equation (6.5).

$$AC_{ns_{t_i}} = \prod_{j=1}^{|AP_{ns_{t_i}}|} \left(1 - \prod_{k=1}^{|ap_j|} Ep(v_k)\right) \quad (6.5)$$
$$, \text{where } v_k \in vuls(ap_j) \forall ap_j \in AP_i$$

Using the above equation, the attack cost associated with the exploitation of vulnerabilities can be computed as shown in equation (6.6) taking into account all network states.

$$ACE = \frac{\sum_{i=0}^{|NS|} AC_{ns_{t_i}}}{|NS|} \quad (6.6)$$

The inner product computes the exploitability of each attack path and combines them using the disjoint set theory. This is processed for all network states.

Time: Duration

The amount of time taken for the attacker to compromise each stepping stone in an attack path is another significant factor, as the longer the attack takes, the more likely it will be detected. Hence, increasing the amount of time to attack can negatively affect the attacker. Also, it is assumed that the attacker will minimise the time taken for an attack. Hence, the minimum time taken by the attacker to compromise the target in each network state is computed based on the time taken to exploit each vulnerability in the attack path, which is presented as a function $t(ap_i)$. In practice, the minimum time to exploit can be approximated (i.e., the function $t(ap_j)$) through empirical

studies [112], as well as using other timing models as appropriate. Assuming that exploiting a vulnerability has a specific time frame, then there is no need to consider the skills of different attackers. Equation (6.7) shows the normalised metric representing the time taken to compromise the target in a given network state. The time has been normalised by the maximum amount of time to compromise the target by the attacker.

$$ACD = \sum_{i=0}^{|NS|} \frac{\frac{min(t(ap_j))}{max(t(ap_j))}}{|NS|} \forall ap_j \in AP_{ns_{t_i}} \tag{6.7}$$

The ACD metric computes the ratio of the shortest and longest times taken for the attacker to exploit the target in each network state. Hence, higher ACD value represents that a significant proportion of the network states can be exploited in a shorter time than the expected maximum amount of time.

6.1.1.5 Defence Efforts Metrics

There are different type of costs associated with deploying security hardening measures in the network. In this section, the cost associated with defence efforts are captured and presented in Section 6.1.1.3.

Time: Implementation Downtime

The implementation of a security measure causes a downtime in the network. The aim of this metric is to show the downtime experience as a result of the implementations of security measures. Downtimes can be estimated and measured, which can be used for input to this metric calculations. First, equation (6.8) shows the downtime, calculation of a given network state ns_i.

$$max(dt(cm_k, h_j)), \forall h_j \in H_i \tag{6.8}$$

Equation (6.9) shows the downtime experienced when implementing security measures for dynamic networks. The downtime has been normalised by the maximum downtime experienced.

$$NDT = \sum_{i=1}^{|NS|} \frac{max(dt(cm_k, h_j))}{|NS| \times max(dt(cm_k, h_j))} \quad \forall h_j \in H_i, \forall cm_k \in CM \tag{6.9}$$

The higher NDT value represents more downtime observed when implementing the defence measures in the network. As the NDT value converges to zero, it represents the minimum downtime for all network states.

Overhead: Service

As a form of defence mechanism, the network topology can be reconfigured to improve security. However, there is a cost associated with maintaining communication (i.e., edges) between the network components. Such costs depend on which communication service is in use, and how the communication paths are changed. For the basics, the difference between the edge set is defined as the edge changing cost (ECC). Assuming that the cost of changing the edge is the same. Then, it is only the number of edge changes between the network states that will be counted. Networking technologies deploy edge changes in parallel (e.g., SDN) but the amount of change still affects the network performance of the affected region. Hence, the more edge changes, the higher cost is observed (e.g., delay or downtime). The edge variation cost can be computed as shown in equation (6.10), where the cost of each network state is normalised by the maximum edge variation cost, and the total cost

normalised by the number of network states.

$$ECC = \sum_{i=1}^{|NS|} \frac{\frac{|et(ns_{t_i}) \ominus et(ns_{t_{i-1}})|}{|et(ns_{t_i}) \cup et(ns_{t_{i-1}})|}}{|NS| - 1} \tag{6.10}$$

Delay: Medium

Defence mechanisms such as traffic redirection, host isolations, shuffle in moving target defences [73], *etc.* involves the changing/removing the connections between hosts. This event may attracts a delay and loss of data between the communications (similar to the downtime of implementation under *Node* category). Hence, it is important that such defence mechanisms do not affect the system performance by limiting the edge changing time. The equation (6.11) shows the computation of the time duration of the edge pair changes in ns_{t_i}.

$$et(ns_{t_i}) = max(et(h_j) \forall h_j \in H_i) \tag{6.11}$$

Given the time duration of the edge pair changes, the edge variation time can be calculated for all network states as shown in equation (6.12). The edge variation time is normalised by the maximum amount of time taken for changing the edge sets.

$$ECT = \frac{\sum_{i=1}^{|NS|} et(ns_{t_i})}{max(et(ns_{t_i})) \times (|NS| - 1)}, \forall ns_{t_i} \in NS \tag{6.12}$$

6.1.2 Stateless Metrics

The stateless security risk assessment provides network state-independent view of the security. That is, the security metric value calculated represents all the observed network states.

Two main approaches are used: 1) Visibility Approach (VA), and 2) Weighted Approach (WA). The VA approach combines all the observed network configurations onto a single GSM and then calculates a metric which represents the states. The TI-HARM can be used to calculate the metrics for the VA. In contrast, the WA approach evaluates the security of each network state and then combines them based on their time duration converted into weights (i.e., the proportion of the network state visibility).

6.1.2.1 Visibility Aggregation

The VA approach collects all visible network states. This approach enables one to capture all the network states information in the security assessment and maintain the same security assessment as long as the observed states are not changed. The limitation of the VA approach is that it does not reflect the exposure of different network states (i.e., the time information is not taken into account).

VA: Path Number

The ultimate goal of this metric is to quantitatively represent the number of ways an attacker can use the existing security weakness (i.e., vulnerabilities and their relationship) to compromise a network system over a period of time. This metric shows the total number of attack paths that are visible for a period of time. Thus, a high number of attack paths reveals more choices to be taken by the attacker when the scanning is carried out. Here, the network administrator's task is to minimally reduce the number of attack paths for all the states. Equation (6.13) shows the set of attack paths for a network state ns_{t_i}.

$$AP_{ns_{t_i}} = \{ap_0, ap_1, ap_2, ..., ap_n\} \tag{6.13}$$

Then the unique number of attack paths for the network states can be calculated by equation (6.14).

$$VA : APN = |AP_{ns_{t_0}} \cup AP_{ns_{t_1}} \cup AP_{ns_{t_2}} \cup ... \cup AP_{ns_{t_n}}| \tag{6.14}$$

VA: Persistent Attack Paths Number

The goal of the metric is to calculate the weakest part of a dynamic network in terms of the set of attack paths that appear in all the states. Typically, this set of attack paths will provide the attacker more time to plan a successful attack on the network hosts. Moreover, some defence mechanisms are not able to remove all attack paths, and as a result, the security administrator needs to identify the persistent attack paths for other forms of defence. In this regard, the number of the most persistent attack paths are captured over a period of time using this metric. First, the set of attack paths for each network states can be captured by using equation (6.15).

$$AP_{ns_{t_i}} = \{ap_0, ap_1, ap_2, ..., ap_n\} \tag{6.15}$$

The set intersection of all the states attack paths will capture the persistent paths for the time window in consideration. So, the calculations for the Persistent Attack Paths Number (PAP) is giving by equation (6.16).

$$VA : PAP = |AP_{ns_{t_0}} \cap AP_{ns_{t_1}} \cap AP_{ns_{t_2}} \cap ... \cap AP_{ns_{t_n}}| \tag{6.16}$$

VA: Security Stateless Risk

This metric calculates the overall security of the network states by aggregating all the observed components in the states. However, it does not take into account the time duration of the network states. The VA stateless

risk for the multiple network states can be calculated by Algorithm (7).

Algorithm 7 VA Stateless Risk

1: S: a set HARM for all network states
2: s_{init}: an empty HARM
3: **for all** $s \in S$ **do**
4: **if** components of s_i not in s_{init} **then**
5: $s_{init} = s_{init} \cup s_i$
6: **end if**
7: **end for**
8: Calculate the security risk of s_{init} (i.e., $= \sum_{ap_j \in AP_{ns_{t_i}}} r_{ap_j}$)

VA: Security Cost

Security cost is the amount of real money spent to reach a security level. To calculate this, the notations, CM is used to denote the set of all the hardening options to deploy from all the network states, cm_i is used to represent a hardening option i (i.e., $cm_i \in CM$), $c_j(ns_{t_i})$ is used for an atomic security cost j (e.g., cost of maintenance) for a state ns_{t_i}, C_{cm_i} is used for the set of atomic cost associated to cm_i and tc_{cm_i} as the total cost of a hardening option cm_i in the network states (which is calculated by equation (6.17)). The metric is calculated by equation (6.18).

$$tc_{cm_i} = \sum_{ns_{t_i} \in NS} \sum_{j=0}^{|C_{cm_i}|} c_j(ns_{t_i}) \tag{6.17}$$

$$VA : SC = \sum_{cm_i \in CM} tc_{cm_i} \tag{6.18}$$

6.1.2.2 Weighted Aggregation

The WA approach incorporates exposure of different network states, which overcomes the limitations of the VA approach. However, the WA approach cannot guarantee the same security assessment, which depends on the dynamic

behaviour of the network. Moreover, it requires more computational resources due to the security assessment of each network state, compared to the VA approach.

