FORMAL ANALYSIS METHODS OF NETWORK SECURITY DESIGN

Mariusz Stawowski
Cybernetics Faculty, Military University of Technology, Warsaw, Poland

Keywords: Network Security Principles, Security Design Analysis, Graph Models and Methods, Formal Security Analysis.

Abstract: An assessment of network security design correctness requires an analysis of many aspects, e.g. security zones correctness, access control protection layers as well as protections tightness against intrusions. Using formal methods based on graph theory in medium up to large-scale networks can greatly speed up and improve accuracy of performing security analysis. The analysis models and methods described in this document allow for quick identification of network security design errors resulted from breaking the "Compartmentalization of Information" and the "Defense-in-Depth" security principles, checking if protections used allow for security incidents handling as well as verification of many other security aspects. The analysis methods developed here can be used during network security design process and also for security assessment of existing computer information systems.

1 INTRODUCTION

Network security design verification is performed mainly based on IT systems security principles and risk analysis results. Security analysis in medium and large-scale networks is a complicated and time-consuming task. Mistakes can be made easily and security holes can be overlooked. The difficulties result mainly from the fact, that network security system is composed of many different, integrated elements. Network security operations also depend on IT systems environment.

The analysis can be performed using formal and informal methods (e.g. engineering practices). Attempts to develop standards and formal analysis methods are being made in many scientific centres. Proven world-wide frameworks and guidelines exist in the fields of IT security management and insuring CIA Triad (e.g. COBIT, IATFF, ITIL, ISO 27001). There is an apparent progress in the development of network security analysis methods based on the graph theory (e.g. Attack Graphs, Archipelago project). The research is still required in the field of formal assessment of network security design correctness (e.g. network security zones correctness, proper design of network protection layers like firewalls, intrusion prevention, content control and anti-virus systems).

2 NETWORK SECURITY DESIGN PRINCIPLES

The rules and guidelines for network security designing were elaborated by the organizations specializing in IT security (e.g. CERT, DISA, NIST, NSA, SANS). During an analysis of the network security design, the following basic IT systems security principles should be taken into account:

- "Compartmentalization of Information" - IT system resources of different sensitivity levels (i.e. different value and threat susceptibility) should be located in different security zones.
  An extension of this rule is an "Information Hiding" principle, which says that IT system makes available only such data which are necessary for conducting the IT system tasks.
- "Defense-in-Depth" – protection of IT system resources is based on many security layers.
  The extensions to this principle are the following rules: "Layered Protections" – security layers complement and insure one another; "Defense in Multiple Places" – security layers are located in different places of the IT system.
- "The Principle of Least Privilege" – IT system subjects (e.g. users, administrators) should

Stawowski M. (2007).
FORMAL ANALYSIS METHODS OF NETWORK SECURITY DESIGN.
In *Proceedings of the Second International Conference on Security and Cryptography*, pages 313-318
DOI: 10.5220/0002118903130318

have minimal privileges necessary for proper functioning of the organization. This rule applies also to data and services made available for external users.

An extension to this rule is a "Need-To-Know" principle which says that users and administrators of IT system have access to information relevant to their position and duties performed.

- "Weakest link in the chain" – a security level of the IT system depends on the most weakly secured element of the system.

There is also known the "Defense Through Diversification" principle which extends the „Defense-in-Depth" rule. It says that security of IT system resources should be based on protection layers consisting of different types of safeguards. When two layers of the same type are being used, they should come from different vendors. The rule should be used with caution because it increases complexity of security system and because of that obstructs its proper management and maintenance.

3 NETWORK MODELS

3.1 Network Security Model

In order to perform security design analysis using formal methods, the mathematical model of IT system focused on mapping network protections has been developed. The basic element of the model is a graph describing IT system's network structure as well as functions defined in its vertices and edges representing IT system network and protections features.

