The CoralReef software suite as a tool for system and network administrators

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Abstract— **Until now, system administrators have lacked a flexible real-time network traffic flow monitoring package. Such a package must provide a wide range of services but remain flexible enough for rapid in-house customization. Existing passive data collection tools are typically narrow in scope, designed for specific tasks from packet capture (tcpdump [1]) to accounting (NeTraMet [2]). In response, CAIDA has created the `CoralReef` suite designed to provide network administrators and researchers with a consistent interface for a wide range of network analysis applications, from raw capture to flows analysis to real-time report generation. `CoralReef` provides a convenient set of passive data tools for a diverse audience.**

`CoralReef` is a package of device drivers, libraries, classes, and applications. We briefly outline the architecture and provide relevant case studies and examples of `CoralReef`'s use as applied to real-world networking situations. We will show how `CoralReef` is a powerful, extensible, and convenient package for network monitoring and reporting.

I. Introduction

With the growth in traffic volume and increasing diversity of applications on the Internet, understanding and managing networks has become increasingly difficult and important. To this end we have created the `CoralReef` passive traffic monitoring suite, which allows network users, administrators, and researchers to measure and analyze network traffic. The `CoralReef` software suite is a comprehensive collection of tools devloped by CAIDA to collect, store, and analyze traffic data. `CoralReef` can be deployed on a dedicated monitor host using data capture cards that tap a fiber optic link, or on virtually any UNIX system without special hardware using `libpcap` interfaces. `CoralReef` software handles everything from the low level details of cell and packet capture to the production of high level HTML reports in near real-time. Network and system administrators can use the `CoralReef` suite to monitor and interpret a wide range of observed network behavior.

`CoralReef` evolved from OCXmon monitors, developed jointly by MCI and NLANR [3][4]. The OCXmon monitors ran on MS-DOS, could only monitor ATM links, and provided only basic cell capture (in device-dependent format) and limited flow summary capability. `CoralReef` runs on UNIX, and supports device independent access to network data from OCXmon hardware, native OS network interfaces, and trace files; programming APIs; a variety of bundled analysis applications; and greater flexibility in remote access and administration. `CoralReef` is developed and tested under FreeBSD, Linux, and Solaris, although specialized hardware drivers are not available for all operating systems. `CoralReef` has two releases, a "public" non-commercial use version and a version available only to CAIDA members. Both versions implement the same set of libraries and APIs, but the members-only version incorporates performance and operational enhancements geared toward CAIDA members. What makes `CoralReef` unique is that it supports a large number of features at many layers, and provides APIs and hooks at every layer, making it easier for anyone to apply it in unanticipated ways and develop new applications with minimum duplicated effort.

Because commercial software tools lack sufficient flexibility, network administrators often develop their own network analysis tools, typically based on `tcpdump` [1]. A part of `tcpdump` is the library `libpcap` [5] which provides a standard way to access IP data and `BPF` (Berkeley Packet Filter) devices. The `tcpdump` tool also has a packet data file format (`pcap`) which has become a *de facto* industry standard. Several network analyzer tools are built on top of `libpcap`, such as the Ethereal [6] protocol analyzer and `NeTraMet` (RFC 2722 [7] and RFC 2724 [8]), which are geared toward long term collection for metering and billing. Other network analysis tools include the MEHARI [9] ATM/IP analysis system; Narus [10] for long-term workload and billing; the DAG ATM/POS capture cards and software [11] by the WAND group at the University of Waikato, New Zealand; Clevertool's netboy [12]; Network Associates Sniffer Pro [13]; and NIKSUN's NetVCR [14].

This paper describes version 3.5.0 of the `CoralReef` suite. Section II presents an overview of `CoralReef` libraries, applications, and their relationships. In section III we describe how to set up a `CoralReef` monitor. Section IV contains multiple examples of using `CoralReef` to answer realistic networking questions. Section V describes the continuous HTML report generation capabilities of `CoralReef`. Finally, we conclude the paper in section VI with a summary.