WA: Security Stateless Risk

This metric uses the hosts (nodes) risk value (e.g., from CVSS BS) to calculate the metric at the attack path level, to network state level and then the overall risk for the time duration. The attack path level risk r_{ap_i} is calculated by equation (6.19), the network state risk by equation (6.20), and the WA stateless risk is calculated by equation (6.21).

$$r_{ap_j} = \sum_{h_{t_i} \in ap_i} pr_{h_{t_i}} \times aim_{h_{t_i}}, \quad ap_i \in AP_{ns_{t_i}} \tag{6.19}$$

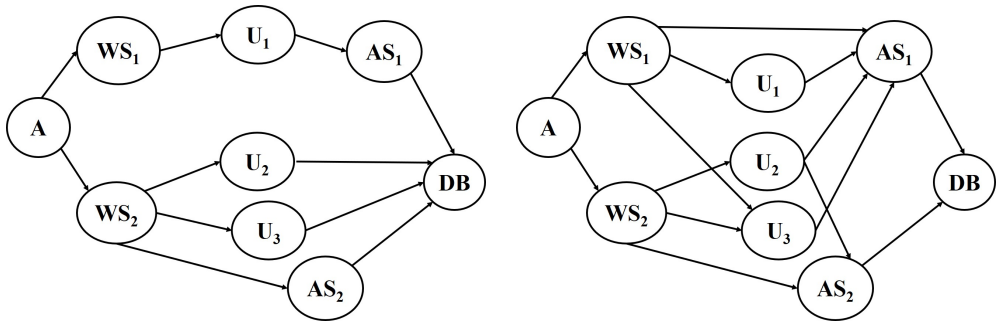
$$R_{ns_{t_i}} = \sum_{ap_j \in AP_{ns_{t_i}}} r_{ap_j} \tag{6.20}$$

$$VA : SR = \sum_{ns_{t_i} \in NS} \left(R_{ns_{t_i}} \times \frac{t(ns_{t_i})}{T} \right) \tag{6.21}$$

6.1.3 Application of Dynamic Security Metric Modules

This section describes the use of the proposed metrics using an example dynamic network. The network and the attacker model are shown in Section 3.2. The reachability of the hosts, the metrics associated to the hosts are shown in Figure 6.4, Table 6.1 and Table 6.2 (and Table 6.3 as well), and the network topologies are shown in in Figure 6.4. Time is assigned to the network topologies, the number of hours is chosen arbitrarily for demonstration only, the actual duration of each network state can be measured based on reconfiguration schedules. The attack goal is to reach the target host DB through an elevation of privilege. Assuming that each host has a remote-to-root vulnerability, and different operating systems have different exploitability values, the time is taken

to exploit and the security measure deployment downtime as summarised in Table 6.1 and Table 6.2. The value from NVD [118] and other random (e.g., time) but reasonably assigned values are used for demonstration. In practice, these values can be retrieved from empirical studies [112, 162], and system and network configuration details. It is also assumed that the time taken to update the set of edges for each host is determined by the number of edges updated (including addition and removal) from the previous network state (i.e., the sum of the number of updated edges). Given this scenario, the description of the computation of each metric is given below.



(a) ns_0 topology: initial network topology, state duration = 5 hrs

(b) ns_1 topology: state duration = 4 hrs

(c) ns_2 topology: state duration = 4 hrs

(d) ns_3 topology: state duration = 5 hrs (i.e., state ns_1 is repeated)

Figure 6.4: Topology configurations for the example network with pre-defined changes that are captured at different time

6.1.3.1 APN Computations

The number of the attack scenarios from the network states can be captured using the APN metrics. For instance, AP_{ns_0} =

Table 6.1: Metric values associated with hosts and vulnerabilities

Hosts	OS	CVE ID	Exploitability
AS_1, U_1	Windows 10	2017-8589	1.00
WS_1, U_2, U_3	Linux	2017-9953	1.00
WS_2	Windows 8	2017-8464	0.86
AS_2, DB	Ubuntu	2015-5479	0.86

Table 6.2: Metric values associated with hosts and vulnerabilities

Hosts	Time to exploit (hrs)	cm downtime (hrs)
AS_1, U_1	1.00	0.50
WS_1, U_2, U_3	2.00	0.80
WS_2	1.00	0.20
AS_2, DB	3.00	0.60

Table 6.3: Metrics associated with vulnerabilities

OS	CVE ID	aim_v	pr_v
Windows 10	2017-8589	10.00	1.00
Linux	2017-9953	5.00	0.50
Windows 8	2017-8464	9.30	0.93
Ubuntu	2015-5479	4.30	0.43

$\{(A, WS_1, U_1, AS_1, DB), (A, WS_2, U2, DB), (A, WS_2, U3, DB),$
$(A, WS_2, AS_2, DB)\}$ is the set of attack paths in ns_0 with the cardinality value of $AP_0 = 4$. While state ns_1, ns_2 and ns_3 have 7, 5 and 7, respectively. Then, the APN can be computed as shown in equation (6.22).

$$\begin{aligned} APN &= \frac{\sum_{i=1}^{|NS|} \frac{max(|AP_{ns_{t_i}}| - |AP_{ns_{t_{i-1}}}|, 0)}{|AP_{ns_{t_i}}|}}{|NS| - 1} \\ &= \frac{(\frac{3}{7}) + (\frac{0}{5}) + (\frac{2}{7})}{3} \\ &= 0.7143 \end{aligned} \tag{6.22}$$

If the APN value tends towards 1, then the number of attack paths is increasing as the network transits to other network states. On the other hand,

if the APN value tends towards zero, then the number of attack paths is decreasing as the network transits to other network states. So, maintaining the number of attack paths is better than increasing the paths number.

6.1.3.2 APE Computations

The APE metric measures the amount of attack path exposure for all network states. There are 9 possible attack paths when all the network states are considered. So, equation (6.23) is used to calculate the exposure of each path as follows.

$$\begin{aligned} APE &= \frac{\sum_{i=0}^{|NS|} t(ap_j)}{|AP| \times \sum_{i=1}^{|NS|} t(ns_{t_i})} \forall ap_j \in AP_{ns_{t_i}} \\ &= \frac{103}{9 \times 18} \\ &= 0.6023 \end{aligned} \tag{6.23}$$

If the initial set of attack paths are exposed in all the network states without any new attack paths, then the APE value tends toward 1. Hence, it is better to achieve a low value of APE which represents that an attack path is only exposed in one or just a few network states.

6.1.3.3 ACE Computations

The ACE metric computes the exploitability for the attacker to reach the target. The attack cost associated with exploiting vulnerabilities in each of the example network states can be calculated as shown in equation (6.24).

$$\begin{aligned} ACE &= \frac{\sum_{i=0}^{|NS|} \left(\prod_{j=1}^{|AP_i|} \left(1 - \prod_{k=1}^{|ap_j|} Ep(v_k)\right)\right)}{|NS|} \\ &= \frac{0.05096 + 0.000024 + 0.0004 + 0.000024}{4} \\ &= 0.0128 \end{aligned} \tag{6.24}$$

If vulnerabilities have low exploitability value (e.g., 0.1), the ACE value tends toward one. Given that the exploitability score of the vulnerabilities is high, the ACE metric value for the network states was computed near zero. This means that the attacker efforts in terms of the exploitation are easy. So, the network administrator needs to make the network configuration more difficult to exploit by ensuring that ACE value tends towards one.

6.1.3.4 ACD Computations

The ACD metric computes the ratio of the shortest and longest times taken for the attacker to exploit the target in each network state. Hence, lower ACD value represents that a significant proportion of the network states can be exploited in a shorter time than the expected maximum amount of time. Equation (6.25) shows the calculation steps for the example networks.

$$\begin{aligned} ACD &= \sum_{i=0}^{|NS|} \frac{\frac{min(t(ap_j))}{max(t(ap_j))}}{|NS|} \forall ap_j \in AP_{ns_{t_i}} \\ &= \frac{\frac{6}{7} + \frac{6}{8} + \frac{6}{7} + \frac{6}{8}}{4} \\ &= 0.8035 \end{aligned} \tag{6.25}$$

6.1.3.5 NDT Computations

The downtime to implement hardening solutions for the different vulnerabilities is assumed as in Table 6.1 and Table 6.2. Also, it is assumed that no hardening measure is deploy on ns_0, however, on ns_1, ns_2 and ns_4, hardening solutions are deployed on the Windows, Linux and Ubuntu, respectively. So,

the NDT can be calculated as shown in equation (6.26).

$$\begin{aligned} NDT &= \sum_{i=1}^{|NS|} \frac{max(dt(cm_k, h_j))}{|NS| \times max(dt(cm_k, h_j))}, \forall h_j \in H_i, \forall cm_k \in CM \\ &= \frac{0}{4 \times 0.8} + \frac{0.5}{4 \times 0.8} + \frac{0.8}{4 \times 0.8} + \frac{0.6}{4 \times 0.8} \\ &= 0.5937 \end{aligned} \tag{6.26}$$

The higher NDT value represents more downtime observed when deploying the security measures in the network. As the NDT value converges to one, it represents the maximum downtime for all network states.

6.1.3.6 ECC Computations

If ns_0 is assumed to be the initial network states, and the states ns_1, ns_2 and ns_3 have been reconfigured (as it is presented) over time. Then the ECC for the example network can be calculated by equation (6.27). The lower value represents fewer changes to the set of edges between the network states.

$$\begin{aligned} ECC &= \sum_{i=1}^{|NS|} \frac{\frac{|et(ns_{t_i}) \ominus et(ns_{t_{i-1}})|}{|et(ns_{t_i}) \cup et(ns_{t_{i-1}})|}}{|NS| - 1} \\ &= \frac{\frac{7}{9} + \frac{2}{7} + \frac{2}{7}}{3} \\ &= 0.4497 \end{aligned} \tag{6.27}$$

6.1.3.7 ECT Computations

The EVT measures the time taken to assign the edge sets in the network state, which determines the delay observed in the network. The time taken to update the edge pairs of a host is assumed to be the number of updated edges. Then, the ECT calculation for the example network is as shown in

equation (6.28).

$$\begin{aligned} ECT &= \frac{\sum_{i=1}^{|NS|} et(ns_{t_i})}{max(et(ns_{t_i})) \times (|NS| - 1)}, \forall ns_{t_i} \in NS \\ &= \frac{0}{1 \times 3} + \frac{0}{1 \times 3} + \frac{0}{1 \times 3} \\ &= 0.0 \end{aligned} \tag{6.28}$$

Although no edge is updated in the example, however, edges can be updated as a result of IP shuffling and other hardening techniques (an example can be found in [73]). Here, the ECT value is zero because there is no edge update. If the ECT value converges toward one, then the maximum delay for changing the edge set is observed for all network states.

6.1.3.8 VA: Path Number

The path number quantify the number of possible ways an attacker can compromise a dynamic network. For instance, there are 4, 7, 5 and 7 number of attack paths in the states ns_0, ns_1, ns_2 and ns_3, respectively. However, some of the attack paths are common among the sets of paths. So, the set union of the set of attack paths can be calculated for all the network states in order to get all the possible ways an attacker can compromise the networks by equation (6.29).

$$\begin{aligned} VA : APN &= |AP_{ns_{t_0}} \cup AP_{ns_{t_1}} \cup AP_{ns_{t_2}} \cup AP_{ns_{t_3}}| \\ &= 9 \end{aligned} \tag{6.29}$$

This metric shows the number of possible ways an attacker can compromise the network.

