A Distributed Hash Table Assisted Intrusion Prevention System

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***Abstract*—Using collaborative intrusion detection to sense network intrusions comes at a price of handling an enormous amount of data generated by detection probes, and the problem of properly correlating the evidence collected at different parts of the network. The correlation between the recorded events has to be revealed, as it may be the case that they are part of a complex, large-scale attack, even if they manifested at different parts of the network. In this paper we describe the inner workings a peer-to-peer network based intrusion detection system, which is able to handle the intrusion detection data efficiently while maintaining the accuracy of centralized approaches of correlation. The system is built on a distributed hash table, for which keys are assigned to each piece of intrusion data in a preprocessing step. The network traffic requirements of such a system, and the load balancing that can be achieved by using the Kademlia peer-to-peer overlay network are discussed as well.**

Keywords-collaborative intrusion detection; attack correlation; peer-to-peer; distributed hash table; Kademlia.

I. Introduction

In the earliest days of the Internet, services on the network were all based on trust. As e-commerce emerged, network hosts became victim of a wide range of everyday attacks. Due to the high amount of confidental data and resources that can be exploited, the possibilites and open nature of the Internet opened serious security questions as well.

The attacks network administrators fight against are both human and software initiated. They get more and more sophisticated, originating or targetting ocassionally multiple hosts at the same time. A large number of nodes can be simultaneously scanned by attackers to find vulnerabilities. Automatized worm programs replicate themselves to spread malicious code to thousands of vulnerable systems, typically of home users. Others compromise hosts to build botnets, which can deliver millions of spam e-mails per day.

As the manifestation of attacks, e.g., the evidence that can be observed is spread across multiple hosts, these large-scale attacks are generally hard to detect accurately. To recognize such, one has to first collect or *aggregate* the evidence, then *correlate* the pieces of information collected [1]. A collaborative intrusion detection system has to analyze the evidence from multiple detector *probes* located at different hosts, and even on different subnetworks [2]. However, this poses several problems to solve:

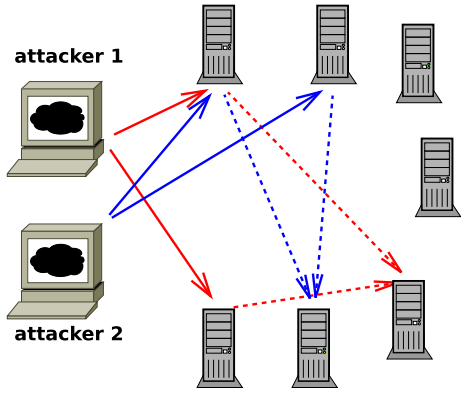


Figure 1. Messages carrying attack information in the *Komondor* system. If any probes in the network detect a suspicious event (solid lines), it sends a report to the DHT (dashed lines). The nodes of the DHT act as correlation units as well, and are able to collect these reports.

- large quantities of possible evidence collected,
- including inadequate data for precise decision making,
- communication and reliability problems,
- frequent change of intrusion types and scenarios.

Some of these troubles are specific for the isolated, host-based detection systems, while others occur only in case of the network scale intrusion detection. Despite of all these difficulties it is still worth collecting and correlating evidence available at different locations for the efficiency and accuracy boost of both detection and protection [3].

In this paper, we present a collaborative intrusion detection system, which organizes its participants to a *peer-to-peer (P2P) overlay network.* For intrusion data aggregation, a *distributed hash table* (DHT) is used, which is built on the Kademlia topology. This is used to balance the load of both aggregation and correlation of events amongst the participants. The organization of nodes in the overlay network is automatic. Should some nodes quit or their network links fail, the system will reorganize itself.

The rest of this paper is organized as follows. In Section II, we first review existing research of collaborative intrusion detection systems. Then we present the architecture of our intrusion detection solution based on the Kademlia DHT overlay in Section III. The results of our intrusion

detection method and statistics of detection are highlighted in Section IV. Research is concluded in Section V.

II. Related Work

Attackers use various ways for intrusion of computer network systems depending on their particular goals. These methods leave different tracks and evidences, called the *manifestation of attacks* [4]. To discuss the internals of a collaborative intrusion detection system, we use the following terms [2]:

- *Suspicious events* are primary events, that can be detected at probes. Not necessarily attacks by themselves, but can be part of a complex attack scenario.
- *Attacks* are real intrusion attempts, which are used to gain access to a host or disturb its correct functioning. Usually these are made up from several suspicious events at once.

The activity of an SSH (Secure Shell, a remote login software) worm program can be seen as an example of an attack. These worms use brute-force login attempts using well-known user names and simple passwords [5], directed against a single host. The attempts are events that make up the attack in this case. Multiple failed login attempts usually indicate an attack, while a single failed attempt is usually only a user mistyping his password.

A. Centralized Collaborative Intrusion Detection

Generally, large-scale attacks can only be detected by *collecting* and *correlating* events from a number of detector probes. The collection of evidence has to be extended to suspicious events as well, which otherwise do not necessarily suggest attacks themselves. In order to achieve this, various collaborative intrusion detection systems (CIDS) have been proposed, for which a detailed overview can be found in [3].

