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EAR: Early warning system for automatic detection of Internet-based cyberattacks
(Code G.S.R.T.: ΗΠΑ-022**)**

D3.1 “System Implementation”

Abstract: This document describes the implementation of the EAR Early Warning System for Internet-Based Cyber-Attacks. The deliverable is accompanied by a Compact Disc containing the relevant source code.

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FORTH	Coordinator	Greece
GA Tech	Principal Contractor	USA
FORTHnet	Principal Contractor	Greece

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Chapter 1

Introduction

In this document we discuss the implementation of the EAR Early Warning System for Internet-Based Cyber-Attacks. The deliverable is accompanied by a Compact Disc containing the relevant source code.

The system operates by passively monitoring network traffic and identifying strings that belong to worms and can be used as signatures for filtering worms. The main objectives of the system are (a) to detect previously unknown Internet worms, (b) to detect them in time, (c) to detect them without false positives, and (d) to detect them without human intervention.

The system operates by detecting substrings in network stream contents that are sent to more than a number of destination hosts within a certain period of time. A fundamental condition for the system to detect a worm is that the attack must contain an invariant string that can be used as a signature. A number of additional heuristics employed to boost performance and reduce false positives are described

During the course of this project several research articles were published. Efficient content-based fingerprinting of zero-day worms [1], published in the IEEE International Conference on Communications (ICC 2005), describes the repetitive-content-based worm detection heuristics. STRIDE: Polymorphic Sled Detection using Instruction Sequence Analysis [2], published in the 20th IFIP International Security Conference (IFIP/SEC 2005), discusses the detection of polymorphic attacks. Design and Implementation of a High-Performance Network Intrusion Prevention System [4] and Generating Realistic Workloads for Network Intrusion Detection Systems [3] , study mechanisms for enforcing the signatures generated by the worm detection system.

Chapter 2

Implementation

In this chapter we discuss the implementation of the EAR Early Warning System for Internet-Based Cyber-Attacks.

2.1 Overview

EAR was implemented on the GNU/Linux platform, but it is designed to be portable to other platforms, including Microsoft's.

EAR is composed of three major modules: a high-performance monitor, programmed in the low-level C language for performance, implements the main filter; generated alerts are processed by a second component, programmed in the high-level Python language, for flexibility; finally, the Graphical User Interface (GUI) is implemented in Python and GTK. Figure 2.1 shows a component diagram.

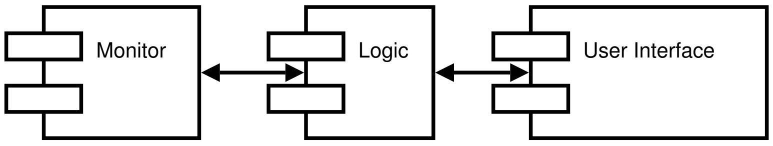


Figure 2.1: System components: a high-performance monitor, programmed in the low-level C language, implements the main filter; generated alerts are processed by a second component, programmed in the high-level Python language; finally, the Graphical User Interface (GUI) is implemented in Python and GTK.

In the following sections we describe each of the three components.

2.2 Monitor

The **Monitor** module is implemented in C, for performance reasons. It communicates with the **Logic** module by emitting records in ASCCI format on its standard output.

It has several submodules, which are illustrated in Figure 2.2, and are described below and in the following subsections.

main This module drives the rest of the system. It uses the **Options** module to parse the command-line arguments and the Libnids library to capture network traffic. It drives the **EAR** module, which is the API of the worm detection system.

options This module is responsible for parsing command line arguments, and is used by the **Main** module.

libnids This is a third-party library for TCP flow reconstruction.

ear This module implements and provides an API to the EAR worm detection algorithms. It uses the **Cache**, **Rabin**, and **Report** modules.

cache This module is responsible for the storage of substring fingerprints, and implements the appropriate data-structures.

rabin This module is responsible for computing substring fingerprints using the Rabin algorithm.

report This module is responsible for reporting results on the standard-output.

