An Intrusion Detection System for Security Protocol Traffic

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Abstract

The Internet has emerged as a medium for wide-scale electronic communication involving financial transactions and other sensitive information. Encrypted exchanges between principals are widely used to ensure data security. Security protocols are rules that govern such encrypted exchanges. This paper describes a system for detecting intrusions on encrypted exchanges over public networks by recognizing the characteristics of security protocols and attacks on them.

1. Introduction

Network Security is an important field of Computer Science. With the emergence of the Internet as a medium for wide-scale exchanges of sensitive information and financial transactions, maintaining the security and integrity of messages sent over public networks is very important. Our research combines two common security technologies to provide protection for electronic information exchange over public networks.

1.1. Background

Current technology for computer and data security is usually based upon Access Control List (ACL) methodology (e.g. UNIX-style password authentication), monitored environments, or data encryption. Monitoring technology matured significantly with the seminal paper by Denning in 1986 [3]. Additionally, the use of encryption grew dramatically after introduction of the Data Encryption Standard [7] and public key technology [8], both in the late 70s. In this paper, we demonstrate a new security technique based on monitoring encrypted exchanges in order to detect intrusions.

1.1.1 Intrusion Detection

The aim of intrusion detection systems is to detect attacks against computer systems and networks. Intrusion detection systems detect attempts by legitimate users of the information systems to abuse their privileges or to exploit security vulnerabilities and attempts by external parties to infiltrate systems to compromise private information, manipulate communications, or to deny service.

There are two main designs available to IDSs for detecting attacks: 1) the misuse detection design and 2) the anomaly detection design [2]. These two methods share many characteristics, yet are complementary in that they each have strengths where the other has weaknesses.

Knowledge-based design detects intruders by pattern-matching user activity against known attack signatures. Signatures are kept in a database containing a repertoire of information describing normal, suspicious, or attack behavior. A strength of misuse detection paradigm is that when it signals that an attack has occurred, it is very likely that an attack has actually occurred. In IDS terminology, it minimizes false positives. A weakness of misuse detection is that only attacks recorded in the database can be recognized. New attacks (and other attacks that have not yet been entered in the database) cannot be recognized. This results in failure to report some attacks (termed "false negative").

The behavior-based design uses statistical methods or artificial intelligence in order to detect attacks. Profiles of normal activity are created and stored in a database. Activity gathered by the event generator that deviates from the normal profile in a statistically significant way can be deemed as suspicious activity or an attack. The strength of anomaly detection systems is that they can detect new attacks and there is no requirement to enter attack signatures into a database.

Conversely, anomaly detection systems have a higher false alarm (or false positive) rate, because they sometimes report different, but non-malicious, activity as an attack.

The widespread research on intrusion detection systems is due to the difficulty of ensuring that an information system will be free of security flaws [2]. The current and continuous reports of newly discovered flaws and vulnerabilities in end-user and architectural systems indicates that we will likely never be able to guarantee the security of electronically transmitted information. Moreover, it strongly suggests that preventative methods will likely never be sufficient to protect our networks. Our approach combines complementary prevention (encryption) and detection (IDS) technologies to provide layered security for network traffic.

1.1.2 Security Protocols

Data encryption has long been used as a means of ensuring the security and integrity of data when transmitted over public networks. Algorithms such as DES, the International Data Encryption Algorithm and the Advanced Encryption Standard make use of keys to encrypt plain text messages before they are transmitted. However, even perfect encryption is not sufficient to prevent communication from being compromised. Encryption is implemented by rules (security protocols) that define and govern the interactions between the parties to encrypted sessions.

Security protocols allow key exchange, authentication, and privacy through strong encryption. These protocols define the content and order of exchanges between the communicating principals. Early security protocols were short, usually with less than five messages. They were also simple, often developed for execution in a single, non-current session, with no branching or decision mechanisms. The classic Needham and Schroeder Conventional Key Protocol is representative of early protocols and is shown in Figure 1.

