

Evaluation of Computer Network Security based on Attack Graphs and Security Event Processing*

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Abstract

The paper is devoted to the security assessment problem. Authors suggest an approach to the security assessment based on the attack graphs that can be implemented in contemporary Security Information and Event Management (SIEM) systems. Key feature of the approach consists in the application of the developed security metrics system based on the differentiation of the input data for the metrics calculations. Input data includes, among others, current events from the SIEM system. Proposed metrics form the basis for security awareness and reflect current security situation, including development of attacks, attacks sources and targets, attackers' characteristics. The suggested technique is demonstrated on a case study.

Keywords: cyber situational awareness, security metrics, security metrics taxonomy, attack graphs, security incidents, SIEM systems

1 Introduction

Currently in information systems a huge set of the security related information and heterogeneous security events are generated. As an answer on the problem of processing, analysis and visualization of this information, Security Information and Event Management (SIEM) systems [2, 1, 3] appeared. To represent security situation for the user of the system the set of the security metrics can be used. Obviously these metrics should be clear and valuable for security decisions and represent security situation in the real-time (or near real-time) mode.

Currently there are a lot of investigations that consider different security assessment techniques and security metrics [4, 5, 6, 7, 8, 9]. In the paper we suggest an approach that allows considering the available input data (information system description, attack graphs, service dependencies graphs and security incidents) for the security metrics recalculation in the offline (static) and online (near real-time) mode. For this goal we define the system of the security metrics that considers the recent research in the security metrics area, modeling of attacker steps as attack graphs, features of SIEM systems, protocols and standards in the area of the information security. We use known and adopted techniques for the calculation of security metrics. Calculated metrics allow to determine current security situation, including existence of attacks, attacker skills, position and goals.

The main contribution of the paper consists in the specification of the structure of the security metrics

Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, volume: 5, number: 3, pp. 14-29

*This paper is an extended version of the work originally presented at the 2014 Asian Conference on Availability, Reliability and Security (AsiaARES'14), Bali, Indonesia, April 2014 [1].

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system (including groups of metrics, metrics, and their interconnections) and in definition of calculation techniques for the defined metrics. We consider that this system should be applied for the security assessment of computer networks on the base of attack graphs in the scope of the SIEM systems. Currently the application of attack graphs for the analysis and prediction of attacker steps is not typical for SIEM systems. Thus, the key difference of the suggested technique from other techniques of the security assessment on the base of attack graphs consists in its integration in the SIEM architecture. It is achieved by taking into account current security information and security events from the SIEM system and delivering to the SIEM system the set of security metrics for the decision support. This paper is an extended version of the paper presented on ICT-EurAsia 2014 [1]. It contains detailed description of the suggested security metrics system; stages of the security assessment technique and algorithms of metrics calculations. The paper is organized as follows. In Section 2 main related works are considered. Section 3 provides description of the assessment technique and its stages. Section 4 contains case study and experiments for evaluating the security assessment technique. Conclusion provides the paper results and plans for the future work.

2 Related Work

A lot of the security metrics taxonomies were developed by now. Some of them are defined according to the goals of the security assessment. For example, in [10] metrics are divided on three categories: technical, operational and organizational. In [11] two categories are considered: organizational and technical. Taxonomy suggested by NIST [12] includes three categories: management, technical and organizational, and 17 sub-categories. Taxonomy in [13] includes three categories (security, quality of service, availability). Each category contains technical, organizational and operational metrics. In [9] metrics are divided according to six business functions : incident management, vulnerability management, patch management, application security, configuration management, and financial metrics.

Other classifications divide security metrics according to the way of their computation. In [8] primary metrics (defined directly on the base of the attack graphs) and secondary metrics (calculated on the base of the primary metrics) are outlined. [14] classifies metrics on the ones that are calculated for the attack graph (for example, attacker skill level or attack potentiality) and the ones that are calculated for the service dependencies graph (for instance, attack/response impact or response benefit).

In [5] metrics are divided according to the value type: existence; ordinal; score; cardinal; percentage; holistic; value; uncertainty. We have not found a system of security metrics that is based on attack graphs and applicable for security assessment in SIEM systems. Thus, we aimed to develop the appropriate system considering the following aspects: the last research in the security metrics area [10, 15, 16]; architecture of the security evaluation component in the scope of the SIEM system (modeling of the attack sequences on the base of attack graphs [17, 18, 19, 20] and service dependencies [15, 14]); different stages of security analysis (static and dynamic). We outlined the following categories or levels (Table 1) [21]: topological, attack graph, attacker, events, and integral (system). We also selected three sub-categories for each category: base characteristics, cost characteristics (these characteristics are calculated with consideration of the monetary value of the resources), and zero-day characteristics (these characteristics are calculated with consideration of the zero-day vulnerabilities).