The IT system network security model can be presented as a vector

$$S = < G , \{ \lambda \} , \{ \beta \} , D^b > \quad (1)$$

where:

$G = < Z , L >$ - an undirected graph describing IT systems network structure (so called network security graph),

Z – a set of G graph's vertices representing IT system's resources (i.e. information and service resources, network and security devices),

L – a set of G graph's edges representing direct connections between IT system's resources (i.e. cabling and L2 OSI devices),

$\{ \lambda \}$ – set of functions on the G graph's vertices,

$\{ \beta \}$ – set of functions on the G graph's edges,

D^b – a binary matrix describing the security analysis scope.

$$D^b = \left[d_{ij}^b \right]_{|V| \times |K|} \quad (2)$$

where:

V – set of IT systems threats,

K – set of network safeguards types,

d_{ij} is 1 if the j safeguard protects against the i threat, and 0 otherwise.

Vertices in the G graph represent different IT system's resources (i.e. information and service's resources, network L3 devices, security devices). In order to perform an analysis more efficiently, the resources should be grouped. The following rules for grouping the resources are being applied: the resources are in the same location and in the same L2 network segment, the resources have the same security requirements, the resources perform the same IT system tasks, e.g. Internet services servers, remote access servers, e-commerce servers, internal application servers, user workstations, monitoring and management systems, etc.

3.2 Network Threats Model

In order to efficiently perform an analysis of network communication control, which can be exploited for conducting potential attacks, we construct the network threat model. The model is constructed with an assumption that vulnerabilities of applications and operating systems will arise allways and it is only matter of time, they are detected and exploited for security violations. Based on this assumption we can further assume, that when the specific network service is available for an intruder, then he potentially can exploit it for performing a security violation. Because of this, every network communication with IT system's resources allowed by firewalls can potentially be exploited for performing an attack.

The IT system network threats model can be presented as a vector

$$T_Z = < G_T , A^b > \quad (3)$$

where:

$G_T = < Z_T , Ł >$ – a digraph describing communication in a computer network, where potentially the attacks can appear (so called network threats graph),

Z_T – a set of G_T graph's vertices representing IT system's resources,

Ł – a set of G_T graph's edges representing the communication in a computer network,
A^b – a binary mattrix describing network services available in the communication.

$$A^b = \left[a_{ij}^b\right]_{|U_S| \times |Ł|} \qquad (4)$$

where:
U_S – set of the network services,
a_{ij} is 1 if the i service is available in the network communication of the j edge, and 0 otherwise.

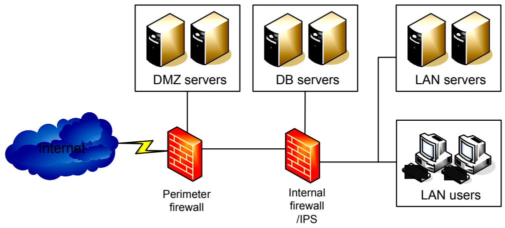
G_T graph constructing is based on G graph and performed in the following manner:

1. The vertices which do not represent information or service resources are removed from the graph. In order to make the further analysis easier, the numbering of vertices in the new graph is the same as in the network security graph.
2. The vertices of a new graph are linked by edges if the following conditions are met:
   - there is a path between vertices in the network security graph (i.e. potentially it might be the communication between the resources represented by these vertices),
   - access control mechanisms (firewalls) allow for a specific communication in the network between IT system resources represented by these vertices (i.e. an attack can potentially be performed using this path in the network).

4 ANALYSIS OF NETWORK SECURITY DESIGN

The basic security means of computer networks are firewalls (i.e. dedicated firewall devices, firewall means in intrusion prevention system (IPS) devices and access control lists (ACL) in network routers and switches). Using firewalls a proper network security architecture is created. Firewall protections divide the IT system network infrastructire into security zones and control communication between them. An example of the network and its formal models is shown in figure 1.

The IT system's network security design analysis is performed based on risk analysis results and design rules. The fundamental principles of network security design are "Compartmentalization of Information" and "Defense-in-Depth".