II. An overview of the `CoralReef` software suite

`CoralReef` is a package of libraries, device drivers, classes, and applications written in, and for use with, several programming languages. The overall architecture and programming interfaces are described in a separate paper[15] and are not covered here. Figure 1 shows an overview of the relationships between `CoralReef` applications. Detailed descriptions of the software tools can be found at the `CoralReef` web site (`http://www.caida.org/tools/measurement/coralreef/`).

Most `CoralReef` applications fall into one of two categories: those with names beginning with "`crl_`", which operate on raw packet data; and those with names beginning with "`t2_`", which operate on aggregated flow data. We will refer to these groups of applications as `crl_*` and `t2_*`, respectively. Sources of raw data include custom Coral drivers for special collection cards, the `libpcap` library for commodity network interfaces, and trace files generated by `crl_trace`, `tcpdump`, or other software.

A. Raw traffic applications

All of the `crl_*` applications take a common set of command line and configuration options. These options include stopping after a specified number of packets or ATM cells or after a specified time duration; link specific parameters; filtering by ATM virtual channels; number of bytes to capture from each packet; and debugging level. Additionally, applications that operate on packets can filter their input with BPF (`tcpdump`) filter expressions. Applications that operate at regular time intervals have a common syntax for

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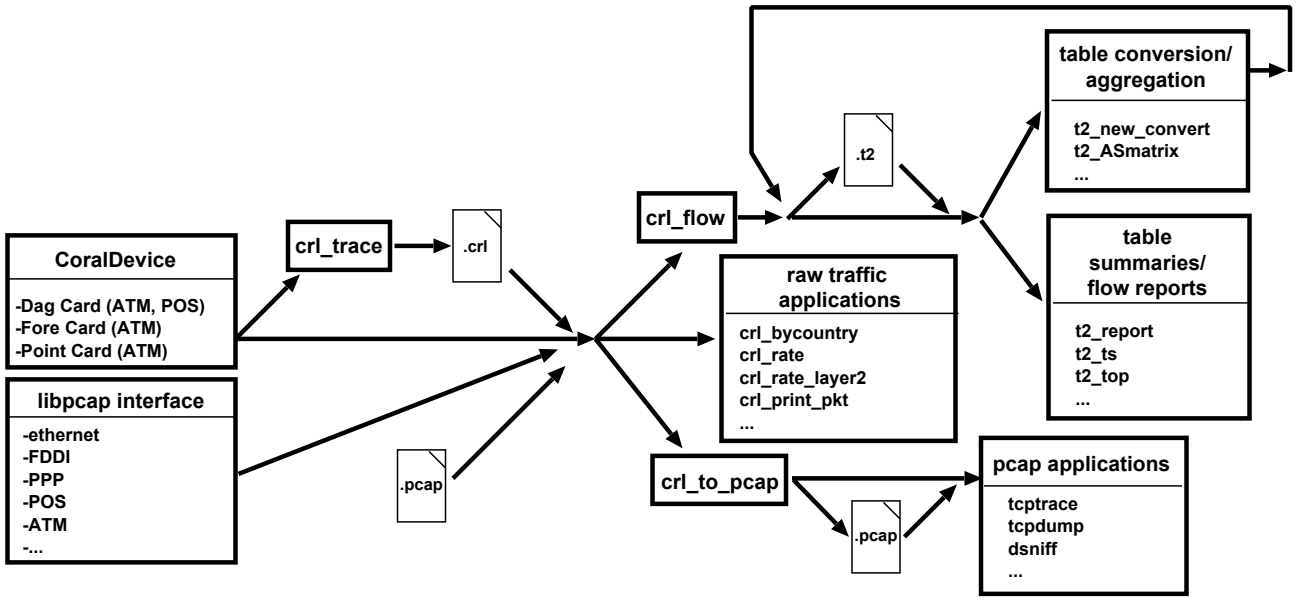