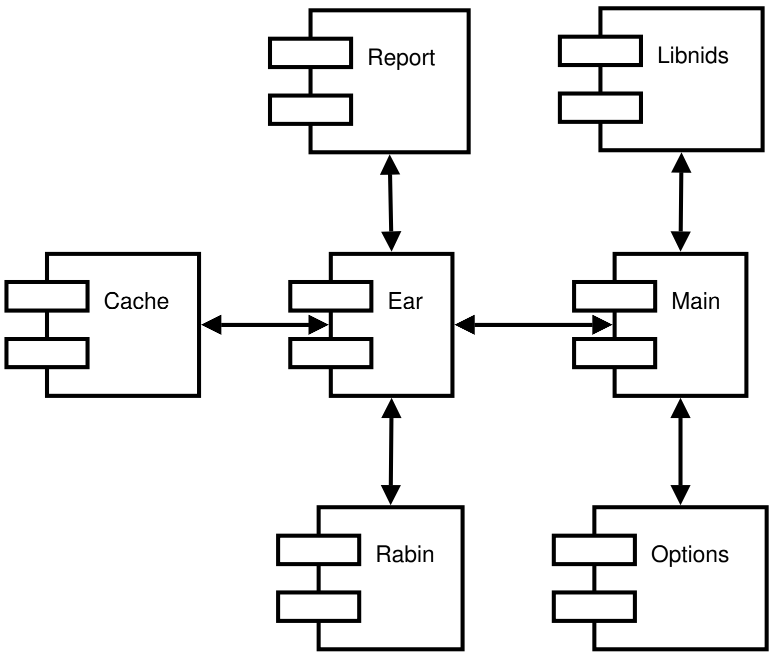


Figure 2.2: Monitor components

2.2.1 Source code layout

Here we describe the files that make up the source code of the **Monitor**.

cache.h and cache.c These files implement the substring cache (**Cache** module).

ear.h and ear.c These files contain the ear API (**EAR** module).

report.h and report.c These files handle reporting (**Report** module).

main.c Source file containing the main function and libnids calls (**Main** module).

options.h and options.c Handling of command-line arguments (**Options** module).

rabin.h and rabin.c Implementation of incremental Rabin fingerprints (**Rabin** module).

The following files contain helper routines possibly used by many modules.

config.h This file contains parameters tunable during compilation-time.

timer.h Inline timer manager functions (xtimeradd, xtimersub, xtimercmp)

cputime.h and cputime.c CPU time utilities.

hex.h and hex.c These files contain hex printing utility functions

2.2.2 Compilation-time parameters

The compile time parameters are configured in config.h which is included from other source files. They include:

MAX_DST This parameter controls the size of the table allocated for storing multiple destinations. The destinations threshold used for triggering an alert is tunable at runtime, but it cannot exceed this value.

VERBOSE This flag controls whether additional information is stored, such as the source addresses, ports, and offsets of the captured substrings. If this flag is not set, then the corresponding fields in the reported results are set to ”N/A”.

2.2.3 Substring cache

The substring cache is responsible for storing information about the fingerprints of encountered substrings. It is implemented in files cache.h and cache.c.

The substring cache is represented by the **struct cache** ADT, which is a container of cache entries, represented by **struct cache_entry**. **struct cache** supports the following operations:

struct cache *cache_create(int capacity, int threshold) Creates a cache that will store information about substrings for a number of msec given by the **capacity** argument. The **threshold** parameter corresponds to the distinct destinations threshold.

void cache_destroy(struct cache *cache) Frees the resources used by the cache's data structures.

int cache_usage(struct cache *cache) Returns the number of substrings currently tracked by the cache.

struct cache_entry *cache_entry_create(struct cache *cache, u_int32_t hash) Create and returns a cache entry initialized with the given hash, clean flags, destination count of zero and set expiration time

struct cache_entry *cache_entry_lookup(struct cache *cache, u_int32_t hash) Looks up a cache entry by its substring fingerprint.

void cache_touch(struct cache *cache, struct cache_entry *cache_entry) Renews the expiration time of the given cache entry.

The current time is maintained using the timestamp of the last processed packet. This way the system works reliably with traces and a syscall is avoided. The **CURRENT_TIME** macro provides this information.