The earliest collaborative detection systems used a centralized approach for *collecting* the events, as seen on Figure 2. The Internet Storm Center *DShield* project collects firewall and intrusion detection logs from participants, uploaded either manually or automatically [6]. The log files are then analyzed centrally to create trend reports.

The *NSTAT* system [7] on the other hand is more advanced, since its operation completely real-time. In NSTAT, the detection data generated by the probes is preprocessed and filtered before being sent to a central server for correlation. This system analyzes the order of events using a state transition mechanism with predefined scenarios to find out the connection between them.

The advantage of centralized methods is that the server is able to receive and process all data that could be gathered, i.e.,it has all the information necessary to recognize the intrusion attempt. The correlation can be carried out with several different methods. SPICE [8] and CIDS [9] group events by their common attributes. The LAMBDA system tries to fit events detected into pre-defined and known scenarios [10]. The JIGSAW system maps prerequisites and consequences of events to find out their purposes [11].

Centralized solutions have two drawbacks to address. The first one of these is scalability – the high amounts of data to be aggregated and correlated for large networks cannot be handled by a single *correlation unit*. The second one is that the correlation unit is a single point of failure, being even a possible target of attack for shutting down the whole intrusion detection system.

B. Hierarchical and P2P Collaborative Intrusion Detection

By using hierarchical approaches, the scalability problem of centralized intrusion detection systems can be handled. The *DOMINO* system is used to detect virus and worm activity. It is built on an unstructured P2P network with participants grouped into three levels of hierarchy [12]. The nodes on the lowest level generate statistics hourly or daily, therefore they induce only a small network traffic.

The *PROMIS* protection system (and its precedessor, Netbiotic) uses the JXTA framework to build a partly centralized overlay network to share intrusion evidence [13]. The nodes of this system generate information for other participants about the frequency of detected suspicious events. This information is used to fine-tune the security settings of the operating system and the web browser of the nodes. This creates some level of protection against worms, but also decreases the usability of the system.

The *Indra* system is built on the assumption that attackers will try to compromise several hosts by exploiting the same software vulnerability [14]. If any attempts are detected by any participant of the Indra network, it alerts others of the possible danger. Participants can therefore enhance their protection against recognized attackers, rather than developing some form of general protection.

The scalability and single point of failure problems of centralized solutions can also be solved by using structured P2P application level networks. The P2P communication model enables one to reduce network load compared to the hierarchical networks presented above.

The CIDS system [9] is a publish-subscribe application of the Chord overlay network [15]. Nodes of this system store IP addresses of suspected attackers in a blacklist, and they subscribe in the network for notifications that are connected to these IPs. If the number of subscribers to a given IP address reaches a predefined threshold, they are alerted of the possible danger. The Chord network ensures that the messages generated in this application will be evenly distributed among the participants.

The *BotSpot* system aims to discover traffic patterns generated by botnets in recorded NetFlow data [16]. By dropping specific IP addresses from the data to be analyzed, anonymity can also be ensured for its users. The *Spamwatch* system aims filtering of spam messages [17]. It uses a Tapestry-based peer-to-peer network to store data of mail

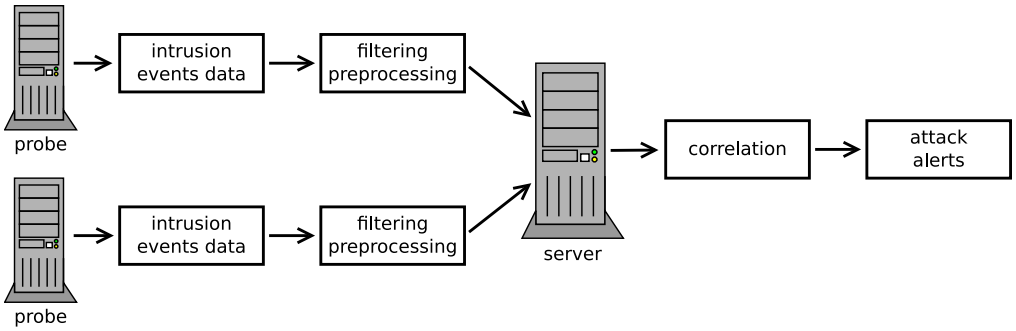


Figure 2. Collaborative detection system with centralized collection and correlation of data from probes. Every piece of information is sent to a server, which handles the correlation, and has the responsibility of alerting participants when an attack is detected.

messages that are tagged as spam by the users of the Spamwatch community [18]. Other users' mail applications can then automatically delete known spam messages.

C. Structured P2P Networks

The intrusion detection systems mentioned above use various P2P substrate networks. By selecting a proper substrate, the traffic generated in a specific application of the network can be reduced.

Structured P2P networks generally implement *distributed hash tables* [19]. DHTs store $\langle key; value \rangle$ pairs and allow the quick and reliable retrieval of any $value$ if the key associated to that is known precisely. This is achieved by using a *hash function* and mapping all data to be stored to the nodes selected by the distance of the hashed keys and their NodeIDs, which are chosen from the same address space. The connections between nodes are determined by their NodeID selected upon joining the network. They are selected so that the number of steps between any two node is usually in the order of $\log N$, where N is the count of all nodes.