6.1.3.9 VA: Persistent Attack Paths Number

The metrics capture the attack paths that appear in all the network states. Here, The set intersection of all the states' attack paths will capture the persistent paths for the time window under consideration. So, the calculations for the PAP is giving by equation (6.30).

$$\begin{aligned} VA:PAP &= |AP_{ns_{t_0}} \cap AP_{ns_{t_1}} \cap AP_{ns_{t_2}} \cap AP_{ns_{t_3}}| \\ &= |\{(A, WS_1, U_1, AS_1, DB), (A, WS_2, AS_2, DB)\}| \\ &= 2 \end{aligned} \tag{6.30}$$

6.1.3.10 WA: Security Stateless Risk

The WA security stateless risk metric overcome the limitations of the VA stateless risk by taking into account time duration of the network states. The WA stateless risk for the example network can be calculated by equation (6.31) as follows.

$$\begin{aligned} WA:SR &= \sum_{ns_{t_i} \in NS} \left(R_{ns_{t_i}} \times \frac{t(ns_{t_i})}{T} \right) \\ &= \left(62.676 \times \tfrac{5}{18}\right) + \left(128.737 \times \tfrac{4}{18}\right) + \left(88.89 \times \tfrac{4}{18}\right) + \left(128.737 \times \tfrac{5}{18}\right) \\ &= 101.5317 \end{aligned} \tag{6.31}$$

6.2 Simulations and Results

Experimental analysis via simulations is conducted to demonstrate the functionalities of the proposed metrics based on attack effort metrics, defence efforts and stateless security metrics. To generalise the proposed approach, a generic dynamic network that randomly connects the hosts, which includes any possible network configurations is used. By doing so, the subset of practical network configurations is included in the analysis. Three factors are considered

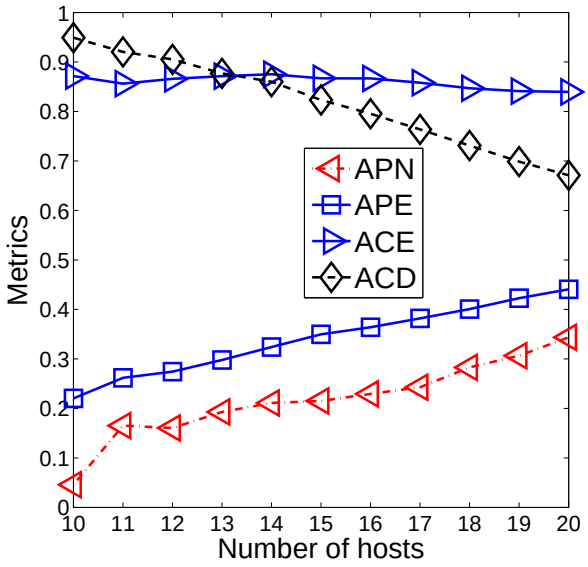
(i) the number of hosts, (ii) the number of vulnerabilities, and (iii) topology reconfiguration (edges changing) [78]. Five network states are captured and used for each of the simulations, and it is assumed that the attacker is located outside the network, where the attacker aims to compromise a specific target host inside the network. The attacker must carry out reconnaissance and execute exploitations in a sequence in order to compromise the target host. Also, if the chain of privilege escalation is broken, then the attacker loses the privilege gained back to the last reachable host in the chain. The T-HARM is used to capture the different attack scenarios for the network states.

The exploitability value for each host is randomly assigned uniformly between values 0.1 and 1 inclusive. The downtime, cost, edge update time are all assigned the value of one unit. These values can be populated from empirical studies or other statistical data to be more accurate. The following sections present results with respect to the number of hosts, the number of vulnerabilities and the edges changes (topology reconfigurations). In the following the attack effort metrics are shown in Figure 6.5(a) and Figure 6.6(a). The defence metrics are demonstrated in Figure 6.7 and the stateless security metrics are demonstrated in Figure 6.5(b) and Figure 6.6(b).

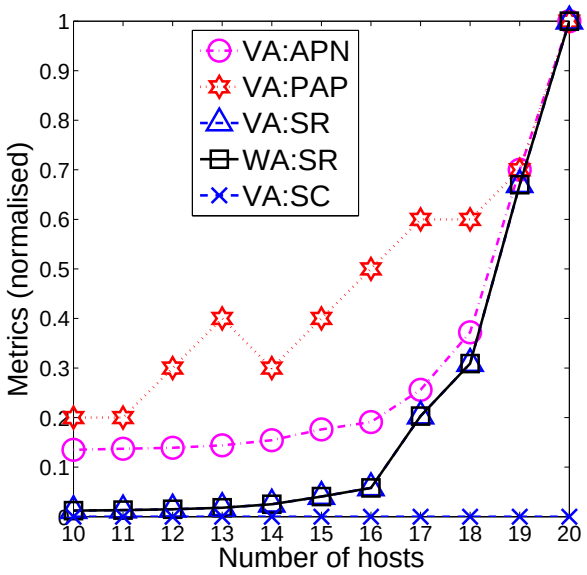
6.2.1 Varying the Number of Hosts

As the number of hosts increases, the management of the network becomes more complex in order to satisfy various constraints (e.g., performance, security). Similarly, understanding the attack efforts is also difficult without examining and collecting security changes made. For this analysis, five network states are used for each point. The results of how the addition of hosts changes the attack effort metrics are shown in Figure 6.5.

Figure 6.5(a) shows the attacker's effort metrics. As the number of hosts increases, the APN and APE increases (as expected) which depicts more advantages to the attacker and thus reduces the attacker effort. While the ACE and the ACD tend towards zero showing that the attacker effort is easy



(a) Attack effort metrics



(b) Stateless metrics

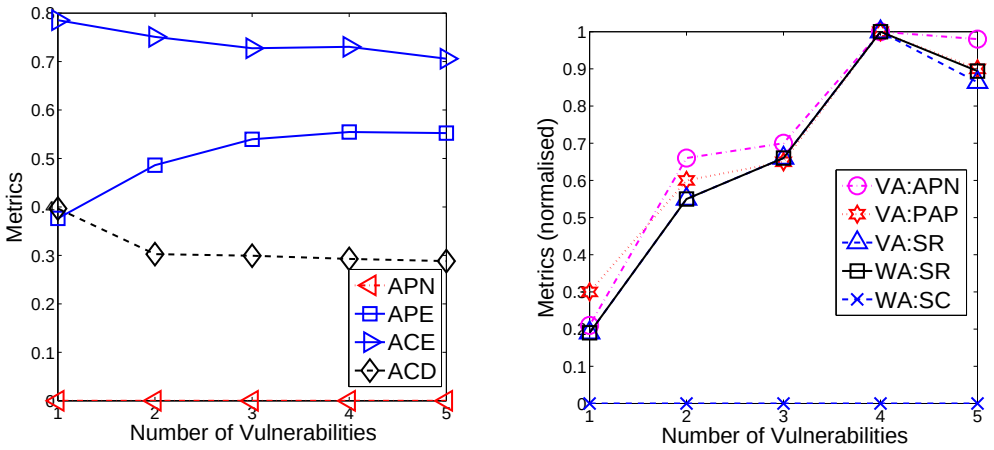
Figure 6.5: Varying the number of hosts

as the exploitability value is low and the time required to exploit a significant portion of the network is becoming more shorter, respectively. This is because as new vulnerable hosts are added to the network, the network security level keeps reducing for the states.

On the other hand, the stateless security metrics (i.e., VA:APN, VA:PAP, VA:SR, WA:SR) increases as the number of hosts increases. Thus, showing deterioration in the security level. However, the metric VA:SC was zero because the there was no defence deployed, and so the costs remain zero for all the states.

6.2.2 Varying the Number of Vulnerabilities

This section also demonstrates the attack effort and the stateless security metrics in terms of the number of hosts found per host in the states. Five network states are captured, and the number of vulnerabilities for hosts are varied. The results are shown in Figure 6.6.



(a) Attack effort metrics

(b) Stateless metrics

Figure 6.6: Varying the number of vulnerabilities

Figure 6.6 shows the attack effort and the stateless security metrics as the number of vulnerabilities is increased. It shows that increasing the number of vulnerabilities does not affect the APN. This is because there are no changes to the attack paths information of T-HARM. However, the APE, ACE and ACD are affected as expected. Similarly, the stateless security metrics increases as the number of vulnerabilities increases. However, the metric VA:SC was zero because the there was no defence deployed, and so the costs remain zero.

6.2.3 Changing Edges (Topology)

Network topology can be reconfigured or edges changed in order to provide security. In this section, the optimal reconfiguration approach in [78] was adopted and used as the network hardening. The approach in the paper provides a method to optimally change the hosts' edges. In order to demonstrate the effects of changing the edges on the metrics, simulations are performed with 20 hosts and fives dynamic states. The results are shown in Figure 6.7. Figure 6.7 shows the defence efforts metrics. The results showed

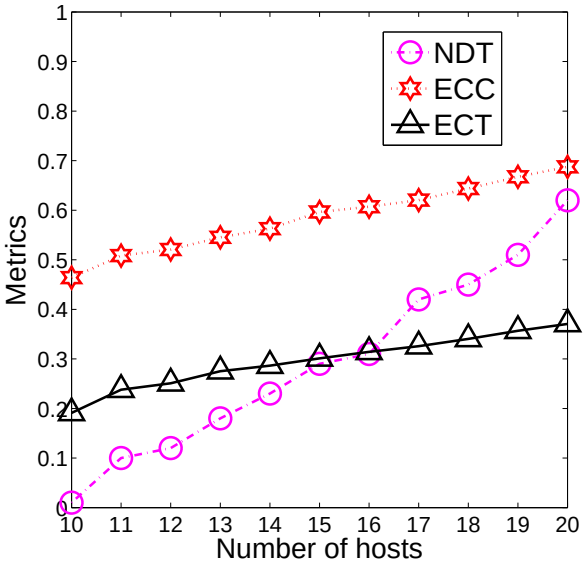


Figure 6.7: Defence Effort: Changing edges

that as the number of hosts increases, the defence effort increases as well. This is showing that there are more edges needed to be changed to satisfy the security goal and thus the increase in the metrics, as there are more hosts considered.

6.3 Summary

This chapter presented two group of security metrics to assess the security of dynamic networks quantitatively. Examples and simulations are used to demonstrate the usability of the proposed set of security metrics. The analysis

results show the in-depth security changes of dynamic metrics and thus provide an approach to quantify the security of networks that are changing in their configurations.