A → S : A, B, Na
S → A : E(Kas: Na, B, Kab, E(Kbs : Kab, A))
A → B : E(Kbs : Kab, A)
B → A : E(Kab : Nb)
A → B : E(Kab : Nb – 1)

Figure 1

Unfortunately, encryption backed by carefully crafted and thoroughly tested security protocols may still not be sufficient to prevent sophisticated intruders from compromising secure communication. Subtle flaws exist in many security protocols that can be used by malicious parties to compromise the security goals by subverting the underlying protocol. For example, sophisticated intruders may be able to spoof valid parties in a data exchange by using replay techniques where information from previous runs of any encrypted exchanges are used in the current run, as shown by Denning and Sacco [3]. As a result, intruders may be able to masquerade as valid parties in communication, steal keys etc. which leads to compromise of the encrypted exchange.

Since the late seventies, hundreds of papers have been written and several international research workshops have focused on cryptographic and security protocol verification and principles for devising secure protocols. While progress has been made, the end is no where in site, as evidenced by the pointed observation in [10]. It is clear that another level of protection must be provided for encrypted data exchanges to detect attacks on the security protocols.

1.1.3 The Secure Enclave Attack Detection System

The Secure Enclave Attack Detection System (SEADS) [6] is a system that can detect attacks on security protocols within an enclave of valid and recognized parties that communicate using a public network. In this environment, security protocol activity based on the message exchanges within the enclave is gathered by an Activity Monitor and compared against a knowledge base of

attack signatures on protocols. This allows the Intrusion Detection Engine (IDE) to detect attempts to subvert the security protocols and to identify suspicious activities. The SEADS architecture is shown in Figure 2.

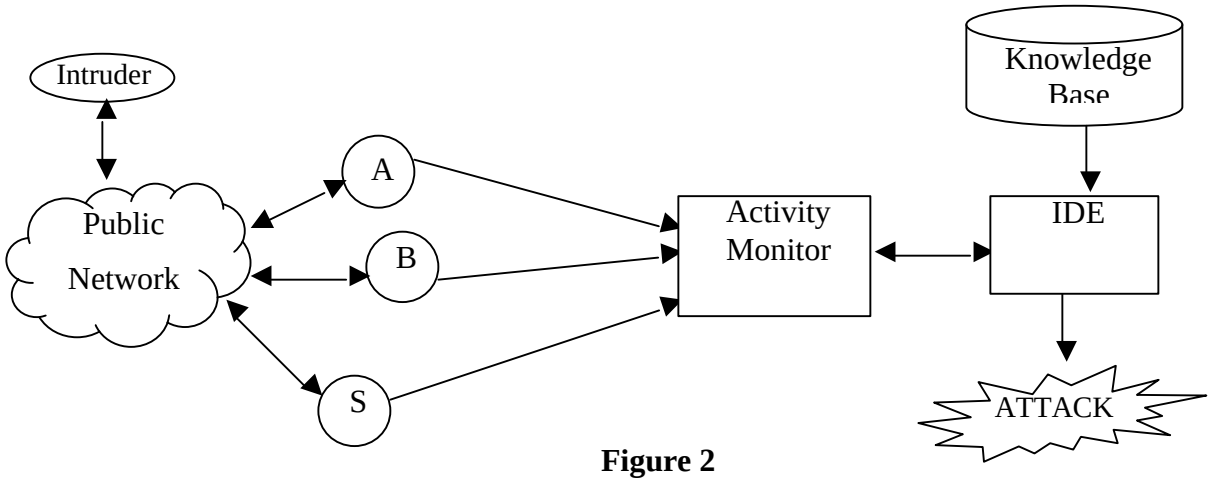

Figure 2

The detection mechanism of the Intrusion Detection Engine (IDE) is constructed based on the knowledge-based paradigm. The IDE detects anomalous, malicious, or suspicious protocol activity occurring within the secure enclave based upon previously gathered attack signatures. We know of no other executing environment that can detect attacks against encrypted traffic.

In the rest of this paper we describe the system we developed to detect attacks on encrypted traffic. In Section 2 we show how signatures are formed and in Sections 3 we describe the detection methodology and give the design and structure of the detection engine. Section 4 describes the Graphical User Interface (GUI) for our system and Section 5 details the capabilities and performance tests run on our system. We conclude with a short summary in Section 6.