DHTs all implement routing between their nodes on the application level to build the topology desired. For the small network diameter however, only some of these are feasible. The *Chord* DHT, for example, arranges its nodes into a ring [15]. To reduce the number of hops required for sending a message, it uses auxiliary network connections, which enable nodes to send message to the opposite side of the ring, and it divides the network to smaller pieces, which are half of the original in every step.

The *Kademlia* network uses a binary tree topology [20], as seen on Figure 3. All Kademlia nodes have some degree knowledge of the successively smaller subtrees of the network they are *not* part of. For any of these subtrees they have routing tables called k-buckets, which store IP addresses of nodes that reside in distant subtrees. When a node looks up a selected destination, it successively queries other nodes, which are step by step closer to the destination. The queried nodes answer by sending their k-buckets to the source. As

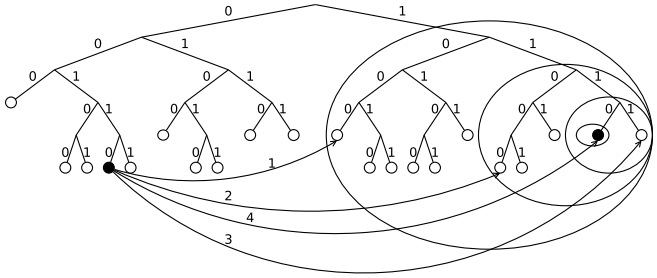


Figure 3. Sequence of lookup messages in the Kademlia overlay network. The node initiating the message successively queries nodes closer to the destination, so it finally receives its IP address for direct communication. (For details of the lookup procedure, see [20].)

nodes closer to the destination have greater knowledge of their neighbors, the lookup will get closer every step, as discussed in [20]. The distance in the binary tree is halved with every message, so the number of messages is $\log_2 N$ with N being the number of nodes in the tree.

DHTs map all $\langle key; value \rangle$ pairs to the nodes, which have their NodeIDs closest to the hashed value of the key. The distance function used depends on the topology of the network. Kademlia uses the XOR function to calculate the distance, which captures the topology of the binary tree well, as the magnitude of the distance calculated with $d(A, B) = A \otimes B$ is the height of the smallest subtree containing them both. The k-buckets are sorted by decreasing distance. The advantage of Kademlia is great flexibility: for the correct functioning of the lookup procedure, any nodes can be put in any of the k-buckets, as long as they are in the correct subtree.

III. The Komondor System Architecture

In this section, our intrusion detection system named *Komondor* is presented. Its most important novelty is that it uses the Kademlia DHT as a substrate network to store intrusion data and to disseminate information about detected events [1]. Having analyzed the collected events, *Komondor*

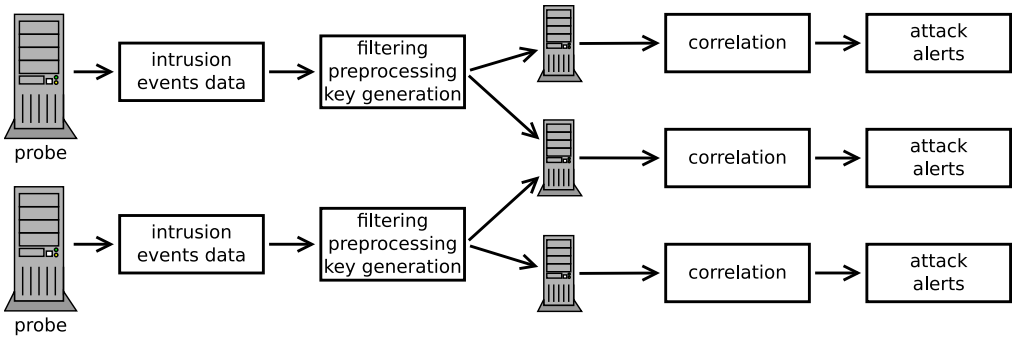


Figure 4. Distributed collection and distributed correlation of intrusion evidence from various probes. The *Komondor* system assigns keys to pieces of evidence so that data can be stored efficiently in a DHT. By using these keys, computational load of correlating can be distributed among several units.

correlation units may start an alert procedure notifying other nodes of the possible danger if necessary.

A. Distributing Load Among Multiple Correlation Units

The *Komondor* peer-to-peer application level network consists of multiple nodes. All nodes have the *responsibility* of collecting and correlating intrusion data. They also report attacks discovered to other nodes of the network, as seen in Figure 1. All participants of the *Komondor* network serve as intrusion detection units and correlation units as well.

The *Komondor* network is designed to enable the correlation methods mentioned in Section II to be used in a distributed manner:

- Pieces, which are correlated should be sent to the same correlation unit, so that it can gather all the information about the attack.
- Pieces of evidence, which are part of distinct ongoing attacks should preferably be sent to different correlation units. This reduces load and improves overall reliability of the system.

Komondor achieves this goal by *assigning keys to preprocessed intrusion data*, as seen in Figure 4 (cf. Figure 2). Keys assigned are used as storage keys in the DHT as well. For different attackers or attack scenarios, different keys are selected, and this way data is aggregated at different nodes of the *Komondor* overlay.