Chapter 7

Security Hardening Optimisation for Dynamic Networks

Hardening the dynamic networks is a very challenging task due to their complexity and dynamicity. Moreover, there may be multi-objectives to satisfy, while containing the solutions within the constraints (e.g., fixed budget, availability of countermeasures, performance degradation, non-patchable vulnerabilities, *etc*).

The first step to compute the optimum set of security hardening options is to evaluate the security posture of the network. One approach is to use GSM to systematically assess the security of the network, and then the security analysis results can be used to compute the optimal hardening solutions. However, most of the existing work relies on static network configuration as input to the security model, and thus they do not take into account the dynamic changes of the networks in their security assessments. Moreover, the security metrics that are used in the existing approaches [40] do not take into account the changing security behaviour of dynamic networks.

In this chapter, an approach for solving a multi-objective security hardening optimisation problem in a dynamic network is developed. To compute the

optimal set of security solutions, three objectives are taking into account, security, cost and downtime, which are represented via security metrics *security stateless risk*, *security cost* and *downtime of implementations*. The framework can easily be extended to incorporate more objectives, as the objectives are given as inputs to the problem. To improve the performance, a NSGA-II [110] is used to find the optimal hardening options given the multiple objectives. The major difference between this work and existing approaches is that existing approaches rely on static network configuration information (where there is no change in the network, security model and hardening solutions) for their evaluations. While in this work, dynamic network changes (or network configurations) and dynamic security metric are considered. The main contributions of this chapter are as follows:

- To combine heterogeneous security hardening options for dynamic networks and evaluate the set of selected options via the T-HARM;
- To solve the multi-objective security hardening optimisation problem using the NSGA-II with multiple constraints;
- To demonstrate the feasibility of the approach in a real-world scenario by taking into account the existence of both patchable and non-patchable vulnerabilities.

7.1 Proposed Approach

A small and large scale network is used to illustrate the proposed approach. The network model is explained in Section 7.1.1 and the attacker model in Section 3.2.2 (i.e., Chapter 3). In Section 7.1.2, the potential defence mechanisms are described. The evaluation metrics are presented in Section 7.1.3. In Section 7.1.4 and Section 7.1.5, the optimisation problem are formulated and the optimisation steps described, respectively.

7.1.1 Network Model

A dynamic network is assumed, where the components can change over time (e.g., workstations can join or disconnect, firewall rules change, *etc*). Since the network components change over time, a time-driven approach is used to capture the network states at every time t_i. Other approaches such as event-driven or user-driven can also be used.

The network consists of heterogeneous devices which have vulnerabilities that may or may not be patchable (i.e., infeasible for the network administrator to patch all vulnerabilities). It is assumed that the capabilities of the security administrator include the deployment of various defence mechanisms, e.g., enabling or disabling a firewall rule, applying security patches for known and patchable vulnerabilities, *etc*. However, all of them cannot be deployed due to the limited resources (e.g., cost and time). For the network hosts (e.g., servers), it is assumed that they do not have backup hosts when such deployment is performed. For example, when a hardening option is deployed (e.g., security patching) on a host h_1, the h_1 will be temporarily down for this period of the deployment.

7.1.2 The Defence Mechanism

Here, two types of vulnerability are considered; patchable and non-patchable. The patchable vulnerabilities are known vulnerabilities that the software vendors continue to release their security updates. The non-patchable vulnerabilities are known vulnerabilities but cannot be patched because the software vendors have not yet released the security patch, or the vendors no longer support the product. To this end, it is important to use several hardening options to restrict attacker's actions and to protect organisations' IT assets from cyber-attacks regardless whether the vulnerabilities are patchable or non-patchable. Therefore, four proactive defence mechanisms are considered, vulnerability patching, traffic redirection, host isolation and disabling of

application, and their combinations in order to illustrate this approach. Three main defence mechanisms are used for simplicity, but more defence mechanisms can be added without affecting the usage of the proposed approach (i.e., the number of defence mechanisms can vary for selecting the optimal set of security hardening options).

7.1.2.1 Vulnerability patching

In this section, the implementation for the vulnerability patching is explained. The Algorithm 8 shows the method used to patch the vulnerabilities. Here, V is used as input to the algorithm (line 3). These input are determine from the GA algorithm (which is explained in section 7.1.4). Line 4 and 5 identifies each vulnerability in the network states then patches it. In line 7, 8, and 9 the metrics are calculated and stored in line 10.

Algorithm 8 : Vulnerability patching

```
1: procedure VULNERABILITY_PATCH
2:     metrics → {}
3:     for all v ∈ V do
4:         for all s_{t_i} ∈ S do
5:             patch v
6:         end for
7:     end for
8:     calculate WA : SR
9:     calculate VA : SC
10:    calculate NDT
11:    metrics ← WA : SR, VA : SC, NDT
12: end procedure
```

7.1.2.2 Host isolation

As there are non-patchable vulnerabilities on the network hosts, some vulnerabilities may be left unattained which may cause severe damage and loss of network assets. Host isolation is used as a defence mechanism against such type of vulnerabilities. In the following, the implementation of this mechanism is explained.

Algorithm 9 presents the isolation of hosts that are having non-patchable vulnerability from the networks. Specifically, the algorithm takes set of hosts (H) (line 3) which is determined from the GA algorithm (explained in section 7.1.4). Then, check if there is a host that the vulnerability cannot be patched (line 4). Line 5 and 6 check if there is an adjacent host that is providing similar service as the host that is having the non-patchable vulnerability (e.g., web server 1 is non-patchable and the web server 2 is patchable). In line 8, all incoming connections to the critical hosts are migrated to the next hosts that is not critical (to ensure service availability), and all incoming and outgoing connections associated to the critical hosts are removed (line 8 and 9). In line 12, 13 and 14 the set of metrics are calculated and stored in line 15.

Algorithm 9 : Host isolation

```
1: procedure ISOLATE_HOSTS
2:     set metrics → {}
3:     for all h_j ∈ H do
4:         check for non patchable v
5:         if h_j have non patchable v then
6:             for h_j ∈ s_{t_i}(s_{t_i} ∈ S) do
7:                 if there exist similar h_adj^type then
8:                     migrate IN_con of h_j to the h_adj^type
9:                     disconnect OUT_con of h_j
10:                end if
11:            end for
12:        end if
13:    end for
14:    calculate WA : SR
15:    calculate VA : SC
16:    calculate NDT
17:    metrics ← WA : SR, VA : SC, NDT
18: end procedure
```

7.1.2.3 Traffic redirection

An attacker can use other critical hosts to reach a particular target in a network. In this section, traffic redirection [32] is used as a defence mechanism for such an attack scenario. The implementation of the traffic redirection is

explained as follows.

The algorithm for traffic redirection is described in Algorithm 10. Similarly, the algorithm takes a set of hosts (H) for all the period as input (line 3). In line 4, a host-based risk is calculated for the host and if the host is found to be critical (line 5) and it is not the only host providing a type of service (e.g., there is redundancy for database server), line 8 is implemented. In line 8, all the incoming connection to the hosts are disconnected and then redirected to another host which provide a similar service to the critical host (line 7 and 8). The algorithm performs this for all the critical hosts, and afterwards, the metrics in Section 7.1.3 are calculated by line 11, 12 and 13.

Algorithm 10 : Traffic redirection

```
1: procedure TRAFFIC_REDIRECTION
2:     metrics → {}
3:     for all h_j ∈ H do
4:         calculate r_{h_j}
5:         if h_j is critical then
6:             for h_j ∈ s_{t_i} do
7:                 if there exist similar h_adj^type and it is not critical then
8:                     migrate IN_con of h_j to the h_adj^type
9:                 end if
10:            end for
11:        end if
12:    end for
13:    calculate WA : SR
14:    calculate VA : SC
15:    calculate NDT
16:    metrics ← WA : SR, VA : SC, NDT
17: end procedure
```

A similar algorithm to Algorithm 8 is used for the mechanism; disabling the vulnerable application. However, instead of patching the vulnerability, the application that is having the non-patchable vulnerability is disabled.

7.1.3 Security Metrics

To safeguard against cyber-attacks, a security administrator can implement different kinds of defence mechanisms. For instance, in order to defend against

the attacker exploiting a non-patchable vulnerability, the security administrator may choose to isolate the hosts involved, disable the vulnerable application, redirect traffics that are associated with the hosts, *etc.* For each of these choices, the level of coverage, downtime and costs may be different. Moreover, one or more of the options may be able to defend against multiple attack scenarios. So, the security administrator is typically faced with the challenges of evaluating and selecting the best options when there are multiple options to select from. Security metrics [79] can be used to evaluate the effectiveness of different security hardening options. However, they lack the capabilities to understand the overall security posture of dynamic networks. In this section, security metrics that take into account changes in network states (i.e., stateless security risk, security cost and downtime of implementations) are used to evaluate the effectiveness of the security hardening options for the dynamic networks. The security metrics are described in Chapter 6.

7.1.4 Problem Formulation

In order to improve the security of networks, a set of security hardening options can be selected from a pool of security solutions to be deployed. However, computing the optimal security hardening set can be time-consuming, and it becomes infeasible for large-sized networks as the solution search space suffers from a state space explosion. Existing studies show that the solution search space grows exponentially for an enumerated search [137] because there are always 2^n number of available choices, where there are a total of 'n' number of options. With this number of choices, the enumerated search is not efficient in finding the optimal solution [40].

Since the enumerated search is not suitable for finding the optimal solution, the GA with three security objectives is considered. These security objectives are: reducing the overall system risk, reducing the security hardening implementation downtime and reducing the security cost of a dynamic network given a fixed budget as a constraint. For the example dynamic networks, several

security hardening options are possible based on the vulnerability patching, traffic redirection, disabling of applications and host isolations. The options listed in Table 7.5 (which is computed from the T-HARM) are used as the possible hardening options for the network. Applying any of these hardening options may reduce the system risk, but at the same time will incur some defence cost and may increase the downtime experienced as well. The focus of this chapter is to find the optimal solutions that maximise the security while minimising the defence cost and downtime given a fixed security budget as the constraint. This will be achieved by optimally selecting the set of available security hardening options under considerations. In the following, the security hardening options are explained, and the optimisation problem is defined.

- Let P^* denote the set of vulnerabilities for the patch.
- Let Q^* denote the set of hosts for possible isolation.
- Let D^* be the set of traffics to drop.
- Let O^* be the set of applications to disable.
- $X^* = P^* \cup Q^* \cup D^* \cup O^*$ (i.e., is the set of all the hardening options).