2.2.4 Cache entry

Each cache entry contains the 32-bit fingerprint of the corresponding substring, the time when the entry will expire, the distinct destination count, the destinations, and some flags. If the **VERBOSE** compile-time flag has been defined, the cache entry also contains the destination ports, the sources, the source ports, and the flow offsets of the substrings. The entry also contains a synonym_count field, used for hashing.

A single destination can be stored within the entry, but for more than one destinations, an additional table is allocated and used (**struct cache_dest**). So the cache entry also contains a pointer to the extra table, but this pointer could be allocated as a C union with the single destination stored within the entry, as the two variables are never used at the same time.

Each cache entry can have one or more of the following flags set:

CACHE_EMPTY The slot is unused.

CACHE_MULTIPLE_DST Substring has multiple destinations stored in extra table

CACHE_TRACK Substring should be tracked

CACHE_IGNORE Substring should be ignored

CACHE_PIN Substring should not be evicted

2.2.5 Hashing of cache entries

The cache entries are stored in a hashtable in the **struct cache** data structure.

The hashtable uses linear probing as a collision resolution scheme. To determine whether a slot can be reused, the current time is compared against an entry's time of insertion. Therefore, old entries are implicitly evicted after a time out.

More specificaly, a slot can be used if it is empty (the CACHE_EMPTY flag is set) or it has been expired. A entry is considered expired if it has been for long enough in the cache and the CACHE_PIN flag is not set.

The following hash statistics are maintained by cache_entry_lookup(), and printed in status reports:

hash_lookups The number of hashtable lookup operations.

hash_probes The number of probes (a lookup may require multiple probes in the event of collision).

hash_collisions The number of hash functions collisions.

2.2.6 EAR

The EAR module is the interface to the worm detection algorithms. It provides the following operations:

struct ear *ear_create(int span, int capacity, int dst_threshold, int stream_limit, uint32_t sampling_mask
Creates an instance of the monitor.

void ear_process(struct ear *ear, struct tcp_stream *a_tcp, char *data, int dsize, int offset, struct ear_flo
Process a chunk of data.

void ear_destroy(struct ear *ear) Destroys an instance of the monitor.

struct ear_flow *ear_flow_create(void) Creates a flow state object. The **ear_process()** function requires such an object for storing per flow state.

void ear_flow_destroy(struct ear_flow *) Destroys a flow state object.

The **ear_create()** function takes the following parameters:

span The substring size.

capacity The capacity of the cache in milliseconds.

dst_threshold The distinct destination threshold.

stream_limit The size of the portion of the flows that is processed.

mask The substring sampling mask. The system will ignore substrings whose fingerprints do not match the sampling mask.

skip_nul Whether to process substrings that contain ASCII nul characters.

The **ear_process()** function accepts a data buffer and a stream descriptor (**struct tcp_stream**, defined by libnids). It maintains statistics (bytes processed, samples memory usage) and computes incremental rabin fingerprints.

Individual fingerprints are further processed by the **process_hash()** function, which performs deterministic sampling, and then looks up the substring in the cache. If the hash is found, and it is not ignored (**CACHE_IGNORE** flag is not set), and the current destination has not been recorded in the cache entry, then it records the current destination and renews the expiration time of the entry. It also allocates and populates a table for storing multiple destinations if that has not been done already.

If the distinct destinations threshold has been reached, the **trigger()** function is called, which involes the **Report** module.

If the hash is not found in the cache, a cache entry is created and the substring destination is recorded.

If the VERBOSE compile-time option is set, additional information is recorded together with the destination.

2.2.7 Main

The main function creates a struct ear instance using the command line arguments parsed by the options module, and then registers a tcp callback with libnids and invokes libnids. The callback instructs libnids to collect only traffic sent to TCP servers. It invokes **ear_process()** for each data portion captures and instructs libnids to buffer $substringlength - 1$ bytes.

The options module provides a function to parse command line arguments, and exports variables with option values.

2.2.8 Rabin Fingerprints

To compute rabin fingerprints, we use a state common for all flows and a separate hash for each flow. The common state includes a lookup table and the shift out multiplier. The hash has to be initialized to zero. The following functions are provided:

rabin_t *rabin_create(int span_size) Creates the common state.

