Quantitative Characterization of Randomly Roving Agents

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Abstract—Quantitative characterization of randomly roving agents in Agent Based Intrusion Detection Environment (ABIDE) is studied. Formula simplifications regarding known results and publications are given. Extended Agent Based Intrusion Detection Environment (EABIDE) is introduced and quantitative characterization of roving agents in EABIDE is studied.

I. INTRODUCTION

Wireless sensor networks (WSN) are composed of thousands of nodes that are spatially distributed in an unattended area usually without prior knowledge of the network topology. They act as a real time environmental monitoring tool by sensing and reporting environmental data to the base station, which usually happens in a multi-hop way. In many WSN applications, like hostile area monitoring or when WSN acts as an intrusion detection system for a building, the security of the network is crucial. Especially when network nodes are deployed in an unattended area an adversary can have a physical access to them which will allow him to read, modify or erase the content of a node. In some deployments node replication attack also becomes feasible. The aim of an intrusion detection system (IDS) for those networks is to act as the second defence line against network attacks that preventive mechanisms fail to address. An Intrusion detection system for a network is a system that dynamically monitors the events taking place on a network and decides whether these events are symptoms of an attack or constitute a legitimate use of the system. Comprehensive surveys on IDS for WSN are presented in [1], [2].

Agent based intrusion detection systems became popular because of their scalability, reconfigurability and survivability [2], [3], [5], [6], [7], [8]. It is more difficult for an attacker to deal with such IDS as they do not have defined structures and are not predictable. In this work we discuss an agent based intrusion detection system called ABIDE (Agent Based Intrusion Detection Environment) [4], [11] which uses autonomous software agents for intrusion detection in computer networks. In ABIDE autonomous agents are moving randomly in a network along communication links and recording/calculating a unique information on randomly selected nodes. An example of such unique information can be a checksum of the operating system running on a node, which can help to understand whether it has been modified or not. Later each agent passes the data it collected to a special agent which combines the data received from various agents and tries to determine whether an intrusion took place or not (more details on ABIDE are given in Section II). ABIDE tries to calculate the number of agents required by ABIDE for detecting intrusions in a given size network with a given probability. The formulas, that give the relation between the number of agents and the probability of an intrusion to be detected, presented in [11], such as Formula (1), are complex and unobservable and their simplifications or approximations are of interest. By this same reason [11] considers a computer simulation instead of using the Formula (1), to understand the typical number of agents necessary to retrieve the required information in a network. Our work tends to prove simple formulas analytically, for the same numerical characteristics of ABIDE, which can be used to understand the relations between the number of agents and the amount of information that can be gathered by them, without considering a software simulations. We also propose the extended version of ABIDE, called EABIDE and consider the same quantitative characteristics for it. As a result we get formulas representing the relation between the number of roving agents in EABIDE and the amount of information that can be gathered by them in terms of Stirling numbers of the second kind. Known asymptotic estimates for Stirling numbers of second kind can further be applied to get more compact approximations [4], [9], [16].

II. AGENT BASED INTRUSION DETECTION ENVIRONMENT (ABIDE)

Consider a network where each node has a software agent hosting environment (i.e. software agents can move into a node perform some action and leave.). ABIDE [11] uses four different kinds of agents to organize intrusion detection and correction in the system.

1) A Data Mining Agent (DMA) roams around in a network (i.e. randomly chooses a host node and moves there) and acquires environmental information from nodes. DMA is lightweight and uses simplest mining algorithms. For example DMA may calculate a checksum of the operating system that runs on a host node, and if it decides that the value of the checksum is suspicious it can keep the value and curry on for further analysis.
2) A Data Fusion Agent (DFA) roams around or is located on the base station. It receives the data collected by various DMAs and builds a larger picture of events from this data. As the DFA has a combined data it can apply classical intrusion detection techniques to determine whether an intrusion took place or not. Of course the power of the DFA depends on the quantity of information received from DMAs.

3) Nodes that have been identified as suspicious by DFA are further visited by a Probe Agent (PA), sent by DFA, which performs a test on a host node to confirm the intrusion.

4) Once the intrusion is confirmed by a PA a Corrective Agent (CA) can be dispatched by a DFA to take actions.
Theorem 1. We have proven

$$C_n^t \cdot Q(k, m, t)$$

(4)

where $C_n^t$ stands for the number of possibilities to pick $t$ out of $n$ nodes (columns) and $Q(k, m, t)$ stands for the number of possibilities to cover all the $t$ nodes by $k$ agents equipped with a memory of size $m$.