Then the function $f : X^* \rightarrow \{0, 1\}$ is used to describe the binary value corresponding to each security hardening solution $x_i \in X^*$ in the network. The binary value indicates that a hardening option is deployed (1) or not deployed (0). The security hardening vector (hv) for X^* is defined as:

- $hv_{X^*} = (f(x_1), f(x_2), ..., f(x_{|X^*|}))$

Then, the optimisation problem is formulated as shown in Definition 14.

Definition 14. The Optimisation Problem: Given a T-HARM and hv_{X^*}, find the vector hv_{X^*} that optimises the objective functions:

Minimise $(WA : SR(GSM, hv_{X^*}), VA : SC(GSM, hv_{X^*}), (NDT(GSM, hv_{X^*}))$

subject to: $VA : SC \leq SB, NDT \leq DTC$

where $WA : SR(GSM, hv_{X^*})$, $VA : SC(GSM, hv_{X^*})$ and $NDT(GSM, hv_{X^*})$ are the set of values from the objective functions of stateless risk (i.e., weighted approach), security cost and downtime of implementations, respectively. SB and DTC are the constraints imposed on security costs (i.e., a given security budget) and the downtime of implementations, respectively.

Normally, there is no single global solution for a multi-objective problem due to the conflicting nature of objective functions. As a result, the best trade-off solutions called Pareto optimal solutions [110] are used for decision making. The concept of the Pareto optimal solutions (Pareto frontier) is used to find the set of optimal solutions for the defence options to deploy. In the following, the Pareto optimal solutions for the optimisation problem is defined (which is similar to the approach used in [110]). The constraints given in definition 14 determine the solution feasible region (FR).

Definition 15. Pareto optimal solutions*: A solution,* $(WA : SR(GSM, hv_{X^*}), VA : SC(GSM, hv_{X^*}), (NDT(GSM, hv_{X^*})) \in FR$*, is Pareto optimal iff there does not exist another solution,* $(WA : SR_\beta(GSM, hv_{X^*_\beta}), VA : SC_\beta(GSM, hv_{X^*_\beta}), NDT_\beta(GSM, hv_{X^*_\beta}))$*, such that*

- $WA : SR_\beta(GSM, hv_{X^*_\beta}) \leq WA : SR(GSM, hv_{X^*})$ *and* $VA : SC_\beta(GSM, hv_{X^*_\beta}) \leq VA : SC(GSM, hv_{X^*})$ *and* $NDT_\beta(GSM, hv_{X^*_\beta}) \leq NDT(GSM, hv_{X^*})$.
- $WA : SR_\beta(GSM, hv_{X^*_\beta}) < WA : SR(GSM, hv_{X^*})$ *or* $VA : SC_\beta(GSM, hv_{X^*_\beta}) < VA : SC(GSM, hv_{X^*})$ *or* $NDT_\beta(GSM, hv_{X^*_\beta}) < NDT(GSM, hv_{X^*})$.

7.1.5 The Optimisation Approach

The optimisation steps are discussed in this section. The NSGA-II [110] is used as the optimisation algorithm and the set of hardening options as the input to the optimisation algorithm. The size of the hardening options is based

on the hardening options available. The T-HARM is used to determine all the potential hardening options which can be deployed. The NSGA-II starts by generating the initial population from the set of hardening options, where the hardening options are encoded as binary values (i.e., chromosome), in which 1 indicates that a hardening option is deployed and 0 indicates that it is not deployed. A generator is used to generate a possible deployment strategy (i.e., a generation) using the concept of selection, crossover and mutation in the gene (for child population or next generation) [39]. Each generation is evaluated using the metrics outlined in Section 7.1.3 using the T-HARM, which the results are passed to the optimisation algorithm. The optimisation algorithm computes the optimal set of security hardening options to deploy based on the fitness of the generations. A generation is a one-time iteration of the algorithm (in the NSGA-II, a generation index is used to keep track of the number of iterations). Therefore, the security administrator can define the maximum number of generations that is required before the termination.

7.2 Simulations and Results

In this section, simulations are performed using two network models; (i) small-scale network and (ii) large-scale network with up to 300 hosts, in order to demonstrate the proposed approach. First, the sensitivity of the NSGA-II to the input parameters are investigated. Then, the effect of different network properties (e.g., multiple network states and varying network density) on the optimum solutions is investigated (in particular, the varying of the number of network states is considered). In Section 7.2.1, the simulation network, the input for the metrics and the parameters used in the optimisation algorithm are described. The result for the sensitivity analysis is presented in Section 7.2.2, and the results for the effect of varying the number of states on the optimum solutions shown in Section 7.2.4.

7.2.1 Simulation Network

An enterprise network which is divided into two subnets; DMZ and internal network is used. The network topology is shown in Figure 7.1. The network consists of five hosts and firewalls which protect access to the hosts in the DMZ and internal network subnets. The OSes and applications in Table 7.2 are assumed to be running on the network hosts. Known patchable and non-patchable vulnerabilities are collected from the NVD and [60] with respect to the applications and operating system for each host in the network. The vulnerabilities are shown in Table 7.1 and their distribution across the network states in Table 7.2. Some of the vulnerabilities are patchable while other are non-patchable. The non-patchable vulnerabilities are the vulnerabilities that are without a patch at the time of this research. For example, the vulnerability CVE-2012-1675 is an Oracle database 11g vulnerability that is not fixed by a security patch update for this version of the database but a configuration workaround is suggested to prevent attacker from exploiting this vulnerability [1] (a detailed statistics of the non-patchable vulnerabilities and faulty security patches can be found in [12]). Table 7.1 shows the vulnerabilities of each host. Also, the non-patchable vulnerabilities are marked with the symbol (*). However, it is worth noting that the security patches for these vulnerabilities may be available at a later date as vendors usually take time to provide some security patches for their products [12]. In Table 7.5, the hardening options that apply to each of the states are shown. The attacker model described in Section 3.2.2 is used.

Security metrics and economic values: In order to evaluate the different attack scenarios and defence mechanisms, values for vulnerabilities and the hardening options are used.

In specific, the impact metric for each vulnerability from the NVD is used as aim_v for the vulnerability and the pr_v is assigned based on the CVSS BS version 2.0 [115].

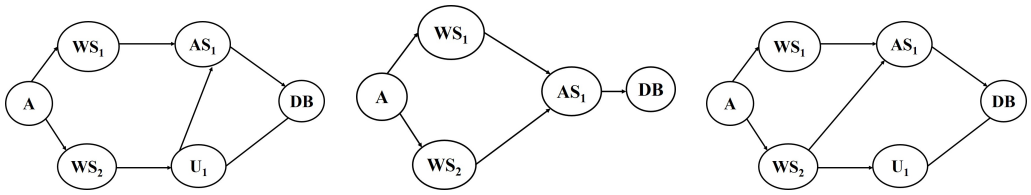


Figure 7.1: Topology configurations for the small-scale network, (a) ns_0 topology: the initial network topology, (b) ns_1 topology: host U_1 is disconnected from th network and WS_1 is connected to AS_1, and (c) ns_2 topology: host U_1 is added back to the network.

Table 7.1: List of vulnerabilities for all the states and their metrics

v ID	CVE ID	aim_v	pr_v
v_1	CVE-2011-4362*	2.90	0.50
v_2	CVE-2018-5750	2.90	0.43
v_3	CVE-2016-2834	10.00	0.93
v_4	CVE-2017-15395	2.90	0.43
v_5	CVE-2018-1083	10.00	0.72
v_6	CVE-2016-7256	10.00	0.93
v_7	CVE-2018-4878*	6.40	0.75
v_8	CVE-2012-1675*	6.40	0.75
v_9	CVE-2015-4026	6.40	0.75
v_{10}	CVE-2016-9644	10.00	0.93
v_{11}	CVE-2018-2680	5.00	0.51
v_{12}	CVE-2018-0825	10.00	0.76

Table 7.2: changes in the network states with respect to the addition of vulnerabilities

host name	OS/apps	ns_1	ns_2	ns_3
WS_1	lighttpd 1.4	v_1		
	Redhat Linux	v_2	v_9	
WS_2	Redhat Linux	v_2		
	Firefox 31	v_3	v_{10}	
AS_1	Chrome 60	v_4		
	Redhat Linux	v_5		
U_1	Windows 10	v_6		
	flash player	v_7		
DB	Windows 10	v_6		v_{12}
	Oracle database 11g	v_8	v_{11}	

The Frost & Sullivan total cost of ownership [57] and existing literature [32, 148] are used to establish a more realistic cost estimate for the hardening options (for example, the estimates provided in [148] is a combination of practical experience and direct research for both the downtime of implementing the solutions and costs). The estimated costs are shown in Table 7.3. In real scenarios, a security administrator can assign these values based on experience on the cumulative cost of time of deployment, reconfiguration, downtime, maintenance, *etc.*

Table 7.3: Hardening options costs

	Hardening options			
Costs($)	Patch	Isolate host	Drop traffic	Disable application
costs of purchase				
cost of installation	80			
cost of roll-outs/upgrade	20			
cost of insurance				
costs of planning	150	300	200	250
cost of training	100	100	100	100
operating cost	450	700	600	650

In Table 7.4, the calculations for the stateless security risk is illustrated for the topology in Figure 7.1. The security costs are calculated by adding all the expenses that are associated with every defence options deployed for the entire period. At this point, the calculations of the security cost are not shown because there is no defence option deploy yet, and so the security cost is zero. However, if the following security option is assumed to be deployed; a vulnerability is patched on a user workstation (U_1) in ns_0, a web server (WS_2) is isolated in state ns_1, and vulnerability is patched on the DB server in the state ns_2. Then, the calculation of the security cost of these options can be as: $\$820 + \$930 + \$850 = \$2600$.

Computation of the hardening options: Given the security hardening options, the population of different hardening options to deploy for the

Table 7.4: Security Stateless risk

State	attack paths	r_{ap}	$WA:SR$
ns_0	$A->WS_1->AS_1->DB$	20.30	29.06
	$A->WS_2->U_1->AS_1->DB$	37.66	
	$A->WS_2->U_1->DB$	29.25	
ns_1	$A->WS_1->AS_1->DB$	20.83	16.04
	$A->WS_2->AS_1->DB$	27.83	
ns_2	$A->WS_1->AS_1->DB$	20.30	25.79
	$A->WS_2->U_1->DB$	29.25	
	$A->WS_2->AS_1->DB$	27.83	
		SR_T	70.89

dynamic network can be generated and evaluated using the metrics described in Section 7.1.3 via NSGA-II. The following parameters are used for the NSGA-II algorithm: population size = 100, maximum number of generations = 150, crossover probability = 1.0, mutation probability = 0.1, SB = \$3500 and DTC=60 min.