This is different from other P2P distributed intrusion detection networks, in which only one attack correlation method is used. In Komondor, attack correlation and event aggregation is decoupled by the means of selecting a key in an early phase of correlation, and using it as a DHT key for storage. The *Komondor* system is essentially a *middle layer inserted into the intrusion detection data path.*

Correct key selection is critical, since pieces of evidence, which might be correlated to each other must be assigned the same key and sent to the same *Komondor* node for correlation. Note that these pieces do not have to be detected by the same probe, yet they can be aggregated by the same correlation unit. The nodes of the DHT are the correlation units, which have to implement the same correlation methods as their centralized counterparts. The correlation procedure is started as soon as the preprocessing stage with the key selection, and it is finalized at the correlation units.

The detected and preprocessed data of suspicious events is stored in the *Komondor* overlay. In this system, the key assigned at the preprocessing stage of detection is used as a *key for DHT operations* as well. The value parts of the $\langle key; value \rangle$ pairs stored are any other data, which might be useful for detection or protection. As all nodes use the same key selection mechanism and the same hash function, events related to each other will be stored at the same node, as seen in Figure 1. This way the algorithm ensures that the aggregator node has perfect knowledge of all events related to the attack in question, and is able to recognize the attack as well.

The reason why a structured overlay was selected for the *Komondor* system is that it combines the advantages of both the distributed and centralized detection systems. Event data collected has to be sent to a single collector node only (this would not be possible with an unstructured overlay, as those have no global rule to map a key to a node.) Moreover, when *Komondor* nodes are under multiple but unrelated attacks, the network and computational load of both aggregation and correlation is distributed among nodes. Moreover, the *Komondor* system does not have a single point of failure: the responsibility of correlating particular events is transferred to another node in this case. The overlay can also be used to disseminate other type of information as well, for example the attack alerts, which enable nodes to create protection.

B. Kademlia as the DHT Topology of Komondor

The nodes of *Komondor* create a *Kademlia DHT* overlay. This is the topology, which can adapt its routing tables to the dynamic properties of traffic generated by the intrusion detection probes. As discussed below, other DHTs wouldn't be able to adapt their routing tables to the dynamic properties of this kind of traffic.

Storing information of events generated by the probes

Table I
NUMBER OF MESSAGES IN STRUCTURED OVERLAYS FOR INTRUSION DETECTION

Overlay	Chord	Kademlia
Routing algorithm	recursive	iterative
Node lookup	0	$\log_2 N$
First event stored	$\log_2 N$	$1 + \log_2 N$
n **events with the same key**	$n \cdot \log_2 N$	$n + \log_2 N$
Average number of messages per event	$(n \cdot \log_2 N)/n$	$(n + \log_2 N)/n$
Average number of messages with $n \to \infty$	$\log_2 N$	1

generates significant overlay traffic, which will load not only detector and collector nodes, but other nodes along the path from the former to the latter one as well, as routing between nodes is handled on the application level. If the *events are in correlation* with the same attack, the *key chosen is likely to be the same*, making the distribution of keys highly uneven. However, by using Kademlia, network traffic can be significantly reduced in this scenario. The reason for this is that the routing algorithm of Kademlia is very flexible: any node can be put to the routing tables of any other node while still obeying the rules of the routing protocol. Routing tables of other DHT overlays like CAN or Chord are much more rigid, and therefore the routing algorithm of those cannot optimize the number of messages for the store requests with the same key.

Table I compares the number of messages generated in intrusion detection for Kademlia and Chord, with the latter being an example for having rigid routing tables. Chord uses a *recursive routing mechanism,* which means that messages are forwarded by overlay nodes along the path from the source to the destination of the message, as seen on Figure 5. If *Komondor* would be built on Chord, the number of messages generated in the overlay would be in the order of $\log_2 N$ for each detected event, where N is the node count of the overlay.

Contrary to Chord, Kademlia uses an iterative algorithm. To store a $\langle key; value \rangle$ pair, a Kademlia node first looks up the IP address of the destination node by successively querying nodes closer to the destination. After finding out its address, data is sent directly from the source and the destination. This also implies that the payload of the message is contained in every message for Chord, and only in the last message for Kademlia. For Kademlia, the node has to first look up the address of the destination, which also takes $\log_2 N$ messages. Having done that, it requires one more message $(+1)$ to send the payload as well. If multiple events are to be stored, which are detected by the same probe (this is a likely scenario for a node that is under attack), the *lookup procedure can be optimized away*, as the key and therefore the collector node is the same, too. For sending data of n events, the number of messages generated is only $n + \log_2 N$ for Kademlia and $n \cdot \log_2 N$ for Chord, which is worse at the factor of n for the latter one. The limit of messages per event drops to 1 for Kademlia in this common intrusion detection scenario.

The above optimization is made possible by the fact, that any node can be inserted to the routing tables of any other arbitrarily selected node in Kademlia, while still obeying the selection rules of the protocol. The k-buckets of the nodes cover the whole NodeID space of the binary tree, and the exact selection of nodes do not affect the correctness of the lookup mechanism, only its latency properties. The original Kademlia paper [20] suggests that nodes with long session uptimes are selected for routing, which is feasible in file sharing applications to enhance reliability. *Komondor* nodes, which are selected by attack events to be stored, should be selected to reduce network traffic.