2. Detecting Intrusions Using Security Protocol Characteristics

The goal of our research is to show that formal definitions of attacks on security protocols can be represented as signatures that can be stored in a knowledge base and compared against ongoing activity to detect attacks. This is done using specific characteristics of protocols. When

our system recognizes a specific signature of activity that corresponds to a known attack, we signal that an attack has occurred.

Additionally, because of the characteristics of our system, we are also able to identify suspicious behavior that may or may not represent an attack. Again, this suspicious activity is recognized based on the characteristics of the security protocols that we monitor, not on the long-term behavior of any principal(s). From this perspective, our technique may be considered *online* analysis of Security Protocols. Moreover, we know of no other project that analyzes executing security protocols. Moreover, our environment consists of a real world scenario comprised of multiple users engaged in multiple concurrent sessions, and using many different protocols, with all the traffic interleaved.

Finally, we also define and utilize signatures of properly executing protocols as part of our detection paradigm.

2.1. Constructing Signatures of Attacks

An important feature of the our technique is that the detection mechanism does not rely upon knowledge of the payload of the messages exchanged between the principals during protocol sessions. This is because the IDE detects attacks based upon the characteristics of the security protocols themselves. The signatures constructed from protocols and their known attacks are represented by:

(1) The protocols that are in use
(2) The principals (originator and recipient) involved
(3) The messages that are sent
(4) The messages that are received
(5) The concurrent sessions that occur

Consider the canonical *Needham and Schroeder Conventional (symmetric) Key Protocol* (NSCKP) [5] shown in Figure 1. This protocol requires three principals: A, B and the trusted third party server S. The aim of NSCKP is to establish a secret key *Kab* that is to be used by the principals A and B to encrypt their future exchanges. At the end of a correct run of the protocol, both principals should be in possession of the secret key, Kab, newly generated by the server S.

The given description of the protocol includes information about the payload data exchanged by the principals. However, as previously mentioned, the IDE does not rely on payload information for its detection mechanism. Rather, it relies on the proper sequencing of messages in the session. The NSCKP can be represented by the signature given in Figure 3

Protocol	Session	Message #	Action	Sender	Receiver
NSCKP	x	1	send	A	S
NSCKP	x	1	receive	A	S
NSCKP	x	2	send	S	A
NSCKP	x	2	receive	S	A
NSCKP	x	3	send	A	B
NSCKP	x	3	receive	A	B
NSCKP	x	4	send	B	A
NSCKP	x	4	receive	B	A
NSCKP	x	5	send	A	B
NSCKP	x	5	receive	A	B

Figure 3

Each step of the signature is considered an *event*. Alice[1] sending a message to Sally is considered as a 'send' event and similarly Sally receiving a message from Alice is a 'receive' event by Sally from Alice. An important feature of protocol signatures is that they include receive events. Earlier research [6] took into account only the message sending events in the protocol signature. This means that Alice sending a message to Sally (as in event 1), and

[1] We use the convention of referring to principal A as Alice, B as Bob, S as Sally, M as Mallory, etc.

correspondingly Sally receiving the same message (event 2) will be represented as two distinct events in the protocol signature used by the IDE.

Consider a scenario during the run of the NSCKP. Upon sending a message to Sally as part of the first step of the protocol, Alice will inform the activity monitor of SEADS about this. Since a public network is being used for the message transfer between Alice and Sally on insecure lines, the message may be lost or may be intercepted by an intruder. In either case Sally will not inform the monitor that it actually received a message from Alice. Thus, the sequence of events logged in the monitor will show a message sent by Alice to Sally, but not received by Sally, as evident by the lack of the receive notification by Sally to the monitor. It is prudent therefore to include the message receipt as a separate event in the protocol signature, as we further illustrate.

The attack on the Needham and Schroeder Conventional Key Protocol was demonstrated by Denning and Sacco [4]. The attack leverages the lack of temporal information in message three. Although Bob decrypts this message and legitimately assumes that it was created by the server Sally, there is nothing in the message to indicate that it was actually created as part of the current protocol run. Thus, suppose, a previously distributed key Kab has been compromised, through cryptanalysis or other means, and is known by a malicious intruder, Mallory. If Mallory monitored and recorded message three of the corresponding protocol run, consisting of E(Kbs: Kab, A), he can now fool Bob into accepting the key as new by the protocol given in Figure 4.