Fig. 1. Overview of CoralReef Applications

specifying the interval size.
Pure utilities:
• `crl_trace` — captures network traffic to a `.crl` trace file
• `crl_info` — reports hardware and link configuration details of a trace file
• `crl_time` — outputs timestamps and inter-arrival time information for packets or ATM cells
• `crl_encode` — encodes the IP addresses in a `.crl` file to protect privacy
• `crl_to_*` — captures network traffic or converts trace files to other file formats
Simple tools:
• `crl_print` — prints headers and payloads of ATM cells
• `crl_print_pkt` — prints multiple layers of protocol headers and payloads of packets
• `crl_rate_layer2` — at regular time intervals, outputs cell count and bit rate for each ATM channel
• `crl_rate` — at regular time intervals, outputs IPv4 and IPv6 packet and byte counts, and counts of non-IP packets
Static Reports:
• `crl_hist` — reports packet and byte counts by IP length and protocol, port summary matrices for TCP and UDP, fragment counts by protocol, packet length histograms for the entire trace and for a list of applications, and the top 10 source and destination port numbers seen for TCP and UDP traffic
• `crl_bycountry` — reports the amount of traffic flowing to and from networks, and between networks, ASes, and countries
Specialized Utilities:
• `crl_portmap` — captures all packets from any hosts that connect to another host's portmap port
• `crl_flow` — at regular time intervals, aggregates packet data into flows by source and destination IP addresses, protocol, and source and destination ports

B. Traffic flow applications

The `t2_*` applications operate on tables generated by `crl_flow` or other `t2_*` applications, with the same time intervals.
• `t2_report` — generates HTML summary reports (described in Section V)
• `t2_ASmatrix` — with a routing table (described in Section V), aggregates by source and destination Autonomous System numbers and source and destination ports
• `t2_top` — sorts a table by packets, bytes, or flows, and displays the top N entries
• `t2_rate` — outputs counts of IP packets, bytes, and flows
• `t2_convert` — aggregates a table by specified keys

C. Other applications

• `crl_to_pcap` — converts Coral traces or live data to pcap format for use with existing `libpcap` tools
• `parse_bgp_dump` — converts Cisco router "`sho ip bgp`" output to the routing table format used by `t2_ASmatrix`, `t2_report`, and `crl_bycountry`
• `parse_bgp_mrtd` — converts MRTd[16] output to the routing table format used by `t2_ASmatrix`, `t2_report`, and `crl_bycountry`

D. Libraries

• `libcoral` — reads trace files and live network interfaces, and provides common functionality for all `crl_*` applications
• `Coral.pm` — perl interface to `libcoral`
• `ASFinder` — maps IP addresses to AS numbers and network prefixes
• `AppPorts` — maps protocols and port numbers to application names
• `NetGeoClient` — maps IP addresses and AS numbers to geographic locations
• `Tables` — manipulating and processing the tables used by the `t2_*` applications

III. Using `CoralReef` in an operational setting

`CoralReef` can only monitor traffic that is visible to a network interface. If the network you want to monitor is a shared medium such as non-switched Ethernet or FDDI, any interface on that network is sufficient. Monitoring a link between routers or on a switched network requires directing traffic into additional dedicated interfaces, which may be either standard interfaces read via `libpcap`, or special hardware accessed through Coral drivers. A link can be tapped either with a physical splitter (Figure 2a) or by configuring a span or mirror port on the appropriate switch or router (Figure 2b). Note that tapping both directions of a link with splitters requires a dedicated interface for each direction.

The hardware needed depends on the utilization of the links being monitored and the amount of aggregation desired. For straighforward packet traces, the main constraint is usually disk performance and capacity; we recommend ultra-wide SCSI rather than an IDE drive. For flow collection and analysis, memory and CPU speed are more important. Individual applications in a `CoralReef` pipeline can run