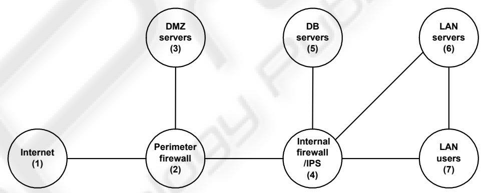
Perimeter firewall access control rules

No	Source	Destination	Service	Action
1	Any	Perimeter firewall	Any	Drop
2	LAN users	Any	HTTP, HTTPS	Accept
3	LAN users	DMZ servers	IMAP	Accept
4	Any	DMZ servers	HTTP, SMTP, DNS	Accept
5	DMZ servers	DB servers	SQL	Accept
6	DMZ servers	Any	SMTP, DNS	Accept
7	Any	Any	Any	Drop

Internal firewall access control rules

No	Source	Destination	Service	Action
1	Any	Internal firewall	Any	Drop
2	DMZ servers, LAN users	DB servers	SQL	Accept
3	Any	DB servers	Any	Drop
4	LAN users	Any	HTTP, HTTPS	Accept
5	LAN users	DMZ servers	IMAP, DNS	Accept
6	LAN users	LAN servers	FTP, NetBIOS	Accept
7	Any	Any	Any	Drop

G graph of network security model



G' graph of network threats model

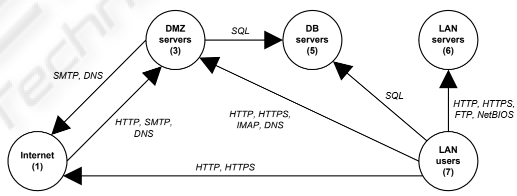


Figure 1: An example of formal models construction.

From the „Compartmentalization of Information" principle results the following detailed network security design rules:

1. IT system resources of different sensitivity level should be located in different security zones, i.e.:
   - devices and computer systems providing services for external networks (e.g. the Internet) should be located in different zones (so called DMZ) than internal network devices and computer systems,
   - strategic IT system resources should be located in dedicated security zones,
   - devices and computer systems of low trust level such as remote access devices RAS and wireless networks (WLAN) access devices should be located in dedicated security zones,

2. IT system resources of different types should be located in separate security zones, i.e.:
   - user workstations should be located in different security zones than servers,
   - network and security management systems should be located in dedicated security zones,
   - systems in development stage should be located in different zones than production systems.

Using the network security model (1) it can be verified that the network security design applies to the „Compartmentalization of Information” and "Defense-in-Depth" principles.

4.1 Assessment of Security Zones Design Correctness

In the properly designed security system, which apply to the „Compartmentalization of Information” principle, information and services resources of different sensitivity level should be located in separate security zones. Verification of security design correctness in this respect can be quickly performed based on the analysis of adjacency matrix of the G graph from the network security model (1).

$$\underset{i,j\in Z:\lambda_R(i)=1\wedge\lambda_R(j)=1}{\forall}\left[M^b[i,j]=1\right]\Rightarrow\left[\lambda_W(i)=\lambda_W(j)\right]=\text{TRUE} \quad (5)$$

where:
M^b – G graph’s adjacency matrix,
λ_R – function describing if the IT system resource is the information or service resource,
λ_W – function describing the IT system sensitivity.

The IT system resource sensitivity depends on its value for the company and susceptibility to threats. A resource has a high sensitivity when its value and threat susceptibility are high. The λ_W function is calculated based on the λ_A function and the X^b matrix, using the following formula.

$$\lambda_W(i)=\lambda_A(i)+\sum_{v=1}^{|V|}X^b(i,v);\quad i\in Z \quad (6)$$

where:
λ_A – function describing the IT system resource value,
V – set of IT system resources threats.

X^b binary matrix describes the IT system resources susceptibility to network threats. Matrix values are calculated based on the risk analysis results.

$$X^b=\left[x_{ij}^b\right]_{|Z|\times|V|} \quad (7)$$

where:
x_{ij} is 1 if the susceptibility of the i resource to the j threat is relevant, and 0 otherwise.

The „Compartmentalization of Information” rule applies also to resources of different type (i.e. public servers, internal servers, RAS servers, test systems, management systems and workstations), which should be located in separate security zones.

$$\underset{i,j\in Z:\lambda_R(i)=1\wedge\lambda_R(j)=1}{\forall}\left[M^b[i,j]=1\right]\Rightarrow\left[\lambda_T(i)=\lambda_T(j)\right]=\text{TRUE} \quad (8)$$

where:
λ_T – function describing the IT system resource type.