(3) *M(A) → B : E(Kbs : Kab, A)
(4) B → M(A) : E(Kab : Nb)
(5) M(A) → B : E(Kab : Nb –1)
*M(A) stands for *M* masquerading as A.

Figure 4

After effecting the attack, Bob believes he is following the correct protocol. Mallory is able to form the correct response in (5) because she knows the compromised key Kab. She can now engage in a communication with Bob using the compromised key and masquerade as Alice.

We can generate a signature recognizable by the IDE for the above attack on the Needham and Schroeder protocol. The signature is comprised of only three events, two receive events and a send event as shown in Figure 5.

Protocol	Session	Message #	Action	Sender	Receiver
NSCKP	x	3	receive	A	B
NSCKP	x	4	send	B	A
NSCKP	x	5	receive	A	B

Figure 5

Since the malicious intruder (M), is not part of the secure enclave, it will not co-operate with the activity monitor and, hence, will not inform the monitor whenever it sends or receives messages. Thus the above attack signature will consist only of events reported by Bob (a valid principal) to the monitor.

2.2. The Recognition Machine

In section 2.1 we described in detail how the attack signatures are constructed from the description of security protocols. The IDE interfaces with the activity monitor to receive events corresponding to protocol sessions executing within the enclave and compares the events with the attack signatures stored in the knowledge base. The comparison mechanism in the IDE is achieved by using Finite State Machines.

```
begin PROTNAME SIGNUM ATTACKTYPE
INITIALSTATE principal (→/←) principal NEXTSTATE msgNum sessNum
PREVIOUSSTATE principal (→/←) principal NEXTSTATE msgNum sessNum
end
```

Figure 6

Each time the IDE receives an originating event from the monitor (i.e. an event that corresponds to the first event of a new protocol session) the IDE constructs a finite state machine recognizer for each signature stored in the knowledge base for that particular protocol. These recognizers remain active until an event occurs that invalidates the signature.

2.3. Signature Format in the Knowledge Base

Each signature is stored in the Knowledge Base as a procedure defining a finite state machine. Information in the first line identifies the entry, followed by the state identifiers and the transitions that occur. Figure 6 is a symbolic representation of a signature, following the notation detailed in Appendix A.

2.4. Construction of the Finite State Machine

When a session begins, the IDE constructs a Finite State Machine (FSM) recognizer for each signature stored in the knowledge base, corresponding to the protocol used in that session. The state transition diagram for attack signature #1 on the NSCKP protocol (as described in section 2.1) is shown in Table 1.

Initially the recognizer will be in the start state (SS). As the IDE receives events from the monitor for this particular protocol session it advances the FSM for this signature if the arriving events match those in the attack signature. Upon a transition to the final state in any of the finite state machines corresponding to the attack signatures of the protocol, the IDE signals an attack notification.

Current State	Event	Protocol	Session	Sender	Receiver	Message Number	Next State
SS	receive	NCCKP	X	A	B	3	S1
S1	send	NCCKP	X	B	A	4	S2
S2	receive	NCCKP	X	**B**	**A**	5	**FS**

Table 1

2.5. Attack Detection

The IDE uses distinct detection methodologies for protocol attacks depending on the number of sessions used in each specific attack. Attacks on security protocols may be over only a single session of the protocol or may utilize information gleaned from multiple runs of the protocol. Thus, attacks may be classified as *Single session* attacks or *Multi-session* attacks.

2.6. Single Session Attacks

Single session attacks are those attacks which may occur in a single session. The signature of such an attack may differ from the protocol itself in only something so subtle as a missing receive statement. In our environment, these subtle differences are easily recognized.

Interestingly, we consider the attack on the Needham and Schroeder Conventional Key Protocol (NSCKP) a single session attack even though the attack depends on a previously compromised key from another session. The telling factor is that the attack can be detected by recognition of a single protocol session. In the NSCKP case, even though it is, technically a replay attack, it can be recognized by the signature given in Table 1 without any knowledge of the previous session.