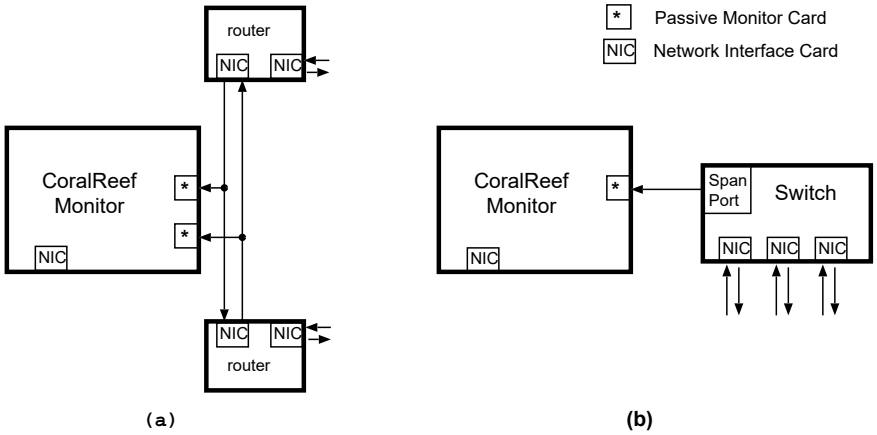

Fig. 2. Examples of tapping a link

on separate machines to distribute the load. A common example of this is to run `crl_flow` on the monitor machine and `t2_report` on a different machine.

IV. Examples

In this section, we briefly present examples of using `CoralReef` in an operational setting. A more complete outline of uses can be found in the `CoralReef` documentation or the user community mailing list.

Several `-C` options are common to all `crl_*` applications. In the following examples, we use `-Ci=`*time* to specify the repeated interval at which the application processes data and outputs results, and `-C'filter` *expression'* to specify a BPF filter expression that selects the packets to be measured. To stop the applications after a specific duration, you would use the `-Cd=`*time* option. The `crl_*` applications can read traffic from a variety of sources; in these examples, the data source is "`if:fxp0`", a native Ethernet interface (fxp0) read via `libpcap`.

IP addresses in the sample outputs have been encoded for privacy. Some output has been edited to better fit the page and for illustrative value.

Timestamps in application output are printed in UNIX timestamp format.

A. Using `crl_rate` to check utilization of subinterfaces

The `crl_rate` application counts packets and bytes on interfaces and subinterfaces at regular intervals. On Ethernet interfaces, subinterfaces are IEEE 802.1Q VLANs. On ATM interfaces, virtual channels are reported as subinterfaces. Other types of interfaces do not have subinterfaces.

A.1 Goal: continuously measure traffic on a link, in packets and bytes.

Command line:

```
crl_rate -Ci=10 if:fxp0
```

Sample output: See listing 1.
Explanation: This output shows that there was traffic on 7 VLANs on Ethernet interface fxp0 in a 10 second period. A similar table would be printed every 10 seconds. The "non_ip" column counts packets of protocols like ARP, AppleTalk, and IPX. The total IPv4 traffic on this link in 10 seconds was about 99.5 Megabytes, or 79.6 Megabits per second. Note that the bytes counted are those in layer 3 and above; bytes in lower layer encapsulations like Ethernet and ATM are not counted.

This simple example is a good way to test your `CoralReef` monitor and software setup to verify that the output matches your expectations.

There was only one interface in this example, labeled 0 in the output, but it is possible to monitor multiple interfaces simultaneously.

A.2 Goal: find out how much KaZaA traffic is on your link.

Command line:

```
crl_rate -s -Ci=300 -C'filter port 1214' if:fxp0
```

Sample output: See listing 2.
Explanation: In this example, we were not interested in subinterfaces (VLANs), so we used the `-s` option to omit them. Because of high variability in these kinds of measurements, larger intervals are usually more useful. In this example, we used a 5 minute interval. To limit the measured traffic to KaZaA[17], we used a BPF filter to match only traffic to or from KaZaA's well-known port (1214). In the first of the two intervals shown, there were about 1.33 Gigabytes of KaZaA traffic, or 35.5 Megabits per second.

B. Using `crl_flow` to collect flow data

The `crl_flow` application summarizes data by IP flows. In this context, a flow is identified by the 5-tuple of source address (`src`), destination address (`dst`), protocol (`proto`), source port (`sport`), and destination port (`dport`). A flow is unidirectional, so there will be one flow for each of the two directions of a network connection, with sources and destinations swapped.