Topological characteristics can be defined from the network topology and the description of hosts [22, 9]. They involve host parameters [22], application characteristics [9], features of service dependencies [15, 14], characteristics that consider information about the vulnerabilities and possible attacks [9]. We outline, for example, *Host Criticality*, *Host Vulnerability*, etc. Attack characteristics (such as attack potentiality/probability) are defined on the base of attack graphs [15]. They include such metrics as *Attack Potentiality* and *Attack Impact*. Attacker parameters are related to possible attackers and are

outlined in [6, 7, 15, 23]. Here we consider *Attacker Skill Level*. To consider events in the near real time mode the events level is introduced. Metrics of each level can be adjusted with new input data on the next level (for example, attacker skill level from the attacker level can be specified on the events level according to the information from the security events). Integral (system) characteristics involve features that define common security estimations [7, 24, 3, 25]. Main metrics of this level are *Risk Level* and *Security Level* of the system. These metrics can be defined for all previous levels but with different accuracy. From another hand, important aspects in our classification are cost-benefit analysis and analysis of zero-day attacks. Cost-benefit analysis is usually used for decision support and involves cost metrics that determine costs of impacts and responses [17, 14], for example *Business Value* of the asset. For zero-day attacks analysis, the metrics reflecting possible zero-day attacks are used [4], for example, *Host Vulnerability to Zero-Day attacks*.

Table 1: Classification of security metrics

Classification level	Input data	Security metrics
Topological	<ul style="list-style-type: none"> - System model (including service dependencies); - Information about system vulnerabilities/weak places (including indexes according to the Common Vulnerabilities Scoring System, CVSS [16]) 	<ul style="list-style-type: none"> - <i>Host Vulnerability</i> - <i>Host Weakness</i> - <i>Intrinsic Criticality</i> - <i>Propagated Criticality</i> - <i>Host Vulnerability to Zero-Day attacks</i> - <i>Business Value</i> etc.
Attack graph	<ul style="list-style-type: none"> - All information from the previous level; - Attack graphs 	<ul style="list-style-type: none"> - <i>Attack Potentiality</i> - <i>Attack Impact</i> - <i>Attack Potentiality Considering Zero-Days</i> - <i>Monetary Attack Impact</i> - <i>Response Cost</i> etc.
Attacker	<ul style="list-style-type: none"> - All information from the previous level; - Attacker profile (skills, location in the system, level of the privileges) 	<ul style="list-style-type: none"> - <i>Attacker Skill Level</i> - <i>Profiled Attack Potentiality</i> - <i>Profiled Attack Potentiality Considering Zero-Days</i> etc.
Events	<ul style="list-style-type: none"> - All information from the previous level; - Security events 	<ul style="list-style-type: none"> - <i>Dynamic Attacker Skill Level</i> - <i>Probabilistic Attacker Skill Level</i> - <i>Dynamic Attack Potentiality</i> etc.
Integral (system)	<ul style="list-style-type: none"> - Metrics from the previous levels 	<ul style="list-style-type: none"> - <i>Risk Level</i> - <i>Security Level</i> - <i>Attack Surface</i> etc.

In the paper we suggest an security assessment technique that is based on the classified set of metrics, algorithms of their calculation and approach to the attack modeling suggested in [2, 18]. This technique can be used as the base for the security decision support in SIEM systems.

The developed technique is based on the following requirements. Base requirements to the metrics [16] are such as relevancy, value, objectivity, repeatability, etc.

Common functional requirements to the security metrics are as follows: metrics should indicate the most vulnerable and weak places in the system to understand what to fix first; metrics should allow to assess the attack potentiality and level of the possible impact in the case of the attack success; metrics should allow to define attacker profile including his goals and possibilities to implement attack actions;

metrics should assess benefit in case of the countermeasures implementation; metrics should consider security events in the system for the accurate representation of the current security situation.

Main functional requirements to the security assessment technique are as follows: the technique should implement the comprehensive risk assessment procedures; the technique should support security administrator in generation of efficient security decisions from the time and cost point of view; the technique should consider requirements of the standards and protocols of the information security.

Main nonfunctional requirements to the algorithms of the calculation of the security metrics include requirements to the efficiency (calculation of the metrics for the adequate time interval) and validity (compliance of the assessments with real security state of the information system).

Main stages of the approach are presented in the next section.

3 Technique of the Security Assessment

Suggested security assessment technique is implemented as the part of the security evaluation system based on attack graphs [2, 18]. The architecture of the component is represented in Figure 1.