Detection of single session attacks by the IDE is simply a matter of the relevant attack finite state machine reaching the final state, upon which the IDE will signal a notification. No knowledge of the previous session is necessary for the IDE to detect this attack.

2.7. Multi-Session Attacks

Multi-session attacks are those attacks that use information extracted from more than one previous or concurrent protocol sessions. We make the reasonable assumption that such attack sessions must use the information within a certain time period of the reference session(s), from

which the information is taken in order to subvert the protocol. For multi-session attacks, the IDE classifies them as either Replay Attacks or Parallel Session Attacks.

2.7.1 Replay Attacks

Replay attacks use information extracted from a previous run of a protocol. The first question that must be answered is: "How much time can pass between the reference session and the attack session?" This is an important question in our architecture because of the way replay attacks are detected. The signature of a replay attack consists of the signature of the reference session followed by the signature of the attack session. Thus, the recognizer must remain active until either an attack is detected or the threshold period expires.

We handle this by requiring the author of signatures of replay attacks to include the threshold in the signature, which will vary from protocol to protocol. The default wait constant was chosen to be ten seconds for the IDE prototype. If events occur that triggers a replay recognizer, if the time difference between the attack session and the reference session is greater than the wait time, the IDE will flag this activity as suspicious behavior.

2.7.2 Parallel Session Attacks

A parallel session attack occurs when two or more protocol runs are executed concurrently and messages from one run (the reference session) are used to form spoofed messages in another run (the attack session). As a simple example consider the following One-Way Authentication Protocol (OWAP) [1]:

A → B : E(Kab : Na)

B → A : E(Kab : Na + 1)

Successful execution should convince A that B is operational since only B could have formed the appropriate response to the challenge issued in the first message. An intruder can play the

role of B both as responder and initiator. The attack works by starting another protocol run in

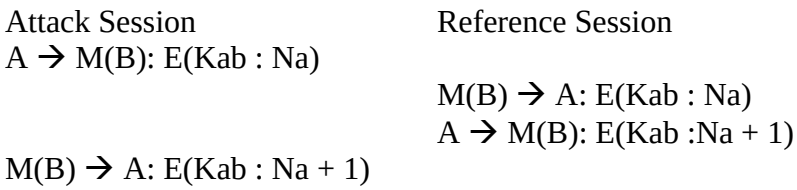

Figure 7

response to the initial challenge.

To initiate the attack, Mallory waits for Alice to initiate the first protocol session with Bob. Mallory intercepts the message and pretends to be Bob, starting the second run of the protocol by replaying the intercepted message. Alice replies to Mallory's challenge with exactly the value that Mallory requires to accurately complete the attack session. The attack is shown in Figure 7.

The IDE detects parallel session attacks by matching the ongoing activity against the attack signatures. The telling factor in this case is the omission of any information from Alice's partners in either session, as reflected in the signature in Table 2.

Current State	Event	Protocol	Session	Sender	Receiver	Message Number	Next State
SS	send	OWAP	X	A	B	1	S1
S1	receive	OWAP	X+α	B	A	1	S2
S2	send	OWAP	X+α	A	B	2	S3
S3	receive	OWAP	X	B	A	2	**FS**

Table 2

3. Design of the Intrusion Detection Engine

This section provides an insight into the design of the Intrusion Detection Engine. Justification of the major design decisions is also given. The design of the IDE uses the object-oriented paradigm. The problem was broken down into smaller components, and appropriate classes were developed to accurately represent the problem.

A major factor in the design of the IDE, was the complexity of the environment being monitored. Within any enclave, we expect to monitor events interleaved from multiple:

- Concurrent sessions
- Different principals
- Different protocols

In addition there is no guarantee that all the sessions will properly conclude. Some sessions may be suspended abnormally and messages may be lost.

3.1. Architectural Design

A number of issues had to be taken into account in the design phase of this research implementation. The design was created in order to ensure that all the requirements and specifications were satisfied.

In the secure enclave it is possible to have multiple concurrent sessions of different protocols executing within the enclave. The sessions may consist of the same or different principals. The Intrusion detection engine must be able to keep track of the different protocol sessions executing within the enclave in order to detect any attacks or suspicious activity. Not all attacks on security protocols occur over a single session. As described earlier, multi-session attacks such as replay attacks or parallel attacks may occur within the enclave. These multi-session attacks span multiple different protocol sessions. The Intrusion detection engine must provide a means to keep track of such executing sessions and detect any attacks.