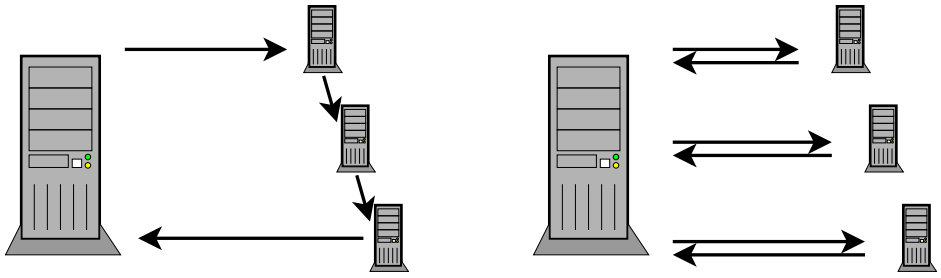
The *Komondor* system uses does not use the data lookup mechanism (looking up a value associated with a specific key) of the DHT as other applications do. Only the data store mechanism is used. Stored events are never looked up, rather the node, which stores them has to process incoming events to recognize attackers. The collector nodes have the responsibility to start a broadcast algorithm [21], if an attack is recognized. The broadcast message must contain data, which can be used by participants to create their own protection.

C. Selection of Keys in the Komondor System

The accuracy of detection, also network and computational load balancing depends on the proper selection of keys. If, at preprocessing stage, the correct key is failed to be chosen, pieces of evidence may mistakenly end up at different correlation units, and therefore the attack may remain unnoticed. Detection efficiency can be increased by assigning more keys, should an event be suspected to be a candidate for being part of different attacks or attack scenarios. One can also implementing several correlation algorithms simultaneously. However, every subsequent key increases network traffic as well.

Examples for key selection include the source or destination IP addresses of offending packets. For every large-scale network scan scenario, a different key selection mechanism is feasible. Consider the network scan types categorized in [12]:

- *Horizontal port scan.* Different hosts are scanned by a attackers, but the port number, e.g., the vulnerability searched for is the same. In this case, a blacklist of attackers can be built using the collection and correlation of detected attempts. The key for the *Komondor* overlay in this case is the identifier of the vulnerability, or the port number.
- *Vertical scan.* A single host is under attack. The attack originates from a single host, too. If this is the case,



(a) recursive (b) iterative

Figure 5. Routing methods in DHT overlays. In overlays with recursive routing, messages are forwarded from node to node. The iterative method requires nodes to look up the address of the destination of the message themselves.

the attacker is known and hosts can protect themselves against it, should it try to attack another friendly hosts. The DHT key should be the IP address of the attacker.

- *Mixed scan.* Multiple attackers use their network capacity to launch an attack against a single host or a subnetwork. This is the usual scenario for the well known DDoS (distributed denial of service) attacks [22], the goal of which is to disrupt some service of an on-line service provider by overloading its network or computational capacities. The key for the evidence storage in the DHT in this case is the subnetwork address attacked. By analyzing the data collected in this scenario, hosts can automatically detect the fact of the network scale attack, e.g., they can discover that the problem is not only related to a single host but a complete subnetwork or organization.

Apparently, the achievable benefit of the collaborative detection for these scan methods also varies with their type and intent.

IV. Results and Discussion

In this section, we present statistics of intrusion attempts detected using the implemented *Komondor* system. The statistics are evaluated to show which types of attacks this system can be used to detect.

The implementation used for testing was written in C++, and run on various versions of Ubuntu, Debian Linux and OpenBSD operating systems. The systems protected provided HTTP, SSH, mail, SQL and other services to their users. The number of probes in the system varied from 7 to 10, each with their own, public IP address. The overlay created was not limited to a single subnetwork.

The present *Komondor* implementation used the open-source *Snort intrusion detection system* [23] to detect intrusion events, and it could collaborate with other host-based intrusion detection solutions as well. The key selected for each event was the *IP address* of the attacker, as found in the Snort log file. It was also used for correlation. We selected common event types from the Snort database and also tagged events with a severity score. Intrusion alert was triggered when the sum of these scores reached a threshold level. This simple correlation method enabled us to determine the efficiency and reliability of the *Komondor* system for known attack types. Data presented here was collected in a three year interval. During this time, 17,088 attacks were detected, with the maximum number of attacks originating from a single IP address being 811. The number of individual events for a single attack reached as much as 80,000 events for some of the worm attacks recorded. The number of nodes in the small *Komondor* test overlay was around 7 and 15 nodes, with most of them being on the same subnetwork.

One of the nodes of the test overlay was assigned special logging tasks. This was achieved by fixing the NodeID of that node to the hexadecimal value 0x00000001. (Our implementation used 32-bit NodeIDs, rather than using the full 160-bit space as usual in Kademlia networks.) The attack storage method used in other nodes was modified to send all data to this node as well, besides sending the events to the nodes as selected by the keys. This anchor node generated statistics, and provided us with a monitoring interface accessible through a web browser.