The definition of flow termination can be chosen by a command line option. The `-I` option specifies that flows terminate at the end of each interval, which is the most useful definition for this kind of continuous monitoring. Other definitions are typically more useful in offline analysis of historic data, as is often needed in research situations.

A table of these 5-tuples, along with counts of packets, bytes, and flows for each, is called a `Tuple_Table`. The "ok" column contains a 1 if `sport` and `dport` are meaningful for the protocol and were not truncated by capturing too few header bytes. Ports are meaningful for TCP, UDP, and ICMP (for ICMP, the `sport` and `dport` columns actually contain ICMP type and code, respectively).

B.1 Goal: continuously collect data on link use, summarized by hosts, protocols, and ports.

Command line:

```
crl_flow -I -h -Ci=10 if:fxp0
```

Sample output: See listing 3.
Explanation:

The `-h` option tells `crl_flow` to print in human-readable format. With no formatting option, `crl_flow` prints a tab-separated format more suitable for input to other scripts. Additionally, `crl_flow -b` outputs a binary format that is readable by the `t2_*` applications, more efficiently than either of the text formats.

The output shown here has been edited to fit the page. Real output would have a `Tuple_Table` for each interface and

```
# time 1001975450.054545 (10.000000), packets lost: 0
# if[subif] v4pkts    v4bytes v6pkts v6bytes non_ip v4pkts/s v4bits/s v6pkts/s v6bits/s
0[135]           1         40      0       0      0     0.10   32.00     0.00     0.00
0[110]        2269    2536140      0       0      0    22.69    2.03M    0.00     0.00
0[169]        9397    3761410      0       0      0    93.97    3.01M    0.00     0.00
0[170]       40097   20640233      0       0      0   400.97   16.51M    0.00     0.00
0[130]        5659    1921566      0       0      0    56.59    1.54M    0.00     0.00
0[131]      118429   70553909      0       0      0     1.18k  56.44M    0.00     0.00
0[108]        1774      92307      0       0      0    17.74   73.85k    0.00     0.00
0   TOTAL   177626   99505605      0       0      0     1.78k  79.60M    0.00     0.00
...
```

Listing 1
`crl_rate` output: traffic on a link.

```
# time 1001977053.013038 (300.000000), packets lost: 0
# if[subif] v4pkts    v4bytes v6pkts v6bytes non_ip v4pkts/s v4bits/s v6pkts/s v6bits/s
0   TOTAL  1999660 1330861215      0       0      0    6.67k   35.49M    0.00      0.00

# time 1001977353.013038 (300.000000), packets lost: 0
# if[subif] v4pkts    v4bytes v6pkts v6bytes non_ip v4pkts/s v4bits/s v6pkts/s v6bits/s
0   TOTAL  1956821 1215396030      0       0      0    6.52k   32.41M    0.00      0.00
...
```

Listing 2
`crl_rate` output: KaZaA traffic.

```
# crl_flow output version: 1.0 (pretty format)

# begin trace interval: 1001981488.441461
# trace interval duration: 10.000000 s
# Layer 2 PDUs dropped: 0
# IP: 101.8403 Mbit/s
# Non-IP: 0.0000 pkts/s
# Table IDs: 0[131], 0[108], 0[130], 0[110], 0[170], 0[169]

...
# begin Tuple Table ID: 0[131]
# expired flows
#src            dst          proto ok sport dport     pkts     bytes  flows
0.1.0.8         1.82.0.1        17  1    53    53        2       497      1
0.1.0.14        0.44.0.1         6  1    80  2223        4       646      1
0.3.0.148       1.95.0.1         6  1  1214 62772      125    187008      1
0.1.1.93        0.71.0.6         6  1 49200    80        3       565      1
0.1.1.93        0.71.0.6         6  1 49199    80        5       647      1
0.1.1.93        0.71.0.6         6  1 49198    80        5       647      1
0.1.1.93        0.71.0.6         6  1 49196    80        6       708      1
0.1.2.59        11.88.0.1        6  1 51643    80        6       817      1
...
# end of text table
...
# end trace interval
...
```

Listing 3
`crl_flow` output: Continuous data collection.

subinterface, repeated every 10 seconds; an interface or subinterface summary preceding each table; and two additional columns in each table showing the first and last packet timestamp observed within each flow. Remember that IP addresses have been encoded for privacy.