$Q(k, m, t)$ can be calculated by inclusion-exclusion principle. First, over $k \times t$ matrices we take all the matrices with exactly $m$ 1s on each row, then we remove all the matrices that have at least one column initially filled in with 0s (such matrices do not obey the conditions we require), then we add matrices with at least 2 columns filled in with 0s and so on. The formula representation of related quantities is

$$Q(k, m, t) = (C_m^t)^k - C_1^t \cdot (C_{m-1}^t)^k + C_2^t \cdot (C_{m-2}^t)^k - \ldots + \sum_{i=0}^{t-m} (-1)^i C_i^t \cdot (C_{m-i}^t)^k$$

(5)

We have proven

Theorem 1.

$$P_k(n, m, t) = \frac{C_n^t \cdot Q(k, m, t)}{(C_m^t)^k} = \frac{C_n^t \cdot \sum_{i=0}^{t-m} (-1)^i C_i^t \cdot (C_{m-i}^t)^k}{(C_m^t)^k}$$

(6)

Proof: The proof follows from (4), (5) and the fact that the number of $k \times n$ matrices with exactly $m$ 1s on each row is $(C_m^t)^k$.

First of all here we receive a real simplification of (1). The formula received is still complex, but it might be easily calculated and the applied Markov inequality may give asymptotic estimates of $t$-subset probabilities (10).

Another important characteristic, the mean value of subset size $t$, might be computed as:

$$\sum_{t=m}^{\min(km, n)} t \cdot P_k(n, m, t) = \sum_{t=m}^{\min(km, n)} t \cdot C_n^t \cdot \sum_{i=0}^{t-m} (-1)^i C_i^t \cdot (C_{m-i}^t)^k \cdot \frac{(C_m^t)^k}{(C_n^t)^k}$$

(7)

IV. EXTENDED AGENT BASED INTRUSION DETECTION ENVIRONMENT (EABIDE)

We generalize the intrusion detection system proposed in [11] by allowing data mining agents (DMA) to collect a redundant data, i.e. in contrast with the original version of ABIDE, where each DMA collects data from $m$ randomly chosen distinct nodes, here DMA is allowed to have more than one instance of the same data in his memory (i.e. on each visit of the same node data might be calculated and stored). DMA do not store several copies of the same data in purpose, this can be unavoidable in networks where network nodes are indistinguishable from DMA point of view. The later might be required by the security system of the network (e.g. if nodes use randomized and encrypted IDs DMA can not recognize the node visited before as it will have different ID, so the data collected from the same node during two different visits will be indistinguishable). As a result when the memory of a DMA is full it will contain data from $1 \leq l \leq m$ distinct nodes in contrast with $m$ in case of ABIDE.

A data fusion agent (DFA), having access to security schemes deployed in the networks, can sort out the data received from a DMA, discard redundant data and keep the $t$ pieces of distinct data.

In Extended Agent Based Intrusion Detection Environment (EABIDE) we are interested in the same question as before.

What is the probability of identifying intrusions in a network of given size with the set of given DMAs in a presence of a single DFA, where DFA needs information from at least $t$ distinct nodes in order to be able to determine whether there is an intrusion or not. Further this can be used to calculate the number of DMAs required for identifying intrusions in a given network with a given probability.

Formally the problem we consider is the following. Given a set of $k$ DMAs which roam around in a network of $n$ nodes. Each DMA has a storage where it can keep $m$ pieces of data. DMA returns to DFA as soon as it acquires $m$ pieces of data, from randomly chosen nodes (from DMA point of view all the $m$ pieces of data will be different). Note that when a DMA moves into a node it is not obliged to take actions there, the node can be used as intermediate hop for roaming, this way randomness of the visited nodes (nodes where a data has been collected) can be guaranteed. It is required to calculate the probability $P_k(n, m, t)$ of DFA having data from exactly $t$ distinct nodes. The difference with the ABIDE is that not only the data gathered by different DMA may intersect but also the data in the memory of a single DMA may be redundant.

V. COVERAGE CHARACTERIZATION OF ROVING AGENTS IN EABIDE

Consider a set $N = \{v_1, \ldots, v_n\}$ of $n$ nodes and subsets $S_i^k \subset N, i = 1, \ldots, k$, where subset $S_i^k$ corresponds to the set of distinct nodes visited by agent $i$ (after removing repeating nodes, i.e. a set of nodes by DFA point of view) and $1 \leq |S_i^k| \leq m$ (here we say a node is visited by agent $i$ if $i$ collected a date from that node, i.e. nodes that were used as
intermediate hops for roaming are not considered as visited). We consider a probability distribution scheme over $N$. We are interested in probabilistic characteristics of union $\bigcup_{i=1}^{k} S_i^*$ and its size. In particular, what is the probability that the union of those subsets contains exactly $t$ elements.