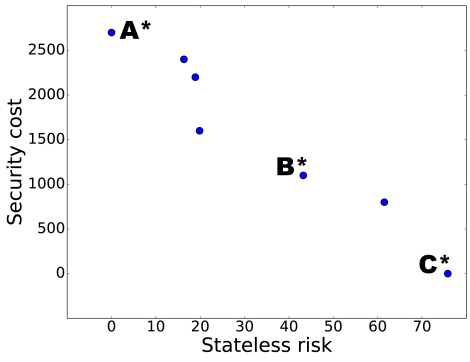
To begin, the T-HARM for the simulation network and the population of different hardening options for the P^*, Q^*, $D^*$and O^* are generated. The hardening options are shown in Table 7.5. The vulnerability on the Oracle database is not considered to allow the analysis to be performed on paths to the target. The GA is used to compute the deployment vectors, and one example is shown in equation (7.1). The values for the objective functions are SR_T=14.32, SC_T=3000, NDT=46.00.

$$\begin{aligned} hv_{1X^*} =& (f(cm_1), f(cm_2), f(cm_3), f(cm_4), f(cm_5), f(cm_6), f(cm_7), f(cm_8), \\ & f(cm_9), f(cm_{10}), f(cm_{11}), f(cm_{12}), f(cm_{13}), f(cm_{14}), f(cm_{15})) \\ =& (0,1,0,0,0,0,0,0,0,0,1,1,1,0,0,1) \end{aligned} \tag{7.1}$$

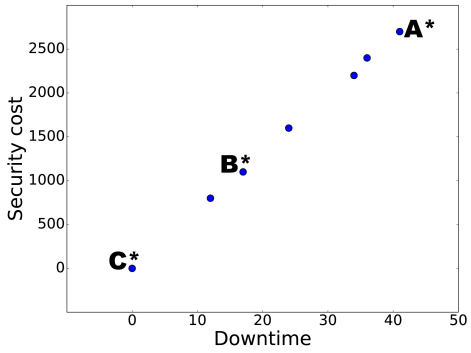
Figure 7.2 shows the final populations of the fitness values that satisfy the constraints and form the Pareto optimal points. The graph clearly shows the

Table 7.5: The possible hardening options for each of the states

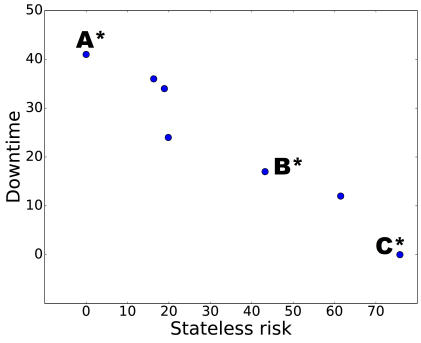
ns_0		ns_1		ns_2	
Hardening option	ID	Hardening option	ID	Hardening option	ID
patch v_2	cm_1	patch v_2	cm_1	patch v_2	cm_1
patch v_3	cm_2	patch v_3	cm_2	patch v_3	cm_2
patch v_4	cm_3	patch v_4	cm_3	patch v_4	cm_3
patch v_5	cm_4	patch v_5	cm_4	patch v_5	cm_4
patch v_6	cm_5	patch v_6	cm_5	patch v_6	cm_5
isolate WS_1	cm_6	isolate WS_1	cm_6	isolate WS_1	cm_6
isolate U_1	cm_7	disconnect $A- > WS_1$	cm_8	isolate U_1	cm_7
disconnect $A- > WS_1$	cm_8	disable lighttpd 1.4	cm_{10}	disconnect $A- > WS_1$	cm_8
disconnect $WS_2- > U_1$	cm_9	patch v_9	cm_{12}	disconnect $WS_2- > U_1$	cm_9
disable lighttpd 1.4	cm_{10}	patch v_{10}	cm_{13}	disable lighttpd 1.4	cm_{10}
disable flash player	cm_{11}	patch v_{11}	cm_{14}	disable flash player	cm_{11}
				patch v_9	cm_{12}
				patch v_{10}	cm_{13}
				patch v_{11}	cm_{14}
				patch v_{12}	cm_{15}



(a)



(b)



(c)

Figure 7.2: Final solutions

trade-off between the three objective functions. For example, there are three labelled points on the graphs (i.e., Figure 7.2(a), Figure 7.2(b) and Figure 7.2(c)), where point A^* shows the maximum SC (in Figure 7.2(a) and Figure 7.2(b)) and the maximum NDT (in Figure 7.2(b) and Figure 7.2(c) but have the lowest at SR (in Figure 7.2(a) and Figure 7.2(c). The results show that SC (security cost) and NDT (downtime of implementation) increases when SR (risk) decrease. Here, one of the set of solutions is {patch v_{10}, patch v_4, isolate U_1, disconnect $WS_2 -> U1$, disable adobe flash player}.

The B^* shows the intermediate solution among the final solutions (in terms of fitness values). The solutions here is to {isolate WS_1, disable lighttpd 1.4}. While the point C^* shows the other extreme point where the SC and NDT are very low but the overall SR is high. Here, there is 'null' candidate to implement.

7.2.2 Sensitivity Analysis

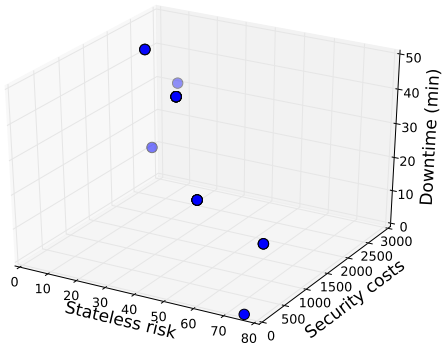
The simulation network is used to investigate the sensitivity of the NGSA-II parameters. The algorithm parameters are set as described above. However, in order to investigate the sensitivity of a particular parameter, only that parameter is varied for the time. For example, in order to investigate the sensitivity of the crossover probability, the population size, the number of generations, mutations and budget are not varied while the crossover probability is varied. The solutions obtained for each of the parameters are compared against the real optimal solutions (i.e., the set of solutions that do not change when parameters change). To begin, the crossover probability of $0.3, 0.5, 0.7$ and 0.9 is used at different times. The results show that changing the crossover probability only shows a negligible change in the set of solutions obtained for them. However, Jun-chun *et al.* [90] have explained that the crossover probability is more suitable for the large-scale network. So, the various crossover probabilities may be more sensitive when a larger network is considered. On the other hand, increasing the mutation probability shows

significant change for mutation probability 0.5, 0.7 and 0.9 with low accuracy percentage compared to the real solutions (An example solution obtained for these values are shown in Figure 7.3(b), Figure 7.3(c) and Figure 7.3(d), respectively). For this case, some points are marked within the rectangle shape to show a few points that match with the real optimum solutions. However, it is worth noting that the set of solutions obtained for 0.5, 0.7 and 0.9 (i.e., high mutation probability) keep changing each time the algorithm is run and so, may change when the algorithm is run again. Conversely, in Figure 7.3(a) there is no change observed for the mutation probability values of 0.3 as the results for the problem are always converging to optimal.
Similarly, the population size of 50, 100, 150, 200, 250 and 300 is used respectively. The final solutions obtained remain the same for all the population size (with a negligible difference in the accuracy of the solution for the population size of 50). Furthermore, the same results are obtained for the case of increasing the number of generations from 50 to 300.

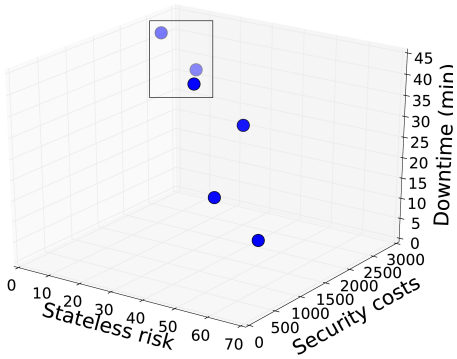
7.2.3 Processing Time

Further analysis is performed to investigate the processing time of the GA when the following parameters are increased; (1) the population size and (2) the maximum number of generations. The accuracy of the results for the (1) and (2) compared to a best-case solution are then presented. Here, the accuracy is defined as the percentage of the number of Pareto optimum points for each parameter that is varied compared to the best case solutions. The best case solutions are the set of Pareto optimum points that do not change when the population size or the number of generations is increased further.

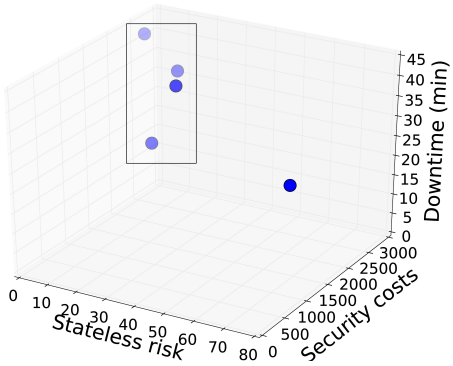
The network model in Section 7.1.1 is used to construct a generic network that randomly connects hosts in each state (with each host connected to at least three other hosts). Three network states with each state having 100 hosts are captured (i.e., 300 hosts are analysed for the entire time window). Similarly, the attacker model in Section 3.2.2 is used to construct the corresponding T-



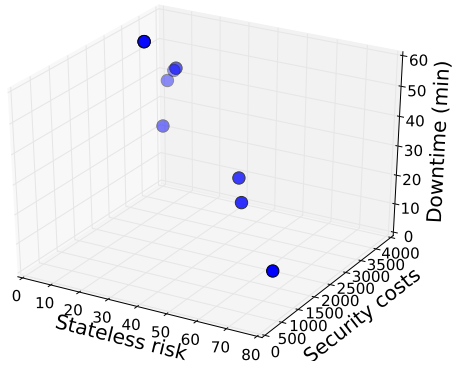
(a) mutation probability = 0.3 (real solution - the set of solutions are not changing)



(b) mutation probability = 0.5



(c) mutation probability = 0.7



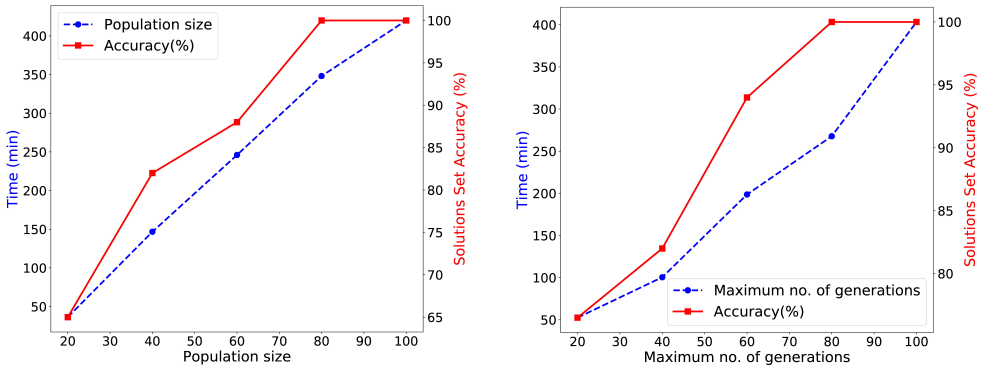
(d) mutation probability = 0.9

Figure 7.3: Changing the mutation probability

HARM for the network states. The same T-HARM is used as input to the GA for each of the parameters (i.e., each population size and each of the number of generations) being investigated. By using this approach, the time it takes for each parameter to finish the search for the solutions is calculated. Moreover, the accuracy of the results obtained compared to the best case solutions can be calculated as well.