SHIFT_IN(rabin, hash, c) Adds a byte to a hash.

SHIFT_OUT(rabin, hash, c) Removes a byte from the hash.

2.2.9 Hex printing

The following utility functions are used to print binary data:

void hex_print(unsigned char *buf, int buflen, char *label) Print a chunk of data in hex to standard output and prepend it with a label.

void hex_print_f(FILE *f, unsigned char *buf, int buflen, char *label) Print a chunk of data in hex to given file and prepend it with a label.

int hex_parse(char *hex, unsigned char **bufp) Parse hex representation, return the length of the resulting data, and set pointer argument to a buffer with the data, allocated with **malloc()**.

2.2.10 Flow reconstruction

For flow reconstruction we use the libnids library which emulates the IP stack of Linux 2.0.x. Libnids offers IP defragmentation, TCP stream assembly and TCP port scan detection. The library is available from `http://libnids.sourceforge.net/`.

2.2.11 Excluding traffic

Libnids is instructed to process only traffic sent from clients to servers. In addition, from each flow only the first X bytes are processed. X is configurable, and typical values include 1K, 10K, 100K.

2.2.12 Reporting

The **Report** module provides the following functions used for reporting alerts, attacks, and statistics:

void report_alert(struct ear *ear, struct ear_result *result, struct cache_entry *cache_entry)

void report_attack(struct ear *ear, struct tcp_stream *a_tcp)

void report_stats(struct ear *ear)

2.2.13 Interface with higher-level modules

The interface between the monitor and the high-level components is ASCII-based. Messages are headed by a keyword followed by message-dependend contents. An alert message is denoted by the ALERT keyword, followed by a line with space delimited data items including the hash of the string that triggered the alert. Figure 2.5 shows a sample alert message.

```
ALERT
0x0547c0f4 1115638576.348604 false
78 3f 6c 69 64 3d 31 30 33 33 0d 0a 41 63 63 65 x?lid=1033..Acce
70 74 2d 4c 61 6e 67 75 61 67 65 3a 20 65 6c 0d pt-Language: el.
0a 41 63 63 65 70 74 2d 45 6e 63 6f 64 69 6e 67 .Accept-Encoding
3a 20 67 7a 69 70 2c 20 64 65 66 6c 61 74 65 0d : gzip, deflate.
0a 55 73 65 72 2d 41 67 65 6e 74 3a 20 4d 6f 7a .User-Agent: Moz
69 6c 6c 61 2f 34 2e 30 20 28 63 6f 6d 70 61 74 illa/4.0 (compat
69 62 6c 65                                     ible

139.91.183.21:1558 -> 12.130.60.5:80 offset: 307 timestamp: 1115638574.068360
139.91.183.21:1559 -> 65.54.211.93:80 offset: 251 timestamp: 1115638574.651066
139.91.183.21:1560 -> 207.68.179.219:80 offset: 236 timestamp: 1115638575.258834
139.91.183.21:1561 -> 65.54.179.204:80 offset: 248 timestamp: 1115638575.820024
139.91.183.21:1562 -> 65.54.179.201:80 offset: 248 timestamp: 1115638576.348604
```

Figure 2.3: Sample alert message.

```
STATUS
timestamp: 1070367006.011381
elapsed_wallclock_time: 63.134552
elapsed_cpu_time: 0.69
bytes_processed: 336671
max_usage: 614
avg_usage: 146.909091
cur_usage: 267
hash_lookups: 7272
hash_probes: 851
avg_hash_access: 0.117024
avg_hash_collision: 0.479373
```

Figure 2.4: Sample status message.

2.2.14 Act on Alerts

The functionality of acting on an alert is implemented by passing the alert message to a shell script. The script can process and forward the alert to external mechanisms, such as content filtering firewalls.

2.2.15 Remote Monitor

It is often the case that the **Monitor** must run on a remote server, but the **GUI** must run on an operator's computer. This functionality is supporting by using the **rear.sh** script instead of the actual monitor executable, which uses SSH to control a remote ear monitor instance.