Additionally, the detection of attacks has to be communicated to the person or system monitoring the enclave. Detailed reports of all attacks or suspicious behavior must be generated by the IDE. Such reports provide in-depth information about the type of attack and principals participating in the protocol session. The Intrusion Detection Engine receives crucial inputs

from the Activity Monitor and from the Knowledge base of protocol signatures. It is important to ensure that interfaces with the Monitor and the Knowledge base are well-defined and reliable.

3.1.1 The Thread Dispatcher and Monitors

As noted earlier, the IDE receives protocol events from the monitor as they occur. The IDE is multi-threaded with a single thread to serve as the thread dispatcher. Since each protocol may have many attack signatures associated with it, when a new protocol session begins, the IDE spawns a new thread to monitor all the FSM recognizers for that protocol. As illustrated in Figure 8, the Thread Dispatcher then routes events to the appropriate thread as they arrive.

To keep track of all the threads existing within the system, a *ThreadList* class is employed,

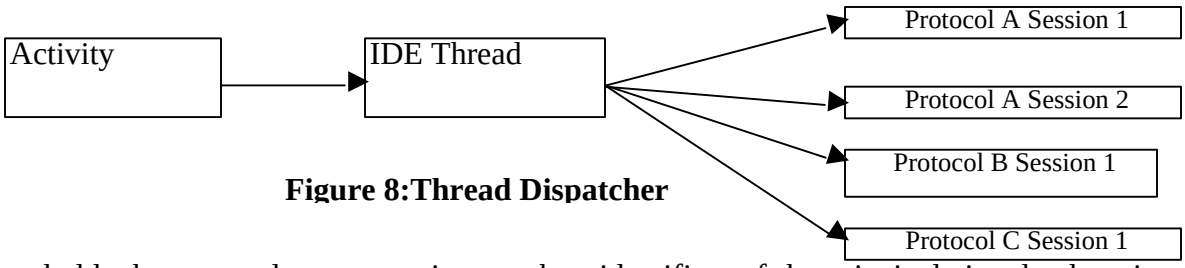

Figure 8:Thread Dispatcher

that holds the protocol name, session number, identifiers of the principals involved, a signal to which the thread listens, and a thread identifier for each thread.

3.1.2 Functionality of Threads

The threads provide the detailed functionality of the Intrusion Detection Engine. Each thread monitors the activity within a single protocol session. As events for a particular protocol session come in from the activity monitor, the thread matches those events against the protocol signatures stored in the knowledge base. If a event matches, the Finite State Machine corresponding to that particular signature is advanced to the next state.

Upon conclusion of an attack session or a normal protocol session, it may so happen that the entire signature from the knowledge base matches the succession of events for that protocol

session coming in from the activity monitor. In such cases, the thread will raise alerts to the console, providing information about the attack or normal session. If an attack is detected by the Intrusion Detection Engine, the detailed information about that attack is written to a text file. This information is used by the Graphical User Interface component of the IDE to generate the attack reports.

Threads terminate in two normal ways: (1) An attack is detected, or (2) The protocol ends normally. However if a particular protocol session hangs with no further events coming into the IDE, the thread will die after a timeout period and it will signal the activity as an abnormal termination. When a thread dies, the corresponding entry from the list of threads designed as an object of the ThreadList class is removed.

Threads are chosen as control structure of choice for the IDE for several reasons. First, the number of concurrent threads spawned by a process is limited only by the virtual memory on the system. This allows the IDE to track a large number of concurrent sessions, accurately representing an Internet environment that is rich with security protocols. Secondly, there are no synchronization issues to be taken care of as all the threads have their own memory space and can also access the global variables. Any data structure that is accessed by all the threads has been protected by means of a critical section.

The overall design of the IDE is reflected in the flow chart in Figure 9.