So the assessment of the network security design correctness in respect of the security zones is performed by the verification that (5) and (8) conditions are fulfilled using the adjacency matrix M^b and the functions λ_R, λ_T and λ_W.

4.2 Assessment of Firewall Protection Layers Tightness

The compliance with "Defense-in-Depth" principle requires that in network path between a threat source and a sensitive IT system resource there is at least two access control devices (i.e. two firewall devices). The security tightness analysis problem described here can be solved by finding and analyzing the shortest path in the graph (1).

For the assessment of the network security design correctness, one of the well-known graph theory algorithms can be used, e.g. the Bellman-Ford or the Dijkstra algorithm. In order to do this, the G graph of the network security model should be converted into G’ digraph, so all the G’ graph’s edges are directed. The edges direction is specified based on the IP routing settings in the computer networks of IT system.

The network security design analysis in respect of compliance with the "Defense-in-Depth" rule for access control protections is performed in the following sequence:

1. Finding in the G’ graph the shortest paths between vertices representing potential threat sources and vertices representing sensitive IT

system resources of information and services type.

2. If in the G' graph, the path of cost lower than 3 is found, then "Defense-in-Depth" principle is violated in the network security design.
3. If in the G' graph the path of cost 0 is found, then the sensitive resource is not protected at all by the access control protections. This means a serious design error.

The necessary condition for network access control protections compliance with the „Defense-in-Depth" principle can be formulated as follows.

$$\underset{i,j\in Z:\mu\min(i,j)\in Dav}{\forall}\left[\sum_{a=1}^{|Kij|}\beta_W(a)\geq 3\right]=TRUE \quad (9)$$

where:

β_W – function describing if the network connection is protected by the access control protections (firewall),

$\mu_{min}(i,j)$ – the shortest path between the i and the j vertices,

K_{ij} – set containing all the G' graph's edges belonging to the $\mu_{min}(i,j)$ path,

D_{av} – set of all the shortest paths in the G' graph between potential threat sources and sensitive IT system information and services resources,

$$D_{av}=\{\mu_{min}(i,j): \lambda_G(i)=1\wedge\lambda_R(j)=1\wedge\lambda_W(j)>5;\, i,j\in Z\} \quad (10)$$

λ_G – function describing if the resource can be a threat source.

4.3 Assessment of Intrusion Prevention Systems Tightness

The IPS protections are responsible for detecting and blocking penetrations and attacks conducted by intruders and malicious applications (e.g. Internet worms). When designing IPS protections the threat of conducting attacks through encrypted sessions (e.g. SSL) should also be taken into account. IPS is not able to inspect these sessions. An effective protection method is to decrypt the sessions prior to IPS devices and inspect unencrypted packets.

Ensuring a proper IT systems safety against intrusions requires designing a relevant IPS protections, i.e. in the network path between potential threat sources and sensitive IT system resources there should be security devices performing the IPS functions; furthermore the IPS protections should operate on the network connections where the traffic is not encrypted.

The IPS protections tightness analysis problem described here can be solved by finding and analyzing the shortest paths in the graph (1). For this task one of the well-known graph theory algorithms can be used. Similarly to the access control protections analysis, the G graph should be converted into the G' digraph.

The network security design analysis in respect of compliance with "Defense-in-Depth" principle for IPS protections is performed in the following sequence:

1. Finding in the G' graph the shortest paths between vertices representing potential threat sources and vertices representing sensitive IT system resources of information and services type, for which IPS protection is required.
2. Finding in the G' graph the path of 0 cost means that the security design is incorrect.

The necessary condition for ensuring the IPS protections tightness can be formulated as follows.

$$\underset{i,j\in Z:\mu\min(i,j)\in Dap}{\forall}\left[\sum_{a=1}^{|Kij|}\beta_S(a)>0\right]=TRUE \quad (11)$$

where:

β_S – function describing if the communication in the network connection is effectively controlled by the IPS (i.e. it is not encrypted and is controlled by the IPS),

D_{ap} – set of all the shortest paths in the G' graph between potential threat sources and the sensitive resources requiring IPS protection,

$$D_{ap}=\{\mu_{min}(i,j): \lambda_G(i)=1\wedge\lambda_R(j)=1\wedge\lambda_I(j)=1;\, i,j\in Z\} \quad (12)$$

λ_I – function describing if the resource requires IPS protection (calculated from X^b and D^b).