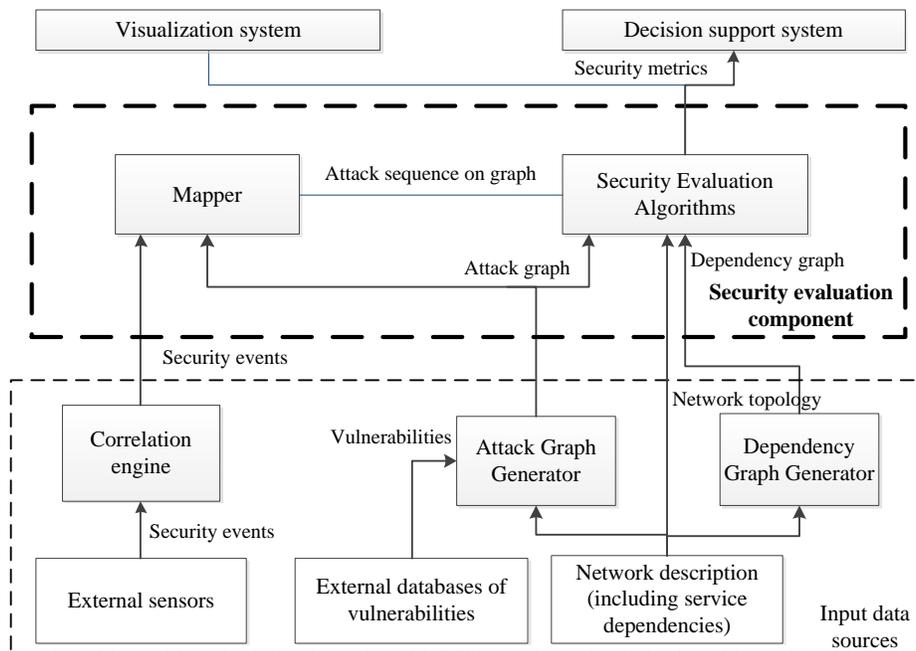


Figure 1: Architecture of the security evaluation component

The component involves the set of security evaluation algorithms for calculation of the metrics and Mapper that allows detecting attacker position on the attack graph according to the security events. Security evaluation component gets input data from the next sources: attack graph generator that builds attack graphs for the analyzed network; dependency graph generator that provides graph of the dependencies between the network services; and correlation engine that generates security events on the base of the security events. Output data includes different security metrics according to the suggested system. Further output data is provided to the visualization system and decision support system.

3.1 Input Specification

To describe the security assessment technique the following input details are used:

1. Test network with host characteristics and values of the topological metrics: *Business Value*, *Criticality* (including propagated criticality via service dependencies), etc.
2. Attack graph that contains system vulnerabilities as vertexes and transitions between the vulnerabilities as arcs (these paths of the sequential exploitation of the vulnerabilities constitute threats introduced by the attackers). Possibility of transition from one vulnerability to another is defined by pre- and post-conditions of the vulnerabilities exploitation according CVSS [16].
3. Calculated unconditional probabilities for each node (in consideration that the attacker can implement all attack actions). These probabilities define possibility of the fact that attacker achieves post-conditions of the exploitation of the vulnerability that corresponds to the appropriate node. Unconditional probabilities are defined on the base of the local conditional distributions for each node S_i , $i \in [1, n]$: $Pr(S_1, \dots, S_n) = \prod_{i=1}^n Pr(S_i | Pa[S_i])$, where $Pa[S_i]$ – set of all parents of S_i [20]. Conditional probabilities of the transitions between nodes are defined on the base of CVSS indexes (*AccessComplexity* and *Authentication*) and define possibility of the fact that attacker achieves post-conditions of the exploitation of the vulnerability that corresponds to the node in consideration that all previous nodes are compromised. Initial probability of the attack is defined by the selected attacker model (network and local) and considers CVSS index *AccessVector*.
4. Calculated impact and criticality values for each node of the attack graph.
5. Security events that include information about the attacked host, privileges and/or impact on the host.

On the stage of calculation of the topological metrics to calculate *Criticality* we consider concept of the logical dependencies graph (partially based on [14]) that represent logical dependencies between applications: nodes represent host applications, arcs specify dependency between them (direction from the parent application to the child mean that services of the parent application need services of the child application to perform its tasks).

For example, availability of the hosts connected to the firewall depends on the firewall availability or confidentiality of the hosts depends on the confidentiality of the authentication server. So for each application we have two criticality scores: *Intrinsic Criticality* and *Propagated Criticality*. *Intrinsic Criticality* is defined by the asset holder according to the *Business Value* of the service as number between 0 and 10.

Propagated Criticality of the dependent application is defined on the base of the *Intrinsic Criticality* of the child application $I_Criticality_{ap-1}$ as:

$$P_Criticality_{ap-2} = W_{ap-1,ap-2} \times I_Criticality_{ap-1},$$

where $W_{ap-1,ap-2}$ – weights matrix which defines influence of criticality of each property of the *application-2* on each property of the *application-1*.

Resulting *Criticality* of the application is defined as:

$$Criticality_{ap-1} = \begin{bmatrix} \max(I_Criticality_{ap-1}(c), P_Criticality_{ap-1}(c)) \\ \max(I_Criticality_{ap-1}(i), P_Criticality_{ap-1}(i)) \\ \max(I_Criticality_{ap-1}(a), P_Criticality_{ap-1}(a)) \end{bmatrix},$$

Host Criticality is defined as maximum criticality of its applications and is defined as:

$$H_Criticality = \begin{bmatrix} \max_k Criticality_{ap_k}(c) \\ \max_k Criticality_{ap_k}(i) \\ \max_k Criticality_{ap_k}(a) \end{bmatrix},$$

where k – number of the application on the host, $k \in [1, m]$.

Other input for the technique is the attack graph [18]. For the goals of the metrics calculation the vulnerabilities of each host are grouped according to their pre and post conditions. Pre conditions are defined by the access vector according to the CVSS index *Access Vector* (AV) which possible values are "Network" or "Local" (we designate pre conditions as AV: Network or AV: Local). Post conditions are acquired privileges (admin, other, none). Groups are as follows (Figure 2):

- Group1: pre conditions – AV: Network, post conditions – acquired privileges: user or other.
- Group2: pre conditions – AV: Network, post conditions – acquired privileges: admin.
- Group3: pre conditions – AV: Network, post conditions – acquired privileges: none.
- Group4: pre conditions – AV: Local, post conditions – acquired privileges: admin.
- Group5: pre conditions – AV: Local, post conditions – acquired privileges: user, other or none.