A. Attack Intervals and Number of Events

Figure 6 shows invalid passwords detected for SSH login attempts on various hosts [5]. Every dot on the graph is an individual attack. The y axis shows the number of events or the number of invalid passwords detected. The duration of an attack is the time interval between the first and the last event detected, and is on the x axis. Several attackers were detected by multiple *Komondor* probes, because the SSH worm that was trying to gain access to the subnetwork tried to login all on-line hosts it found. The number of probes, which detected an attack in question is shown by the color of the dots. (In the case of multiple probes detecting an attacker, the event number on axis x is an average per probe.)

Apparently the attacks, which were detected by one probe only (black dots) have much less events associated to them. The 1,100 attacks shown on the graph have as much as 450 of them stacked up in the $(1; 1)$ point. These evidently came from human interaction. Attacks detected by multiple probes

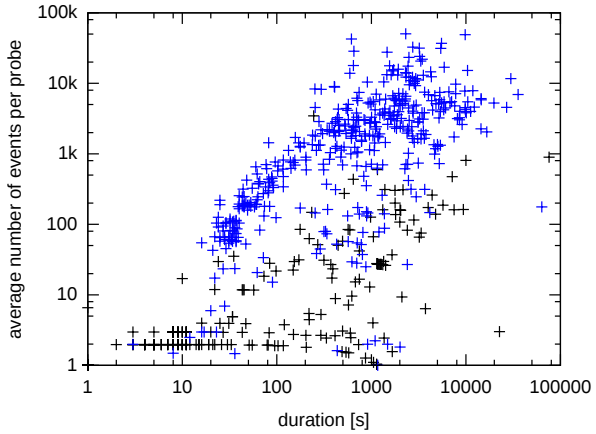


Figure 6. Number of invalid password events detected for various attacks (y axis) plotted by the duration of the attack (x axis), as detected by the *Komondor* test overlay network. The color of the dots represent the number of probes a specific attacker was detected by.

usually suggest automatic worm programs using dictionary attacks against the detector hosts.

This experience suggests that distributed intrusion detection can benefit from the advantages of DHTs:

- Attackers could be detected by several probes at the same time. When multiple hosts are attacked, recognizing an attacker using any evidence from any probe of the *Komondor* network, several hosts could be protected using firewalls at the same time, which might promptly be attacked, too.
- Attack evidence came from multiple probes. One attack is likely to be associated to thousands or tens of thousands of events, which must be stored and processed in the overlay. This type of load can be dealt with the DHT fairly well, as it can select different collector nodes for each individual attack and therefore balance the load.
- When detecting an event, which generates the same key, the Kademlia DHT can significantly reduce network traffic, as the IP address of the collector nodes have to be looked up only once. When the IP address is obtained, the system works as if it were using a centralized approach with the same benefits as those.

B. Attack Types and Confidence

Table II shows various attack types and the efficiency for the *Komondor* system regarding protection. The column *Protection* shows the number of attacks for each type, for which the attack continued after it was blocked on the firewall, and the activity of the attacker was detected by another *Komondor* node of the same subnetwork. For these attacks, the collaborative intrusion detection can greatly enhance the protection of hosts.

Figure 7 shows event numbers and attack durations for different worms attacking SQL servers. The y axis has two scales for each graph. The scales of the left hand side show attack durations (red plot), and the right hand side scale shows the number of events (blue plot). Attacks are sorted by duration. Every value on the x axis is an attack for which the duration and the number of events is shown right under each other.

Table II
NUMBER OF ALL ATTACKS AND ATTACKS FOR WHICH PROTECTION COULD BE BUILT BY *Komondor*, FOR EACH ATTACK TYPES.

Type of attack	Attacks	Protection	Ratio
phpMyAdmin scan	107	71	66%
MSSQL overflow	4355	15	0%
SSH connection lost	490	321	65%
SSH failed password	546	219	40%
SSH invalid user	51	47	92%
FTP failed login	46	2	4%

A worm, which scanned the Web servers for vulnerabilities via HTTP requests is shown on the right hand side subfigure. For any event detected, the IP address of the attacker can be recognized by the correlation units. The left hand side graph presents the properties of the Slammer worm, which penetrates outdated MSSQL servers. This worm does not issue more attempts in a short time interval to the same host, and selects IP addresses of victims randomly. For detecting this type of attacks, the PROMIS and CIDS systems could be used more effectively.

Figure 8 is similar to Figure 7, showing the attack interval and the number of events for attacks. However, invalid SSH login attempts are visualized on this one. The figure shows real attacks and mistyped passwords as well. The left hand side subfigure shows the invalid user name events, and the right hand side subfigure the invalid password events. The usual user interfaces of SSH remote login software show the login names to the users as they type, while the password is hidden for security reasons. This implies that mistyped login names rarely come from authorized users, as they would correct it before sending it to the server. Almost all of this type of attacks are conducted automatically by worm software. However, 40% of detected mistyped password attacks have only one event, and supposedly come from authorized users. These are all false alarms in an automatic intrusion protection system like *Komondor*.

C. Load Balancing Potential of Using Hash Functions for IP Addresses as Keys

Figure 9 shows the distribution of events in IP address space and in overlay key (NodeID) space. The figure shows only the events related to SSH worms.