2.2.16 Monitor Command-Line Syntax

The **Monitor** module produces a single executable called **ear**, that has the following command-line syntax:

```
Usage: ear OPTIONS [ filter expression ]
  -f, --offset=INT         flow offset threshold
  -p, --period=INT         period threshold
  -s, --select-mask=HEX    select mask
  -t, --targets=INT        targets threshold
  -l, --length=INT         substring length
  --skip-nul               skip strings with ASCII nul characters
  -n, --home-net=NET       network under protection
  -r file                  read packets from file
  -i interface             capture packets from interface
  -h, --help               display this help message
```

Figure 2.5: Monitor command-line syntax.

2.3 Logic

The alerts that are issued by the high-performance monitor, are futher processed by the **Logic** module. The following checks are currently supported:

Sources threshold The number of distinct sources appearing to spread the attack is required to be above a threshold.

Contagion threshold Contagion is the number of targets that also appear to act as sources, further propagating the attack. It is required that this number is above a threshold. Figure 2.6 illustrates this.

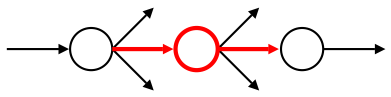


Figure 2.6: Contagion: The worm appears in both incoming and outgoing traffic of a host.

The polymorphic sled detection algorithm (STRIDE) that has been designed in the context of the EAR project, will be eventually integrated here as well.

2.4 Graphical User Interface

We have provided a Graphical User Interface (GUI) for the management of the system by operators. The GUI allows the configuration of the monitor's runtime parameters, and provides a listing of issued alerts.

The main screen of the GUI shows the alerts issued so far. By selecting an alert it is possible to inspect the offending substring, as shown in Figure 2.7. It is also possible to inspect the flows that carried the substring and the offset of the substring withing each flow, as shown in Figure 2.8.

The statistics maintained by the monitor can also be inspected, as shown in Figure 2.9. The following statistics are provided:

Last updated The time that the statistics were last updated.

Current usage The number of currently tracked substrings.

Maximum usage The maximum memory usage.

Average usage The average memory usage.

Utilization The CPU time/ Wallclock time ratio over the last interval.

The monitor parameters can be configured by selecting the EAR Configuration menu entry from the Tools menu. It is possible to configure the following parameters, as shown in Figure2.10:

Min. Targets A worm must have target at least this many targets.

Min. Length A worm must have at least this length.

Max. Offset A worm must occur at most at this offset within its flow.

Max. Period A worm must occur with a period at most equal to this value.

Filter A filter that is applied on network traffic before it is processed. It can be usefull to exclude certain hosts.

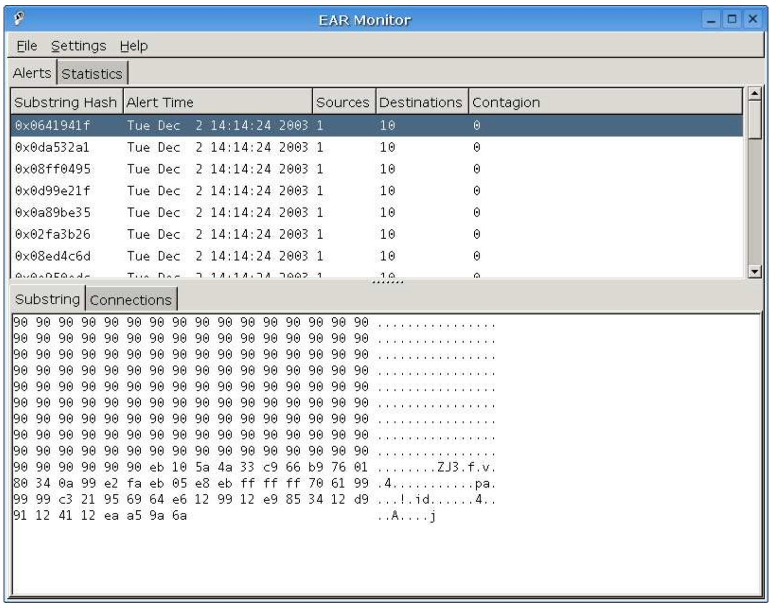
Tracking Mask This value control the deterministic sampling rate.