A system with an Intel(R) Core(TM) 2.50GHz CPU and 8 GB RAM in the python 3.6.2 environment under Windows 10 Operating system is used to perform the simulations. In the simulation, the following parameters are used as the based case (i.e., for the best case solutions): population size = 120, maximum number of generations = 120, crossover probability = 1.0, mutation probability = 0.1 and the input (vulnerability and metric values) described in

Section 7.2.1. Then the population size and the number of generations are varied as required. The results are shown in Figure 7.4(a) and Figure 7.4(b), and similarly, the percentage accuracy of the solutions with respect to the population size and the number of generations are shown on the same graph.



(a) Increasing the population size (b) Increasing the number of generations

Figure 7.4: Runtime of the GA and the percentage accuracy with respect to increasing population size and the number of generations

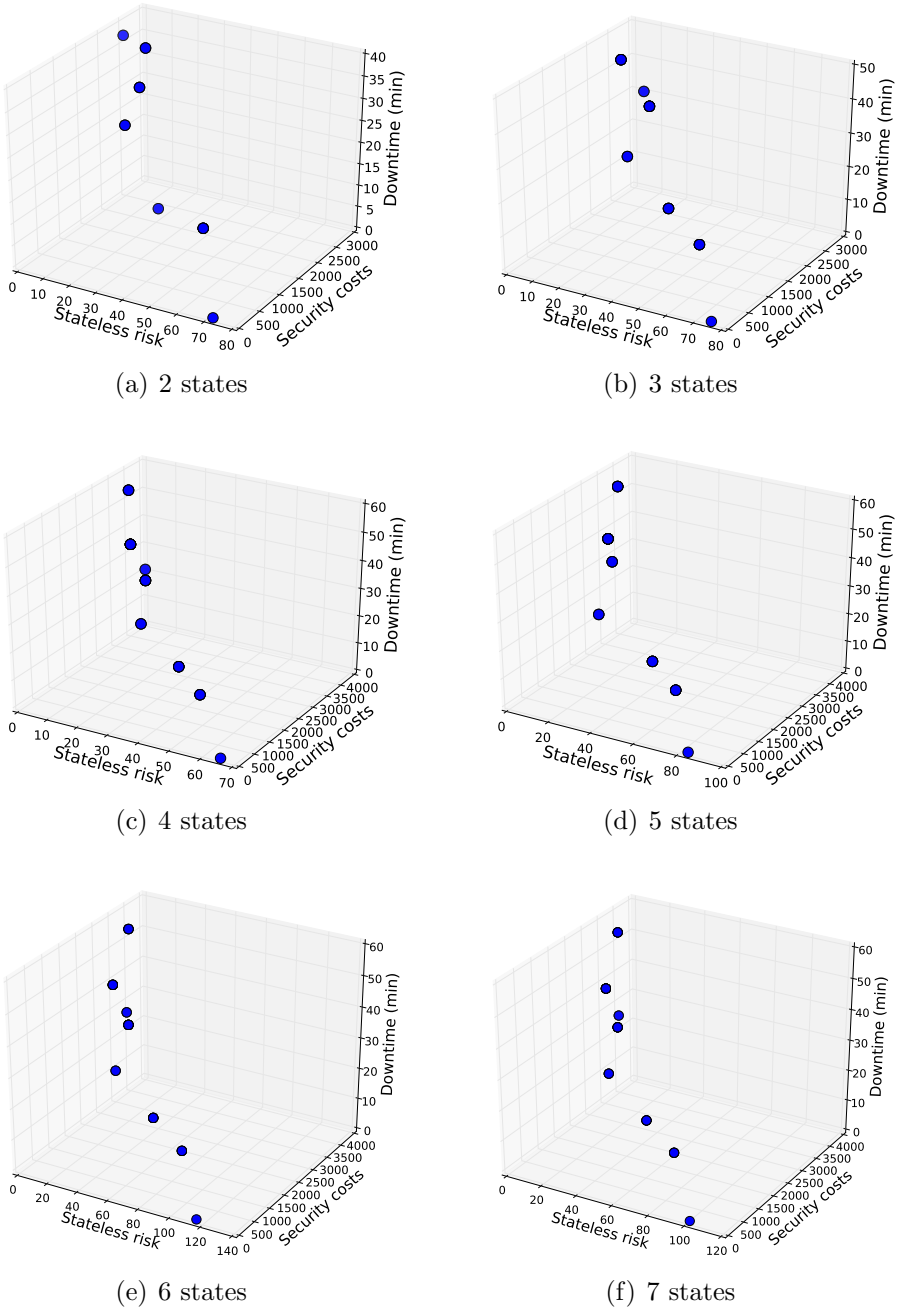
Figure 7.4(a) shows that the time taken to search the Pareto optimal solutions increases linearly as the population size increases. Also, the result (Figure 7.4(a)) also shows that low population size may not be sufficient to find the optimal solutions as the percentage of accurate solutions appears to be low when the population size is low and then convergences to 100% when the population size is 80 and 100. A similar trend is observed for the result in Figure 7.4(b): as the number of generations increases, the time to finish the search for the solutions increases almost linearly, likewise the percentage accuracy of the solutions tends to converge towards 100%.

7.2.4 Effect of Varying Network Properties: multiple states

Varying network states: As modern networks are dynamic with configuration changes, hundreds of states can be captured and analysed. In

this section, the effect of varying the number of states on the optimal solutions and the network security posture is investigated. Specifically, the number of network states is varied incrementally, and then how the optimal solutions are affected are observed. A network which is similar to Figure 7.2.1 is used but with randomly generated dynamic network properties (e.g., addition of hosts, removal of hosts, removal of edges, *etc*). Several states are captured for this simulation (as required). Based on the sensitivity analysis performed in section 7.2.2, the parameter are used as: population size = 120, maximum number of generations = 150, crossover probability = 1.0, mutation probability = 0.1, SB = \$3500 and DTC=60 min in the optimisation algorithm. In Figure 7.5, the results for the different number of states are shown.

The results in Figure 7.5 show that varying the number of network states affect the optimal set of solutions. Also, it is observed that a few of the Pareto optimal points for a pair of consecutive states show similar points. However, manual inspection of the set of solutions for deployment for those points showed that the set of solutions varied among the states. Therefore, a conclusion can be made that the optimal set of solutions changes as the network configuration changes over time for dynamic networks.



(a) 2 states (b) 3 states

(c) 4 states (d) 5 states

(e) 6 states (f) 7 states

Figure 7.5: Changing the number of network states

7.3 Summary

This chapter presented an approach for a multi-objective security hardening optimisation for dynamic networks using a GA.

The evaluation results showed that the proposed approach could be used

to aid security administrators in selecting and deploying an optimal set of security hardening options for dynamic networks. The results also showed that multiple optimal sets satisfy the multi-objectives while satisfying the constraints. Further, it showed that the optimal set changes as the network configuration change over time for dynamic networks. Therefore, the proposed approach can support security administrators with an overview of how the optimal solution changes over time, as well as compute the optimal solution taking into account changes made by dynamic networks. Moreover, the security administrator can understand the pros and cons of each option before deploying them.

Chapter 8

Discussions and Future Work

Changes in dynamic networks affect the security posture of the network. Thus, understanding the security posture of dynamic networks is difficult, especially when a new set of attack vectors are introduced as a result of the changes. Traditional GSMs and metrics, such as AGs and probability of attack success, are used to evaluate the security posture of the network. However, these approaches assumed the network of static nature. As such, changes that happen as a result of hosts joining, host disconnecting, new vulnerabilities discovered, *etc.* which changes the security posture are not captured using the traditional GSMs and the existing security metrics. Hence, security analysis based on them are not comprehensive to capture the changes that are happening in the networks. This is important in order to provide an efficient defence approach for the security of dynamic networks.

The research presented in this thesis is intended to provide the computer networking and security communities with methods to assess and harden the security of modern networks that are dynamic with configurations changes (e.g., SDN and Cloud networks). T-HARM and TI-HARM are developed to assess the security of networks, and also show different aspects of the security of the dynamic networks (specifically, the T-HARM provides the temporal security states of dynamic networks while the TI-HARM provide the time-independent view of a dynamic network). Besides, metrics to assess the

security of dynamic networks are developed to show the security changes in the network quantitatively. Lastly, an approach to optimally select security hardening solutions for dynamic networks from a pool of options (under multiple constraints) was proposed. However, several assumptions are made in this thesis which requires further research in order to enhance the proposed approaches. This chapter discusses the limitations of the approaches and points out further research directions.

8.1 Addressing the Research Questions

As outline in Chapter 1, this thesis uses security modelling approach to answer the following questions:

- Q1: what are the approaches that be used to systematically capture and model the attack scenarios in dynamic networks?
- Q2: what are the characteristics of dynamic networks, and how can we quantitatively measure the security of the dynamic networks?
- Q3: what approach can be used to select the optimal security hardening solutions for dynamic networks taking into account multiple objectives (e.g., maximise security and minimise cost)?