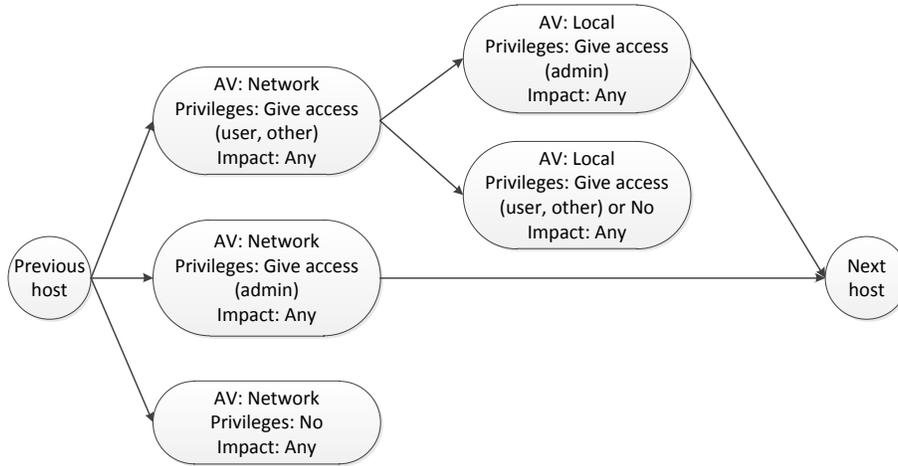


Figure 2: Grouping of the vulnerabilities for the host

Vulnerability groups of the host are connected with vulnerability groups of the host that are accessible from the current host (Figure 2). Further this groups are used for the calculation of the attack potential. Nodes of the graph (vulnerability groups) are defined as a set of possible states.

State success is defined as successful exploitation of one from the vulnerabilities in the group and achievement of the group post conditions. Local probability of the state success is defined with CVSS indexes: *Access Complexity* and *Authentication*. Initial probability of the attack (of the first step) is defined with *Access Vector* index.

For each group the possible *Impact* is determined for the further *Risk Level* calculation. Total *Impact* is defined on the base of the CVSS impact indexes and *Criticality* of the applications in group:

$$Group_Impact = \max_k Host_Criticality \times \begin{bmatrix} Impact_k(c) \\ Impact_k(i) \\ Impact_k(a) \end{bmatrix},$$

where k – number of the vulnerability in group, $k \in [1, m]$.

Security events in this case are not events from the intrusion detection system, these events are correlated events from the SIEM system with information about host with malicious activity and acquired impact on it. These events can be represented on the nodes of the attack graph.

3.2 Security Assessment Stages

The *security assessment technique* includes the following stages:

1. *Definition of the attacker position on the attack graph on the base of the information from the security event.* It can be done on the base of the next steps:
 - (a) Define the list of the vulnerabilities for the host that is described in the security event.
 - (b) Select the vulnerabilities that lead to the privileges and/or impact described in the event.
 - (c) If only one vulnerability was selected, the next steps of the technique should be performed for the node that corresponds to the exploitation of this vulnerability.
 - (d) If multiple vulnerabilities were selected, the next steps of the technique should be performed for all possible nodes.
 - (e) If a vulnerability was not selected, then the event is defined as exploitation of the zero-day.
2. *Determination of the attacker skill level on the base of information from the security event.* The next steps should be performed for all nodes selected on the previous stage:
 - (a) Define the most probable path of the attacker to the current node on the base of the Bayes theorem (posterior probability for the node A considering that B has happened): $Pr(A|B) = Pr(B|A) \times Pr(A)/Pr(B)$, where
 - (b) Select vulnerabilities with the maximum CVSS access complexity [16] for this path.
 - (c) Define the attacker skill level according to the access complexity as “High”/”Medium”/”Low”. Quantitative values are defined: 0.7 “High”, 0.5 “Medium”, 0.3 “Low” *Attacker Skill Level*.
 - (d) Define the probability of skills as $(\text{number of nodes with vulnerability with this access complexity})/(\text{total number of steps in the path})$.
3. *Recalculation of the probabilities of the paths that go through the node that corresponds to the attacker position.* On this step the next features should be considered: defined attacker skill level and that the probability of the compromise of this node is equal to 1. *Attacker skill level (ASL)* is considered in the recalculation of the local conditional distributions for the nodes. CVSS index *AccessComplexity (CVSS_AC)* is replaced according to Table 2.

Table 2: Probability of the vulnerability exploitation in consideration of the attacker skills

CVSS_AC/ASL	Low	Medium	High
Low	Medium (0.61)	High (0.71)	High (0.71)
Medium	Low (0.35)	Medium (0.61)	High (0.71)
High	Low (0.35)	Low (0.35)	Medium (0.61)

4. *Definition of the risks for the attack paths that go through the compromised node* (based on the target asset criticality, attack impact and attack path probability). *Risk level* for the attack graph node A is defined as $RiskLevel_A = UncProb_A \times Impact_A$, where $UncProb_A$ – unconditional probability of the node A and $Impact_A$ considers node criticality and impact of the node compromise.

5. *Selection of the path with maximum value of risk.* This path is selected as the most probable attack path and its end point should be selected as attacker goal.

As the result of the technique, we get the next output data: attacker skill level, attack path and attacker goal. Further this information is used for the decision support.

4 Case Study

4.1 Input Data

The following input data for the security assessment is considered below: topology of the test network (Figure 3), values of the topological metrics, especially *Criticality* of the hosts (calculated on the previous assessment stage), attack graph, security events.