The IP addresses on the top part of the figure were mapped to the rectangular area using a Hilbert space filling curve. This mapping renders the 32 bit address space in such a way,

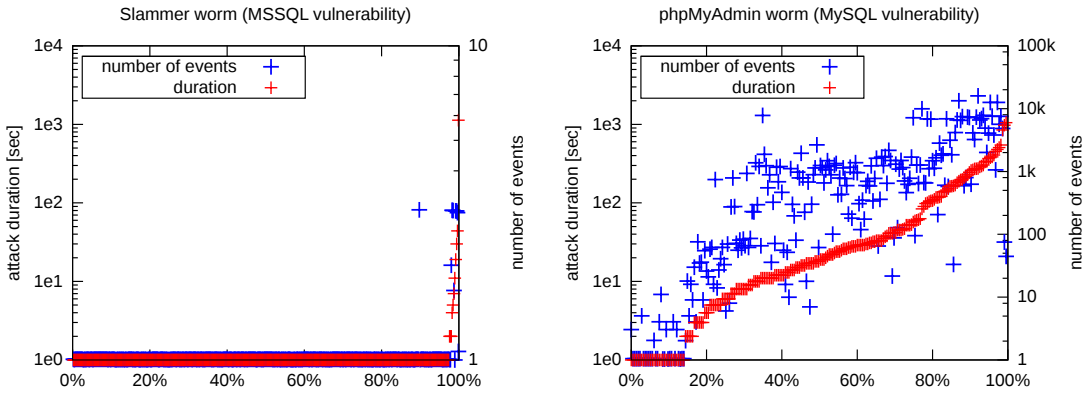


Figure 7. Attack intervals and number of events for different worm activities detected by the *Komondor* system. The left hand side shows a worm, which scanned our Web servers via HTTP in order to find a phpMyAdmin installation to gain access to MySQL databases. On the right hand side the activity of the infamous Slammer worm is shown, which penetrates MSSQL servers.

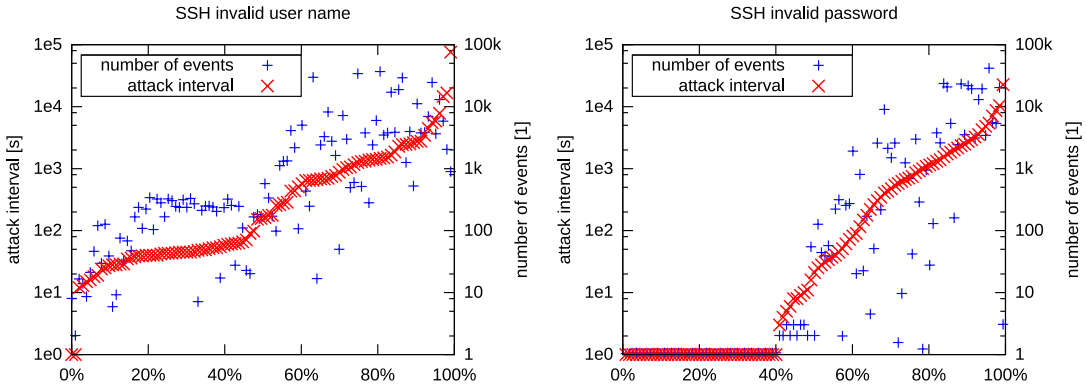


Figure 8. Attack intervals and number of events for SSH login attempts, as detected by the *Komondor* network. An invalid login name almost inevitably suggests an attack, while an invalid password may come from an otherwise authorized user.

that addresses close to each other (therefore, addresses in the same subnetwork) are close to each other. For example, the 0/8 to 63/8 range is in the upper left quarter square, and the 0/16 to 15/16 range in the upper left sixteenth. The first octet of the address determines the numbered square, and the second octet was used to select the place inside every small square similarly, so that dots do not cover each other needlessly.