Skip substrings with ASCII nul Whether to process substring with the ASCII nul character.

Min. Sources A worm must be spread by at least this many sources.

Min. Contagion The value of the contagion threshold.

Home Net The network under protection.



Substring Hash	Alert Time	Sources	Destinations	Contagion
0x0641941f	Tue Dec 2 14:14:24 2003	1	10	0
0x0da532a1	Tue Dec 2 14:14:24 2003	1	10	0
0x08ff0495	Tue Dec 2 14:14:24 2003	1	10	0
0x0d99e21f	Tue Dec 2 14:14:24 2003	1	10	0
0x0a89be35	Tue Dec 2 14:14:24 2003	1	10	0
0x02fa3b26	Tue Dec 2 14:14:24 2003	1	10	0
0x08ed4c6d	Tue Dec 2 14:14:24 2003	1	10	0

```
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 ................
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 ................
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 ................
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 ................
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90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 ................
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 ................
90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 ................
90 90 90 90 90 90 eb 10 5a 4a 33 c9 66 b9 76 01 ........ZJ3.f.v.
80 34 0a 99 e2 fa eb 05 e8 eb ff ff ff 70 61 99 .4...........pa.
99 99 c3 21 95 69 64 e6 12 99 12 e9 85 34 12 d9 ...!.id......4..
91 12 41 12 ea a5 9a 6a                         ..A....j
```
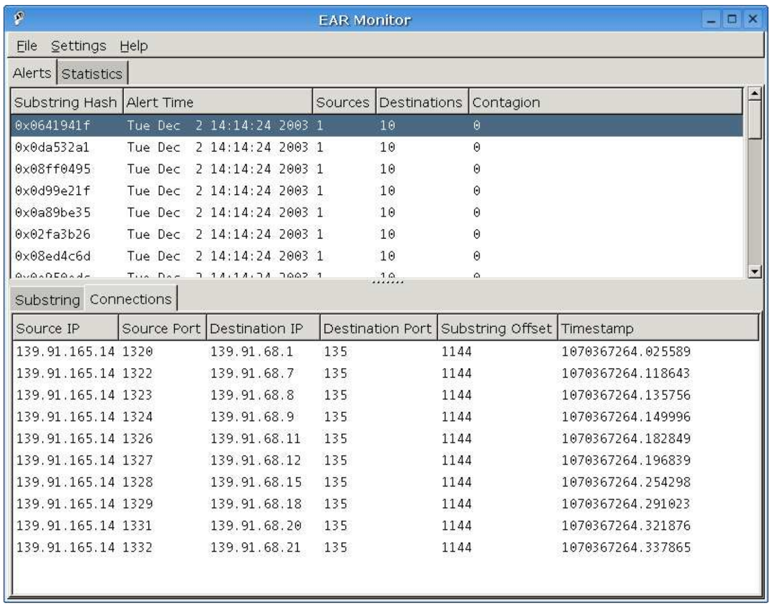

Figure 2.7: Issued alerts and inspection of the detected worm substring.



Substring Hash	Alert Time	Sources	Destinations	Contagion
0x0641941f	Tue Dec 2 14:14:24 2003	1	10	0
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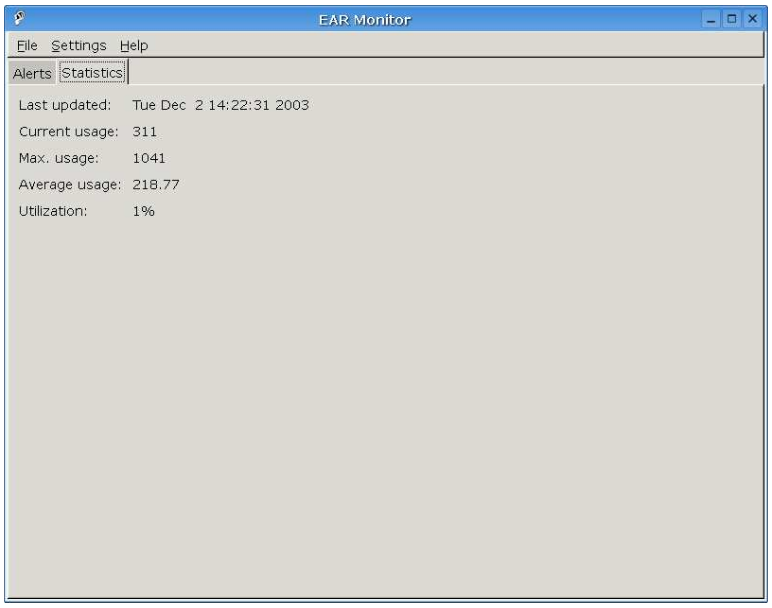
0x08ff0495	Tue Dec 2 14:14:24 2003	1	10	0
0x0d99e21f	Tue Dec 2 14:14:24 2003	1	10	0
0x0a89be35	Tue Dec 2 14:14:24 2003	1	10	0
0x02fa3b26	Tue Dec 2 14:14:24 2003	1	10	0
0x08ed4c6d	Tue Dec 2 14:14:24 2003	1	10	0