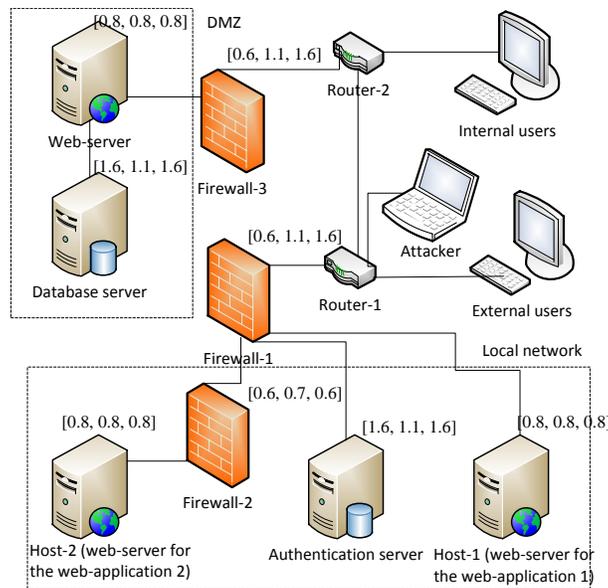


Figure 3: Topology of the test network and *Criticality* values

Test network includes two web-servers with critical web applications Host-1 and Host-2. External users of the local network are directed to the web-applications through Router-1 and Firewall-1. Authentication is needed to work with these applications. Authentication data is stored on the Authentication server. Critical data that the user get or add when working with applications is stored on Database server. Requests from Host-1 and Host-2 are handled by Web-server first. Internal users have access to Web-server via Router-2 and Firewall-3.

The parameters of the hosts for the test network are as follows:

1. *External users* – Microsoft Windows 7 64-bit, Apple iTunes 9.0.3, Microsoft Office 2007 SP1, Microsoft Internet Explorer 7.
2. *Web-server* – Windows Ftp Server 2.3.0, Windows Server 2008 for 32-bit Systems.
3. *Database server* – Apache Software Foundation Derby 10.1.3.1, phpMYAdmin 3.5.2.2, Oracle MySQL 5.5.25, Linux Kernel 2.6.27.33.

4. *Host-1* and *Host-2* – Red Hat JBoss Community Application Server 5.0.1, Windows Server 2008 R2 for x64-based Systems.
5. *Firewall-1* and *Firewall-3* – Linux Kernel 2.6.27.33, Citrix ICA Client.
6. *Firewall-2* – Novell SUSE Linux Enterprise Server 11 Service Pack 1 (with Netfilter).
7. *Authentication server* – Novell SUSE Linux Enterprise Server 11 Service Pack 1, Novell eDirectory 8.8.1.
8. *Internal users* – Apple Mac OS X Server 10.6.1, Apple iTunes 9.0.2 for Mac OS X, Microsoft Office 2008 Mac.

Figure 3 depicts the values of the host *Criticality*. It is calculated on the base of the *Business Value* of the hosts for the system and the dependencies between the network services.

Criticality is a vector that includes three scores $\langle \text{Criticality of Confidentiality}, \text{Criticality of Integrity}, \text{Criticality of Availability} \rangle$.

The example of the user interface for the security evaluation system is shown in Figure 4 [2, 18].