4. The Graphical User Interface

In our research, a Graphical User Interface (GUI) was implemented for an overall view of the attacks and suspicious activities detected within the enclave. The GUI allows the reporting of attacks to the user. The user can specify the time duration and the protocol name to obtain a detailed report of all the attacks (on the specific protocol) that took place during that period. The

report will include the name of the protocol subject to attack, the principals involved in the session, attack time and other relevant information which will allow the user monitoring the system to research the occurrence of attacks within the system.

The GUI also allows the user to back up the active attack report file to another file. The GUI will still read from both files to create the attack reports, but the IDE threads will only be writing to the newly empty active file.

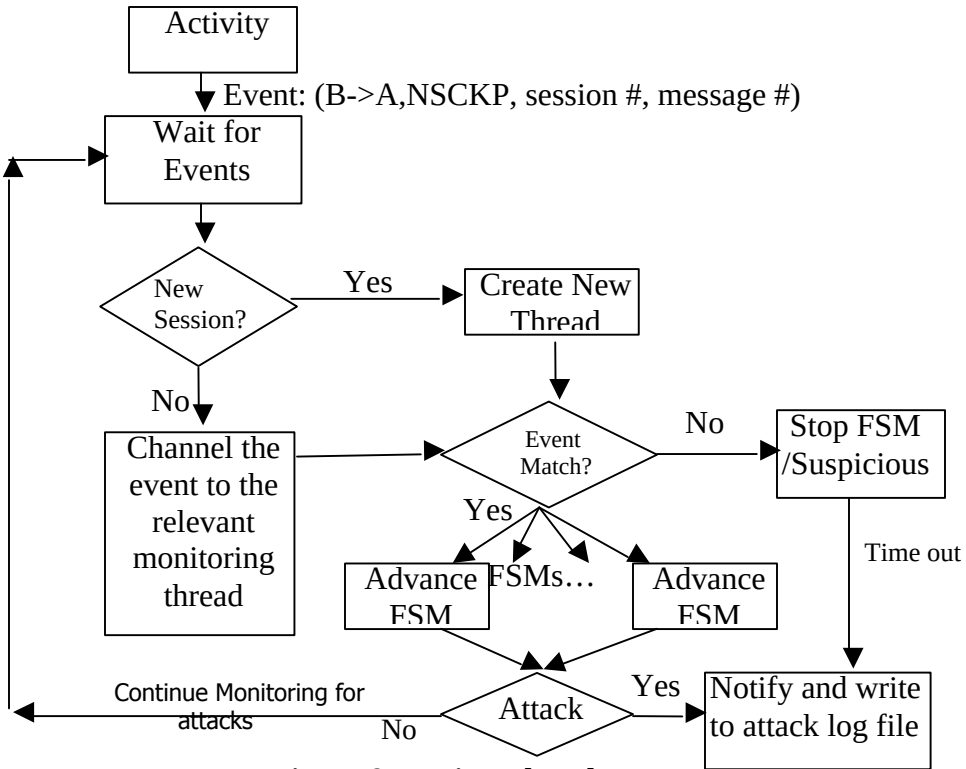

Figure 9: Design Flowchart.

5. Testing

Upon completion of each significant milestone, the IDE was tested to ensure that the product functioned correctly. We approached the testing from four standpoints:

(1) Detection of attacks against protocols in all three categories of single session, replay, and parallel session
(2) Detection of suspicious activity
(3) Effective operation in a highly concurrent environment
(4) Effective user interface.

We began our testing by addressing the ability of the IDE to detect different categories of attacks. The environment being monitored was systematically subjected to attacks of each of the three categories of single session, replay and parallel session. For the single session attacks we simulated those attacks on protocols which span over only a single session. The single session attack on the Needham and Schroeder Conventional Key Protocol (NSCKP) explained in detail in section 2.1, was one of the many attacks which were simulated. The IDE was correctly able to detect all such single session attacks.

To test the replay attacks, we simulated a correct run of protocols such as the Ottway-Rees Protocol (ORP) [9] and, within 10 seconds, we ran an attack session on the same protocol. In every instance, the IDE detected such replay attacks and classified them correctly.