The sample output shows one UDP DNS flow (protocol 17, port 53), one HTTP flow from a web server to a client, several HTTP flows from clients to web servers, and one large flow on TCP port 1214 (KaZaA).

C. Using t2_* to monitor utilization and flows

Although crl_flow does some aggregation, its output is still typically too voluminous to be directly useful. The t2_* applications further aggregate or filter the output of crl_flow for more specific needs. In particular, t2_rate -s outputs a single line per interval summarizing the packets, bytes, and flows observed. t2_top sorts table entries by packets, bytes, or flows, and prints only the top *N*.

Most t2_* applications accept different table types as input, and can identify the table type of their input automatically. crl_flow outputs a Tuple_Table; we will introduce other table types in later examples.

C.1 Goal: continuously measure traffic on a link, in packets, bytes, and flows.

Command line:

```
crl_flow -I -b -Ci=10 if:fxp0 | t2_rate -s
```

Sample output: See listing 4.
Explanation: In this example, t2_rate prints a line for every 10 second interval, the beginning of which is indicated in the first column (time). The next three columns show the total number of packets, bytes, and flows observed during the interval. The "entries" column shows the number of table entries, which, in the case of a Tuple_Table, is equal to the number of flows. The last three columns show the average number of packets, bytes, and flows per second during the interval.

The -b option to crl_flow tells it to output in efficient binary format readable by t2_* applications. The use of this option can drastically improve performance, and is recommended when the intermediate output does not need to be read by a human.

C.2 Goal: continuously find flows consuming the most bandwidth on a link.

Command line:

```
crl_flow -I -b -Ci=10 if:fxp0 | t2_top -Sb -n5
```

Sample output: See listing 5.
Explanation: The "KEYS" columns are the same as the keys in the input table, which in this example is a Tuple_Table from crl_flow. The -Sp, -Sb, or -Sf option tells t2_top to sort by packets, bytes, or flows, and the -n option specifies how many entries to print.

D. Using t2_* to find hosts generating the most traffic

Often we want to aggregate the flows of a Tuple_Table by a subset of its keys. For example, we may want to count the bytes sent between pairs of hosts, regardless of their protocols and ports; or, all the packets sent from a particular TCP port, no matter what host sent or received them.

In addition to the Tuple_Table, CoralReef has other table types defined by different sets of keys. For example, the keys of an IP_Matrix are source and destination IP addresses, and the key of an IP_Table is a single IP address. Table 1 shows all tables and their keys.

The t2_convert application converts one table type to another by aggregating entries with common keys. A conversion operator determines which subset of input table keys to use as the keys of the output table. For example, applying the src_IP_Table operator to a Tuple_Table generates an IP_Table whose keys are the source addresses of the input table. The pkts, bytes, and flows counts of each entry in the new table are the sums of the corresponding counts of the Tuple_Table entries with the same source IP address. Figure 3 shows all the operators that can be applied to the various table types.

D.1 Goal: find the top 5 hosts by bytes of traffic generated

Command line:

```
crl_flow -I -b -Ci=10 if:fxp0 |
t2_convert src_IP_Table |
t2_top -Sb -n5
```

Sample output:

```
#KEYS           pkts      bytes     flows
# (top 5 sorted by bytes)
0.4.0.27       16035   22534236         1
0.4.0.21       12202   13663537        46
0.4.0.30        2965    4230700         1
0.4.0.44        3647    3919348         1
0.4.0.4         1831    2702668         1
# end of text table
#KEYS           pkts      bytes     flows
# (top 5 sorted by bytes)
0.4.0.27       18409   25864829         3
0.4.0.21       13900   15515873        46
0.4.0.30        3097    4417620         1
0.4.0.44        3185    3350880         1
0.4.0.64        1347    1948443         7
# end of text table
...
```