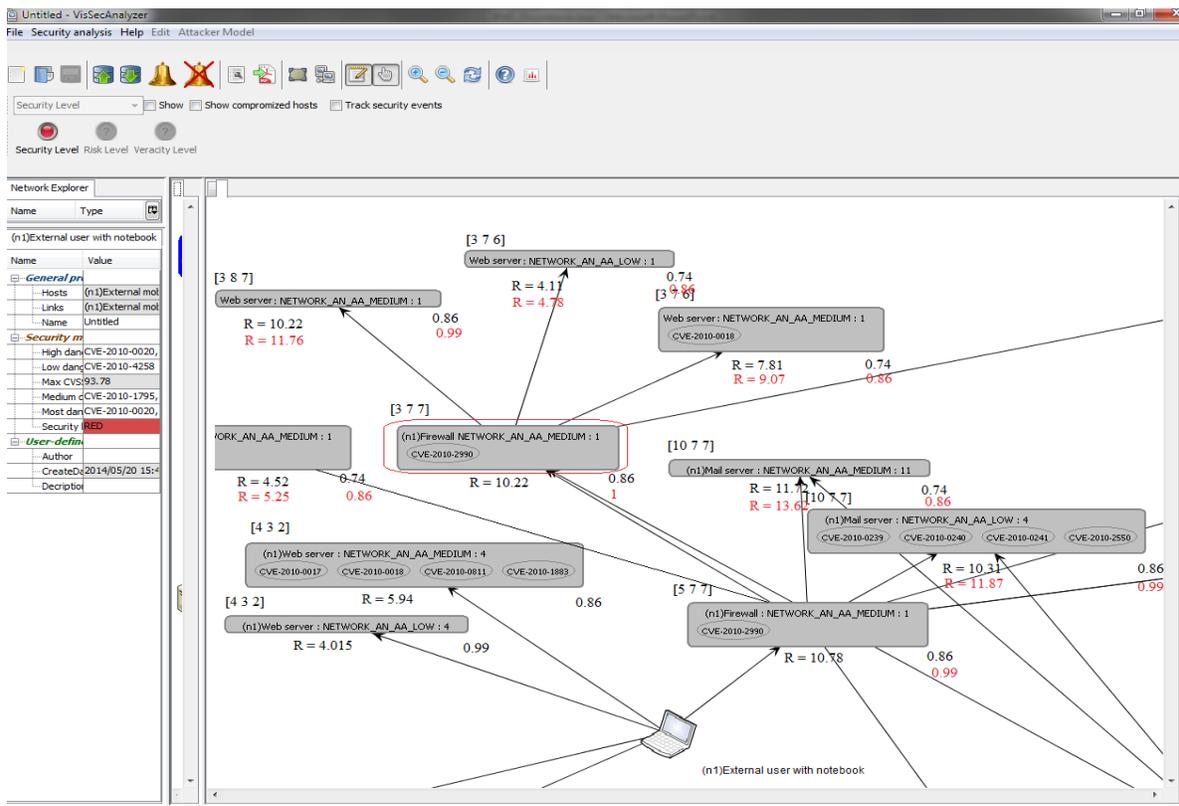


Figure 4: Example of the user interface

It includes tab with fragment of the attack graph in the center part. Nodes of the graph are signed with calculated metrics values (*Criticality*, *Attack Potentiality* and *Risk*). Node with detected security event is outlined with the red frame. Recalculated metrics after detection of this security event are presented in the red color. User interface also contains control toolbar and panel with metrics values in the top part. In the right part there is network explorer with characteristics of the network objects.

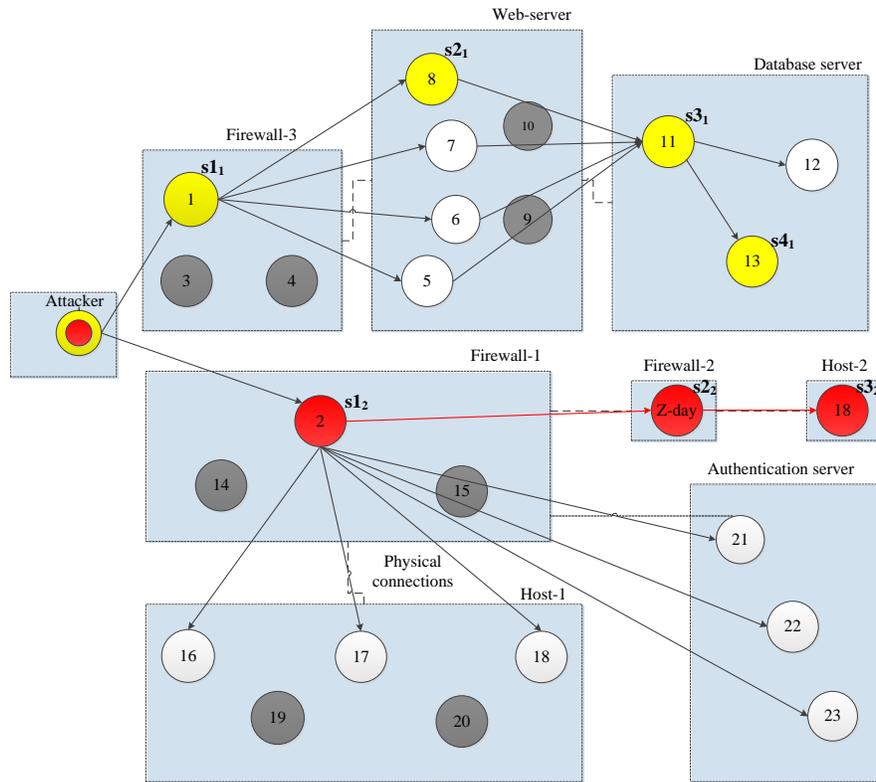


Figure 6: Attack graph with steps of the attackers

1. *Attacker with “Medium” attacker skill level.* He (she) has external access and some information on the network topology. This attacker can use exploits of known vulnerabilities with “Medium” access complexity. His (her) goal is to get data from the database. Figure 6 represents the sequence of the attacker steps with yellow color (s_{1_1} , s_{2_1} , s_{3_1} , s_{4_1} – step 1, step 2, step 3 and step 4 of this attacker accordingly). We define the following events for this case as example: **event1** – malicious activity is detected on step 1 of the attack, it contains the information on illegitimate admin access on the Firewall-3; **event2** – malicious activity on step 2, it contains the information on illegitimate admin access on the Web-server.
2. *Attacker with “High” attacker skill level.* He (she) has external access and no information about network topology. This attacker can exploit a zero-day vulnerability. His (her) goal is to compromise web-application on Host-2. Fig 6 represents the sequence of the attacker steps with red color. We define the following events for this case as example: **event1** – malicious activity is detected on step 1 of the attack, it contains the information about illegitimate admin access on the Firewall-1; **event2** – malicious activity on step 2, it contains the information about illegitimate admin access on the Firewall-2; **event3** – malicious activity is detected on step 3, it contains the information about illegitimate admin access on the Host-2; **event4** – malicious activity is detected on step 4, it contains the information about violation of confidentiality, integrity or availability on the Host-2.