To test our ability to detect parallel session attacks, we ran the parallel session attack on the Woo and Lam Authentication Protocol First (WLAPF), which was successfully detected by the IDE. We also ensured that protocol activity which may be considered abnormal or suspicious was detected by the IDE. Event sequences not corresponding to any attacks currently existing in the knowledge base or normal protocol runs were simulated for protocols. The IDE was correctly able to report such activity as unrecognizable suspicious activity on the basis of its inability to find a complete match for that particular signature in the Knowledge base. It is not always the case that protocol sessions successfully run to termination. Events get lost or the protocol session may stall. We simulated a protocol session in which there is abnormal termination before the current run has reached its completion In such cases the IDE thread monitoring this session times out after the TIMEOUT period and reports abnormal termination of the protocol.

It was important to ensure that the IDE is able to function correctly under a highly concurrent environment. *Sixty* concurrent sessions of different security protocols were simulated. These included attack sessions as well as correct sessions. Specifically, five distinct protocols were executed. A total of one hundred seventy principals were concurrently executing within the enclave. Out of the sixty protocol sessions, forty sessions were attack sessions and twenty sessions were normal protocol sessions. The IDE was able to correctly detect attacks and report them to the Graphical User Interface.

The Graphical User Interface is an integral part of our research implementation. This GUI allows the user to have an overall detailed view of all the attacks that took place within the environment over any given period of time. After each attack is detected, the IDE writes the detailed attack report to an attack log file. This attack report file is used by the GUI to provide the user with customized attack reports. We tested the functionality of the GUI after each simulated attack was detected to ensure that the attack has been logged and its details are displayed by the GUI. Moreover, we ensured that on providing inputs to the GUI it will only display the attack reports for specific protocols over a specific duration of time.

Based on the results obtained from the numerous tests performed on the IDE we can say that the IDE interfaces correctly and seamlessly with the activity monitor and the knowledge base. During the correct functioning of the IDE, there is no loss of events between the IDE and the monitor and hence no loss of functionality of one due to the other. Also, signatures can be added to the Knowledge to allow the IDE to detect the additional attacks on protocols.

Extensive testing on the IDE shows that the IDE fulfills its functionality successfully. The IDE can be used to detect different types of attacks on security protocols under environments of high concurrency. The Graphical User Interface also proved to be very reliable in order to increase the amount of information available to the user upon occurrence of such attacks.

6. Conclusion

We have designed and implemented a Knowledge-Based Intrusion Detection Engine to detect attacks on security protocols executing within a secure enclave. This research provides an necessary extra level of protection for encrypted exchanges.

Extensive research on the characteristics of security protocols enabled this detection methodology to achieve its desired functionality. Extracting the description of security protocols into sequences of events allows the IDE to detect attacks on those protocols.

The IDE will detect any attacks or suspicious activity on security protocols executed by valid principals operating within a secure enclave. The detection of the IDE compares protocol activity gathered by the Monitor against the attack signatures stored in the Knowledge base.

A Graphical User Interface (GUI) was also developed in order to facilitate an overall report of attacks that have been detected by the IDE, along with their occurrence times. Collectively, these components represent a fully functional Secure Enclave Attack Detection System.

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Appendix A
Notation

begin/end: Indicates that the signature starts/ends at this line.

PROTNAME: The abbreviated name of the protocol.

NSCKP – Needham and Schroeder Conventional Key Protocol

SIGNUM: A numeric value which indicates if the signature to follow is one of a correct run of the protocol or an attack.

NUM >= 0 indicates that the signature is an attack signature

NUM = -1 indicates that the signature is that of a normal run of the protocol.

ATTACKTYPE: Indicates the type of attack this signature represents. Possible values are:

S – Single session attack.

R – Replay attack.

P – Parallel session attack.

(See section 2.5 for a discussion about the above three attack types.)

INITIALSTATE/ PREVIOUSSTATE: Indicates the Finite State Machine (FSM) state before the event (send or receive) takes place. (ss: start state, s1:state 1, etc.)

NEXTSTATE: Indicates the Finite State Machine (FSM) state after the event (send or receive) has taken place. (s1:state 1, …. fs :final state)

→/← send or receive event.

principal: May be the single letter identifiers of principals viz. A, B, S etc.

msgNum: The message sequence number in the current run of the protocol.

sessNum: Unused field that may be used to add protocol session numbers if needed. This field will always be set to 1 in the current implementation.