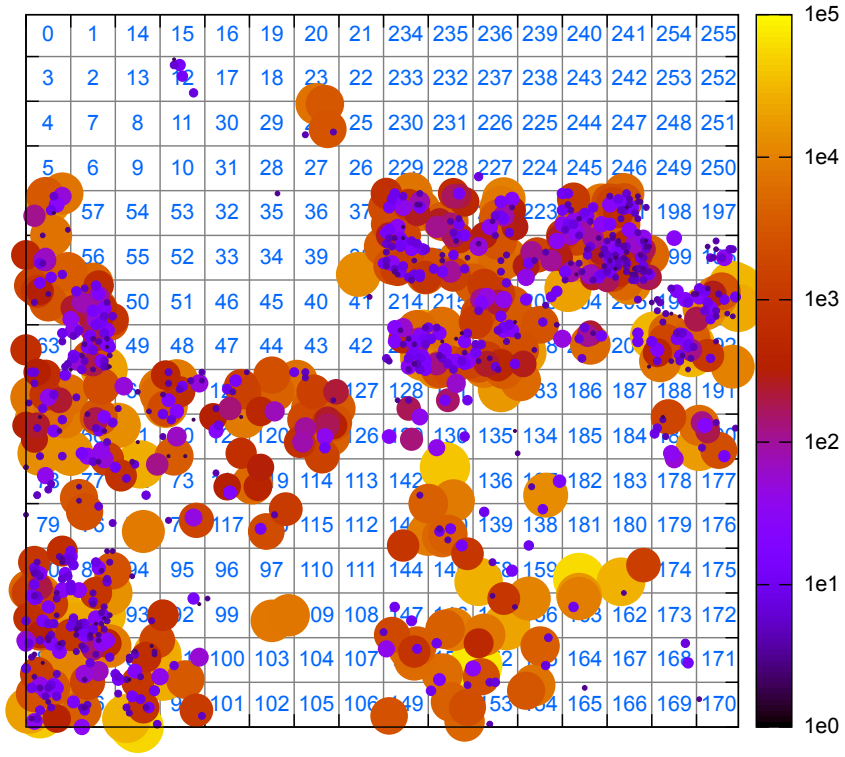
The size and color of the nodes show the number of events for each attack. The number of events related to each attack is quite different for every attack, the difference has a magnitude of about four. If we are using IP addresses for correlation, the hash functions used in the structured overlays for data to node mapping can significantly reduce this, as seen on the bottom side subfigure.

The *Komondor* reference implementation used 32-bit hashed addresses. The bottom side plot on Figure 9 shows the number of events by their hashed values, the first octet of which values are used for the x coordinate, and the next eight bits for the y coordinate. The magnitude of the difference between the highest and lowest number of messages that are related to a single attack could be reduced by 1.85, i.e., about 70 times lower.

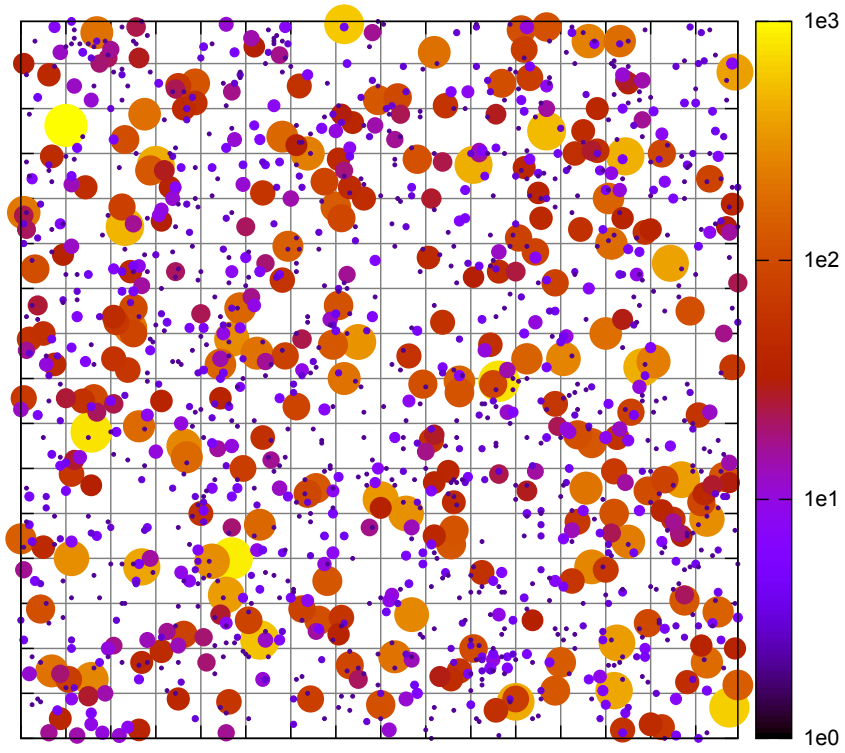
Of course, a single detector node can still detect and send many events to the same collector node, when being under attack. This load imbalance can not further be reduced by hashing the keys, but rather by properly selecting the DHT topology, as discussed in Subsection III-B.

V. Conclusion

Attacks on the Internet mean constantly growing problem for network administrators. Sophisticated attacks have evidence spread across multiple hosts and subnetworks. To detect these attacks promptly and correctly, data must be aggregated and analyzed automatically. In this article, the novel *Komondor* intrusion detection system is presented, which enables current attack correlation methods to be upgraded to work in a distributed environment. This is achieved by inserting a middle layer into the intrusion detection data path, which utilizes the Kademlia DHT overlay. As it is possible to optimize the data storage traffic to $O(1)$ message per attack event, Kademlia is the most feasible



(a) Number of events in IP address space



(b) Number of messages sent to nodes in NodeID space

Figure 9. Network traffic distribution in the structured overlay

choice of DHT topology for a wide area deployment of an intrusion detection system.

The novelty of the method presented is attaching a key to the detected events, which key is then used to send the events for correlating to several correlation units that are organized as a DHT. This mechanism can be used to reduce network and computational load and increase reliability of the system, while still retaining the advantages of centralized approaches of intrusion detection. By mapping the detected events to nodes in the system, all nodes are assigned the same level of responsibility as well. Our ongoing research is focusing on considering the different computational and network capacity of nodes to prevent those with slow connections or CPUs from being overloaded by intrusion detection data.

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