4.2 Security Assessment Implementation

Let us go through the steps of the technique suggested for the described test case:

1. *Definition of the node of graph that corresponds to the attacker position.* For example, for the first scenario to detect the attacked node after event1 we determine all vulnerabilities on the defined in the event Firewall-3 and select vulnerabilities that provide privileges/impact described in the event. For the first scenario it is still vulnerability '1'.
2. *Calculation of the attacker skill level on the base of security event.* For the defined on the previous stage nodes the previous attacker steps are defined (the attack sequence on the attack graph with the maximum probability value). For the first scenario after event1 it is external network and vulnerability '1'. The attacker skill level is defined as maximum access complexity of his steps.
3. *Determination of the probabilities of the attack sequences that go through the node with attacker and definition of the attacker goal.* Figure 7 depicts probabilities after each defined security event for the first scenario (the sequence of attacker actions is represented with yellow color).

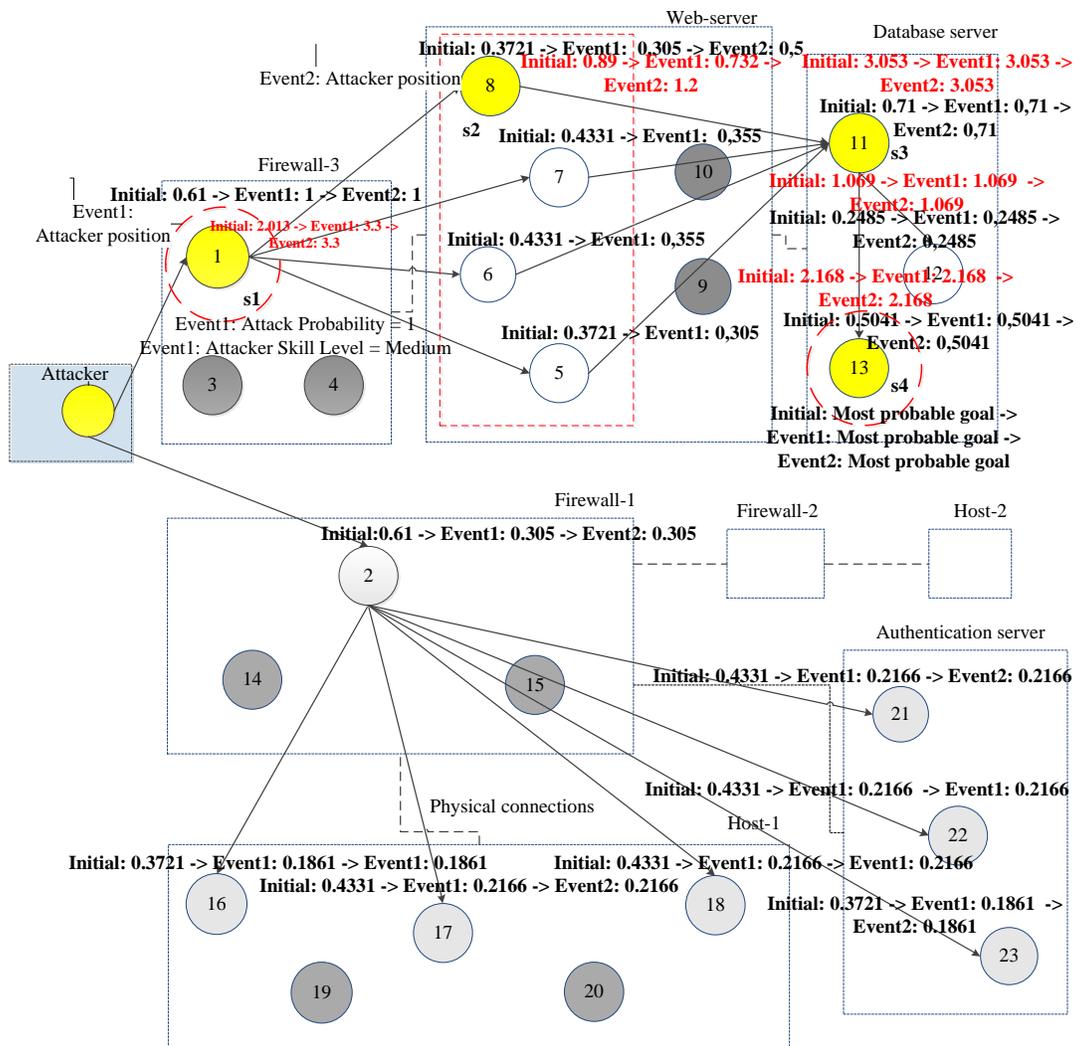


Figure 7: Changes of attack probabilities after security events for the scenario 1

For the first scenario, according to event1, new probabilities are calculated: the probabilities on the nodes 5-8 are decreased, as they were influenced by the new knowledge about the attacker position

and attacker skills. Probabilities of the attacks on the nodes 2, 16-18, 21-23 are decreased, because of the new knowledge about attacker skills. Thus, after the first security event we can suppose that attack goal is Database Server, but additional information is needed. Figure 8 outlines the same calculations made for the second scenario (the sequence of attacker actions is represented with red color).