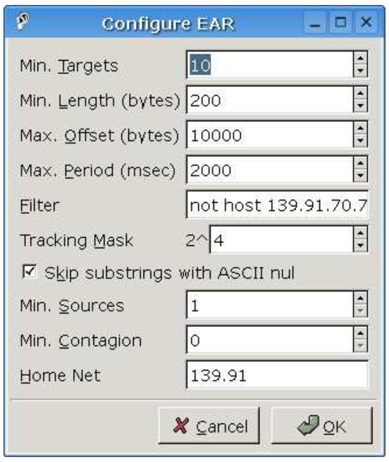
Source IP	Source Port	Destination IP	Destination Port	Substring Offset	Timestamp
139.91.165.14	1320	139.91.68.1	135	1144	1070367264.025589
139.91.165.14	1322	139.91.68.7	135	1144	1070367264.118643
139.91.165.14	1323	139.91.68.8	135	1144	1070367264.135756
139.91.165.14	1324	139.91.68.9	135	1144	1070367264.149996
139.91.165.14	1326	139.91.68.11	135	1144	1070367264.182849
139.91.165.14	1327	139.91.68.12	135	1144	1070367264.196839
139.91.165.14	1328	139.91.68.15	135	1144	1070367264.254298
139.91.165.14	1329	139.91.68.18	135	1144	1070367264.291023
139.91.165.14	1331	139.91.68.20	135	1144	1070367264.321876
139.91.165.14	1332	139.91.68.21	135	1144	1070367264.337865

Figure 2.8: Issued alerts and inspection of the flows that carried the offending substring.



```
Last updated:     Tue Dec  2 14:22:31 2003
Current usage:    311
Max. usage:       1041
Average usage:    218.77
Utilization:      1%
```

Figure 2.9: The EAR statistics panel.



```
Min. Targets            10
Min. Length (bytes)     200
Max. Offset (bytes)     10000
Max. Period (msec)      2000
Filter                  not host 139.91.70.7
Tracking Mask           2^4
[✓] Skip substrings with ASCII nul
Min. Sources            1
Min. Contagion          0
Home Net                139.91
```

Figure 2.10: The EAR configuration dialog.

References

[1] P. Akritidis, K. Anagnostakis, and E. P. Markatos. Efficient content-based fingerprinting of zero-day worms. In *Proceedings of the IEEE International Conference on Communications (ICC 2005)*, May 2005.

[2] P. Akritidis, E. P. Markatos, M. Polychronakis, and K. Anagnostakis. STRIDE: Plymorphic sled detection through instruction sequence analysis. In *Proceedings of the 20th IFIP International Information Security Conference (IFIP/SEC 2005)*, June 2005.

[3] E. P. Markatos S. Antonatos, K. G. Anagnostakis. Generating realistic workloads for network intrusion detection systems. In *Proceedings of the Fourth International Workshop on Software and Performance (WOSP2004)*, January 2004.

[4] Kostas Xinidis, Kostas D. Anagnostakis, and Evangelos P. Markatos. Design and implementation of a high-performance network intrusion prevention system. In *Proceedings of the 20th IFIP International Information Security Conference (IFIP/SEC 2005)*, June 2005.