$$P_k^*(n, m, t) = Pr\left(\bigcup_{i=1}^{k} S_i^* = t\right). \quad (8)$$

This time the matrix $B^{k \times n} = \{b_{ij}\}$ corresponding to subsets $S_i^*$ will be

$$b_{ij} = \begin{cases} 1 & \text{if } v_j \in S_i \\ 0 & \text{otherwise} \end{cases}. \quad (9)$$

From $1 \leq |S_i^*| \leq m$ it follows that on each row of matrix $B$ there is at least 1 and at most $m$ 1s and the rest is filled by zeros. A column $j$ of matrix $B$ represents the node $v_j$ and it composed of exactly $t$ elements alone, if and only if none of the $k$ agents visited the node $v_j$, i.e. non of the subsets $S_i^*$ contains $v_j$. Therefore the union $\bigcup_{i=1}^{k} S_i^*$ will be composed of exactly $t$ distinct elements if and only if $B$ contains exactly $n - t$ columns composed by 0s alone and all the other columns contain at least one 1. It is obvious that the number of possibilities to get information from exactly $t$ nodes, of network of $n$ nodes, with $k$ agents that fetch 1 $\leq l_i \leq m$ unique data each is given by the number of $B$ matrices discussed above. Denote the number of $k \times t$ submatrices $R$, that have 1 $\leq l_i \leq m$ ones on the $i$-th row (for all the possible $l_i$) and have at least one 1 on each column, by $R(k, m, t)$. Then the number of matrices will be

$$C_n^t \cdot R(k, m, t) \quad (10)$$

where $C_n^t$ stands for the number of possibilities to pick $t$ out of $n$ nodes (columns) and $R(k, m, t)$ stands for the number of possibilities to cover all the $t$ nodes by $k$ agents.

For calculating the number of $B$ matrices first we prove the following lemma which shows the similarities between schemes ABIDE and EABIDE.

**Lemma 1.** The probability of covering exactly $t$ out of $n$ nodes with one agent having memory of $m$ units in EABIDE scheme is equal to the probability of covering exactly $t$ out of $n$ nodes with $m$ agents having memory of 1 unit in ABIDE scheme.

$$P_1^*(n, m, t) = P_m(n, 1, t)$$

**Proof:** The proof is simple. Having in mind that at any point of time each node has the same probability to be visited by an agent in EABIDE scheme (even those nodes that have already been visited), each cell of the agent’s memory can be considered as an individual agent having a memory of size 1 which leads to $m$ agents with one unit of memory in ABIDE scheme.

**Corollary 1.** $P_k^*(n, m, t) = P_{km}(n, 1, t)$

**Proof:** The proof is similar to the proof of Lemma 1.

**Theorem 2.**

$$R(k, m, t) = Q(km, 1, t) = \sum_{i=0}^{t-1} (-1)^i C_i^t \cdot (t - i)^{mk} \quad (11)$$

**Proof:** The proof follows from Theorem 1 and Corollary 1.

**Corollary 2.**

$$P_k^*(n, m, t) = \frac{C_n^t \cdot \sum_{i=0}^{t-1} (-1)^i C_i^t \cdot (t - i)^{mk}}{n^{mk}} \quad (12)$$

**Proof:** The proof follows from Theorem 2 and Corollary 1.

Finally, we note that $R(k, m, t)$ has equivalent presentation in terms of Stirling numbers of the second kind $[4]$

$$S(N, K) = \frac{1}{K!} \sum_{j=0}^{K} (-1)^j C_j^k (K - j)^N. \quad (13)$$

Formally in the formula of $R(k, m, t)$ we may add the zero term for $i = t$, and then we receive

$$R(k, m, t) = t! S(mk, t) \quad (14)$$

Stirling number of the second kind $S(N, K)$ is the number of ways to partition a set of $N$ objects into $K$ non-empty subsets. Existing asymptotic estimates for them $[4], [9], [16]$ allow to get simple approximations for $R(k, m, t)$ and therefore for $P_k^*(n, m, t)$.

The following theorem, which is the final postulation of this paper, can be formulated.

**Theorem 3.**

$$P_k^*(n, m, t) = \frac{C_n^t \cdot t! S(mk, t)}{n^{km}} \quad (15)$$

**VI. Conclusion**

In its current state the intrusion detection system called ABIDE [11] considers software simulations to understand the number of data mining agents required for identifying intrusions in a system with a given probability. In the current paper we gave formulas that allow to compute this number analytically. Further we considered the extended version of ABIDE (EABIDE) and proved formulas for the same quantitative characteristics. Formulas for EABIDE are achieved in terms of Stirling numbers of the second kind $[4], [9], [16]$, which allows to obtain asymptotic estimates and further simplifications for quantitative characteristics of EABIDE. In the future it will be interesting to consider the same quantitative characteristics analytically for more general cases of ABIDE and EABIDE schemes with more than one DFA.
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