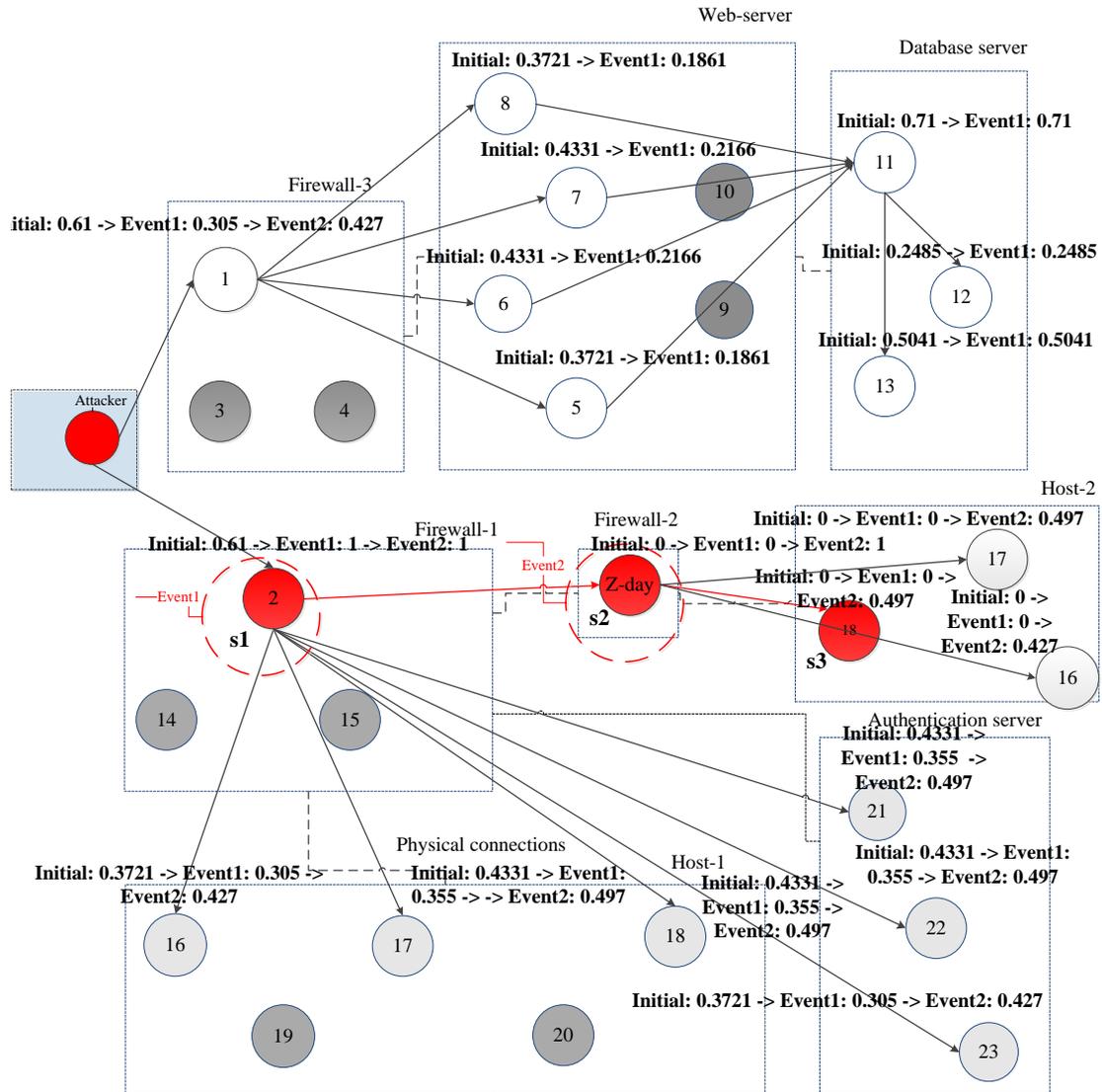


Figure 8: Changes of attack probabilities after security events for the scenario 2

4. *Definition of the risks of the attack sequences.* On this step the *Criticality* and *Impact* values are considered. According to the experiments cumulative risk values on the attacker goal nodes of the graph increase with new events.

Output of the security assessment technique contains the following data: attack path with maximum risk value that defines the most probable attack sequence and attackers goal; the most probable previous attacker steps; attacker skills.

These results allow making decision about the most efficient countermeasures. These experiments

demonstrate the main possibilities of the suggested security evaluation system on security metrics calculation.

5 Conclusion

The paper suggests security assessment technique for computer networks. The technique is based on the attack graphs and can be applied for the SIEM systems that are actively implemented in the modern information systems. It is oriented on the near real time assessment of the security situation. So the technique allows monitoring the current attacker position and forecast his (her) path in the network. It leads to the hard time limitations for calculations. In the paper we suggested some calculation techniques and analyzed their application in scope of the of the security assessment technique for computer networks.

We defined the set of security metrics and traced their changes after appearance of the security events. Technique provides different calculation algorithms according to the available input data and allows to get adequate security assessment in any time of the system operation. On the example of the case study it was shown that new data from the SIEM system influences on the probability and risk values of the attack. This allows monitoring the track of the attacker in the system.

5.1 Future Work

In the future work we plan to proceed specification of the technique and extend the set of the experiments.

5.2 Acknowledgments

This research is being supported by the grants of the Russian Foundation of Basic Research (13-01-00843, 13-07-13159, 14-07-00697, 14-07-00417), the Program of fundamental research of the Department for Nanotechnologies and Informational Technologies of the RAS (contract #2.2), and by Government of the Russian Federation, Grant 074-U01, and State contract #14.604.21.0033.

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Author Biography



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