The network security design analysis can be enhanced by using the network threats model (3). For example, using the G_T graph's path matrix, the IT system resources reachable from the identified threat source can be quickly found and the security layers tightness analysis can be performed only for them (e.g. IPS analysis not performed for the paths blocked by the firewalls).

4.4 Assessment of Incident Handling Readiness

The IT system's protections should be prepared for security breaches. During the incident handling, it is necessary to block the attack source and limit spreading the incident to other systems. Administrator has at her/his disposal two basic incident handling methods: disconnecting the system from the network and restoring its proper operation (e.g. from the backup copy) or restoring the system operation without disconnecting it from the network.

The systems of high availability requirements (i.e. mission-critical systems) can not be disconnected from the network until the incident is handled and its effects eliminated. In such systems the available access control and intrusion prevention means should be used in order to limit possibilities of spreading the incident to other systems.

Formal methods can be used for quick verification if the network security design is correct in respect of its incident handling readiness. For example, using the graph's path matrix from (2) model, all the resources reachable from the specific attack source can be found. Then using (1) model, the network protections (e.g. firewalls) located in the path between the attack source and endangered IT system's resources, can quickly be identified.

5 CONCLUSIONS

The models and methods described in this paper allow for quick identification of network security design errors resulted from violation of "Compartmentalization of Information" (i.e. correctness of network security zones) and „Defense-in-Depth" (i.e. tightness of firewall and IPS protections layers) security principles as well as checking if network protections allow for proper incident handling. Also other principles (e.g. "The Principle of Least Privilege", "Defense Through Diversification") and network protections (e.g. VPN, anti-virus) analysis can be supported with formal methods.

An inspiration for the development of the methods was real problems that were experienced by the author in the security audits. Formal methods can speed up and improve the accuracy of network security design analysis of complex IT systems. Mathematical description allows for simple implementation of the methods in the form of computer programs as well as using for analysis the available mathematical tools.

The effectiveness of the formal analysis methods was in some part practically evaluated by the author during security audits. Network security model (1) can be easily constructed and graph's shortest paths found using available graph tools (e.g. David Symonds' GraphThing). Computer-aided analysis process is faster and more accurate then the analysis done in conventional way (i.e. network scheme review and safeguards verification). For example, the experienced security engineer needed about 8 hours to perform the analysis of e-banking system's network access control protections compliance with the „Defense-in-Depth" principle. Using the formal method (9) and GraphThing application, the same task was performed in about 20 minutes. Practical usage of all presented methods would require implementation for this purpose the dedicated tools.

ACKNOWLEDGEMENTS

This work is the part of the author's doctoral dissertation. The author thanks professor Ryszard Antkiewicz of Military University of Technology in Warsaw for useful discussions and support.

REFERENCES

DISA, 2003. *Infrastructure Security Technical Implementation Guide*, US Defense Information Systems Agency.

FCC, 2001. *Computer Security Incident Response Guide*, US Federal Communications Commission.

Noel, S., Jacobs, M., Kalapa, P., Jajodia, S., Multiple Coordinated Views for Network Attack Graphs, 2005. In *Proceedings of the Workshop on Visualization for Computer Security*. Minneapolis, Minnesota.

NSA, 2000. *Defense in Depth - A practical strategy for achieving Information Assurance in today's highly networked environments*, NSA.

Phillips, C., Swiler, L., 1998. A Graph-Based Network-Vulnerability Analysis System. In *Proceedings of the New Security Paradigms Workshop*. Charlottesville, VA.

Stang, T.H., Pourbayat, F., 2003. *Measuring privacy using network topology*, Oslo University College.

Stawowski, M., 2006. *The Principles and Good Practices for Intrusion Prevention systems Design*, CLICO.

Stoneburner, G., Hayden, C., Feringa, A., 2004. *Engineering Principles for Information Technology Security*, NIST.

Straub, K.R., 2003. *Information Security Managing Risk with Defense in Depth*, SANS Institute.

Zimmerman, S.C., 2001. *Secure Infrastructure Design*, CERT Coordination Center.