To address the research question Q1, a temporal GSM (named T-HARM) and a time-independent GSM (named TI-HARM) are developed in Chapter 3 and Chapter 5, respectively. In particular, the T-HARM captures and analyse the potential attack scenarios of the temporal networks at every time t (i.e., on multiple GSM). While the TI-HARM captures and aggregates all the observed attack scenarios onto one GSM. The formalism and security assessment for the proposed GSMs are given and demonstrated with examples and experimental analysis via simulations. Moreover, a systematic classification of network changes and their formalisms with respect to security changes are also given in Chapter 3.

To address the research question Q2, a comprehensive evaluation of the existing security metrics is performed in Chapter 4, in order to identify which one is suitable or not suitable for the analysis of dynamic networks. Also, the functionality of the T-HARM and TI-HARM are utilised to develop a new set of metrics (in Chapter 6) to quantitatively assess the security of dynamic networks. The usability of the proposed metrics is shown through simulations and examples.

To address the research question Q3, a security optimisation approach with heterogeneous hardening options (i.e., hosts isolation, vulnerability patching, traffic redirection, *etc*) for dynamic networks is developed (in Chapter 7). The optimal deployment solution is computed via the T-HARM while taking into account the limited security budget and time of implementations as constraints. The feasibility of the proposed approach is demonstrated for a real-world scenario by considering the existence of both patchable and non-patchable vulnerabilities.

The proposed approaches can be applied to dynamic enterprise networks and emerging networking technologies, such as SDN [98] and cloud computing [113]. Moreover, the T-HARM can be used to model and assess the effectiveness of dynamic security solutions (e.g., MTD with the dynamic metrics) [71].

Besides, the proposed optimisation approach can be employed for decision making in the presence of many sets of possible hardening solution to deploy when there are constraints such as costs to keep up with.

8.2 Limitations and Future Work

This thesis has some limitations that need to be addressed in the future work in order to extend the research scope. In the following, the limitations and the future work are explained.

8.2.1 Different network characteristics

Although a typical enterprise network configurations are considered for the experiments but generally, a network can be complex with different types of network topologies or a combination of different topologies (e.g., a combination of star and ring) [10, 161]. This thesis did not consider different types of network topologies and network density and how the various characteristics affect security metrics in a dynamic network. Thus, it is important to consider how the different topologies and network density can affect the security of dynamic networks. Moreover, the flexibility and diversity experienced in a heterogeneous network environment [107] changes the security posture of the network continuously, and hence this makes the network more vulnerable to several types of cyber-attack which were not covered in this thesis.

Furthermore, this thesis did not consider other network technologies such as Cloud and IoT [62] in the categorisation of the network changes. Hence, there is a need to perform a more detailed categorisation of modern network changes (for Cloud, IoT, *etc.*) with their respective correlation to the changes in GSMs in order to perform more analysis.

8.2.2 Dynamic Models

A temporal GSM named T-HARM was developed. The T-HARM takes snapshots of the dynamic network at every time point and then dynamically analysed the security. Despite this, modern networks (e.g., Cloud and SDN) usually allow their components to change even more frequently (than enterprise networks) [84] and in consequence, a critical network state (for effective security analysis) can be skipped. Therefore, there is a need of an on-line T-HARM which tracks network changes in real time and then automatically adjust to changes in the security posture of the network. This approach can be done periodically or when a certain percentage of changes are detected in the network.

8.2.3 Attacker Models

In the attacker model, a single target host and a single attacker is considered. Also, an internal attacker who wants to compromise hosts in the internal network is not considered as well. However, multiple attackers trying to compromise different targets can be modelled [134]. So, more research is needed to consider attacker models with multiple attackers, internal attackers and multiple targets, as well as considering various attack scenarios (e.g., Distributed Denial of Service attack [116]).

Besides, our attacker model assumes the same level of behaviour and capability for the attacker. However, real-world attackers can have different behaviours and capabilities which our GSM did not take into account. As a result, this limits our proposed approach to model different kinds of attacks along with the changes in the behaviour of the attacker. To extend our proposed approach, a separate component (or module) which explicitly model the changes in the attacker's behaviour or the attacker's capabilities can be incorporated [83, 133]. Thus, this will allow the security administrator to perform several types of security analysis (e.g., based on the behaviour or capabilities of the attacker).

8.2.4 Security metrics

The varying effects of eleven (11) security metrics is investigated when various changes are observed in the network. However, there are many other quantitative security metrics for assessing the security of networks (e.g., weakest adversary metrics [129], network compromise percentage [104], attack resistant metric [159], K-zero day safety [158], attack surface metric [109], *etc*). So, more comprehensive evaluation of those security metrics for assessing the security of dynamic networks is required. Besides, Bopche and Mehtre [19] proposed graph distance metrics for dynamic security analysis. In particular, they used maximum common sub-graph and graph edit distance metric to

quantify the distance between a pair of successive AGs generated for a dynamic network. However, these metrics are used with AGs, and it is still unknown how they will change when they are used for dynamic GSMs.

8.2.5 Optimal Defence Models

- **Defence mechanism**: In this thesis, a heterogeneous hardening option is considered as the proactive defence mechanism. This thesis showed that these hardening options can be integrated into the T-HARM. However, many proactive defence mechanisms were not considered. So, more defence options should be integrated into the model in the future work. It is believed that incorporating more defence mechanisms may further provide better optimum solutions.

- **Patchable and non-patchable vulnerabilities**: In this work, the feasibility of this approach for real-world network scenarios which are having both patchable and non-patchable vulnerabilities is demonstrated. However, unknown vulnerabilities are not considered. Therefore there is a need to consider the unknown vulnerabilities in the future work. Besides, the impact of the existence of the unknown vulnerabilities in the security of the networks and selection of optimal hardening solutions needs to be investigated.

- **Dynamic security metrics**: To the best of our knowledge, this is the first work to use dynamic security metrics (as fitness functions) to evaluate the effectiveness of security hardening options in the multi-objective optimisation problem (for the security of dynamic networks). Security stateless risk, downtime of implementation and security cost are used, and then the trade-off solutions between them is computed. However, to fully find the optimal solutions for real networks where best users' experiences are minimally affected, then there is a need to consider both security, cost, performance and availability. In the future, the

Symbolic Hierarchical Automated Reliability and Performance Evaluator (SHARPE) [138] can be used to calculate the performance and availability metrics which will be incorporated as additional fitness functions to the optimisation algorithm.

- **Optimisation algorithms**: The results showed that the NSGA-II provides a good spread of solutions over the Pareto optimal set for the three objective functions that were considered. However, there are computational complexity which this study did not take into account. Therefore, in the future work, there is a need to find an approach to reduce the time complexity that is caused by the paths calculations in the evaluations of the fitness function (security stateless risk). The calculation (attack path calculations) of the metric took so much time which resulted in a long time to finish the search for optimal solutions when the population size and number of generations is increased. Besides, other optimisation algorithms need to be evaluated for the most efficient algorithm to use compared to the GA in terms of speed.

8.2.6 Validation

Although practical data from a university network is collected, they were not used in this thesis because of constraints (e.g., time and university security policies). However, real-world network settings data (e.g., security vulnerabilities by NVD [119]) are used to model changes in vulnerabilities in the simulations. To overcome this limitation, a test-bed network can be set-up and then various data can be collected (as required) to validate this approaches in more simulations.

Chapter 9

Conclusions

Dynamic networks can be characterised by many factors such as changes (e.g., vulnerability change, the update of applications and services, topology changes). There is a lack of methods and techniques to capture different security posture when the network changes. Consequently, it is difficult to assess the security of the dynamic networks which changes over time. This thesis identified three major problems with the existing security models, their assessment methods and selection of security hardening options for dynamic networks. First, the assumptions of existing security models that networks are static in nature makes it insufficient to capture and analyse the security of dynamic networks. Secondly, the security metrics have been designed from the perspective of static networks, and so, it is difficult to estimate how existing security metrics will change as the network changes over time, since current metrics have only been used to assess the static networks. Thirdly, changes in the configurations of network states affect the optimal hardening solutions; therefore the optimal solutions calculated by the existing approach may not be optimum for networks that change over time.

So, in this thesis, four distinct contributions to knowledge in the networks security modelling, assessment and security hardening are made. They are listed as follows.

1. This thesis has presented two variant security models to capture and analyse the security posture of dynamic networks. First, a GSM named T-HARM that captures changes in dynamic networks every time t was developed. Then, the T-HARM was formalised, and the approach to assess the security of the dynamic network via the T-HARM was shown. Secondly, a time-independent GSM (named TI-HARM) which takes into account multiple network states, duration and the visibility of components in the states was developed to comprehensively model and analyse the security of changing networks onto a single GSM. The use of different weight threshold for the TI-HARM was shown, and the effect of using different weight threshold to construct the TI-HARM was investigated. Besides, an algorithm for determining the MWT to use in order to prevent misleading security analysis when using the TI-HARM was developed as well.

2. A systematic evaluation of existing security metrics has been presented. In the beginning, a categorisation of various network changes based on the causes of the change was performed. Then, based on the changes identified, a comprehensive evaluation of the existing security metrics was performed. The results were summarised based to their effectiveness to security changes. A security/network administrator can determine the security metric that will effectively present the security posture of a network when a specific type of network configuration change occurs.

3. New set of metrics to assess the security of dynamic networks have been developed. Also, a categorisation of metrics based on their functionalities and what they present has been presented. Examples and simulations are used to demonstrate the usability and quantification of these metrics.

4. An approach for the security optimisation of dynamic network has been developed. In particular, an approach for multi-objective security hardening optimisation for dynamic networks using a GA was presented.

The T-HARM was used, and the optimisation problem was implemented using the NSGA-II algorithm with the input generated from the T-HARM. Multiple objectives and constraints were taken into accounts, such as security and cost, and the effectiveness of the optimal set of security hardening options are computed. For the evaluations, a dynamic network scenario with patchable and non-patchable vulnerabilities was considered, with both vulnerability patching, traffic redirections and host isolations as proactive defence mechanisms. The evaluation results showed that the proposed approach could be used to aid security administrators in selecting and deploying an optimal set of security hardening options. The results also showed that multiple optimal sets satisfy the multi-objectives while satisfying the constraints. The results also showed that the optimal set changes as the network configuration change over time for dynamic networks.

In general, the proposed dynamic models are capable of modelling the attack scenarios from multiple network states. Together with the developed security metrics, they can quantitatively assess the security of dynamic networks. The proposed optimisation approach can support security administrators with an overview of how the optimal solution changes over time, as well as compute the optimal solution by taking into account changes made by dynamic networks and other constraints. Moreover, this approach provides a way for the security administrator to understand the pros and cons of each hardening option before their deployment.

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