Explanation: The output of crl_flow is a Tuple_Table, with keys src, dst, proto, ok, sport, and dport. To aggregate those flows by source IP address, we apply the src_IP_Table operator with t2_convert. Since the flows column in a Tuple_Table is always 1, the flows column in the resulting IP_Table is the number of flows with that source IP address. Sorting this IP_Table by bytes and taking the top 5 entries shows the hosts sending the most bytes.

D.2 Goal: find the top 5 web servers by HTTP flows

Command line:

```
crl_flow -I -b -Ci=10 -C'filter tcp src port 80' if:fxp0 |
t2_convert src_IP_Table |
t2_top -Sf -n5
```

Sample output:

```
#KEYS           pkts    bytes   flows
# (top 5 sorted by flows)
0.3.0.77        126    101845      23
0.1.0.108       102     52397      17
0.1.0.52        180     78166      15
0.1.0.42          8       320       8
0.1.0.182        24      1713       5
# end of text table
#KEYS           pkts    bytes   flows
# (top 5 sorted by flows)
0.1.0.108       192     80733      36
0.3.0.77        131    119220      22
0.1.2.145         5       205       5
0.1.2.135        66     72221       5
0.1.0.119        17     25500       4
# end of text table
...
```

Explanation: This is similar to the previous example, except we limit the traffic to web servers by using a filter option to crl_flow and sort by flows (-Sf) instead of bytes. Aggregating this Tuple_Table by source IP address and then sorting the resulting IP_Table by flows shows the web servers with the most HTTP connections during each 10 second interval.

```
# start           pkts     bytes  flows entries   pkts/s   bits/s  flows/s
1001982746      143315  97458948   6624    6624   14.33k   77.97M  662.40
1001982756      143985  98792491   6465    6465   14.40k   79.03M  646.50
...
```

Listing 4
`t2_rate` output: Utilization and flows.

```
src          dst       proto  ok    sport   dport

#KEYS                                          pkts      bytes  flows
0.4.0.27     0.98.0.1     6    1    46978   64671  16035   22534236      1
0.4.0.30     0.19.0.2     6    1    22      64156   2965    4230700      1
0.4.0.44     0.158.0.1    6    1    22      33222   3647    3919348      1
0.4.0.4      0.17.0.1     6    1    80      58013   1831    2702668      1
0.4.0.3      0.15.0.1     6    1    45925   20      2244    2390668      1
# end of text table
#KEYS                                          pkts      bytes  flows
0.4.0.27     0.98.0.1     6    1    46995   64683   9311   13084084      1
0.4.0.27     0.98.0.1     6    1    46978   64671   9095   12780460      1
0.4.0.30     0.19.0.2     6    1    22      64156   3097    4417620      1
0.4.0.44     0.158.0.1    6    1    22      33222   3185    3350880      1
0.4.0.21     0.73.0.2     6    1    60971   119     1362    1915352      1
# end of text table
```

Listing 5
`t2_top` output: High bandwidth consumers.

Table Type	**Keys**
`Tuple_Table`	source IP, destination IP, IP protocol, ports ok, source port, destination port
`IP_Table`	IP
`IP_Matrix`	source IP, destination IP
`Proto_Ports_Table`	IP protocol, ports ok, source port, destination port
`Port_Table`	port
`Port_Matrix`	source port, destination port
`Proto_Table`	IP protocol
`AS_Table`	AS
`AS_Matrix`	source AS, destination AS
`Country_Table`	country
`Country_Matrix`	source country, destination country
`App_Table`	application
`VPVC_Table`	vp/vc pair
`Prefix_Table`	prefix/masklength
`Prefix_Matrix`	source prefix/masklength, destination prefix/masklength
`Length_Table`	length

TABLE 1
CoralReef table types.

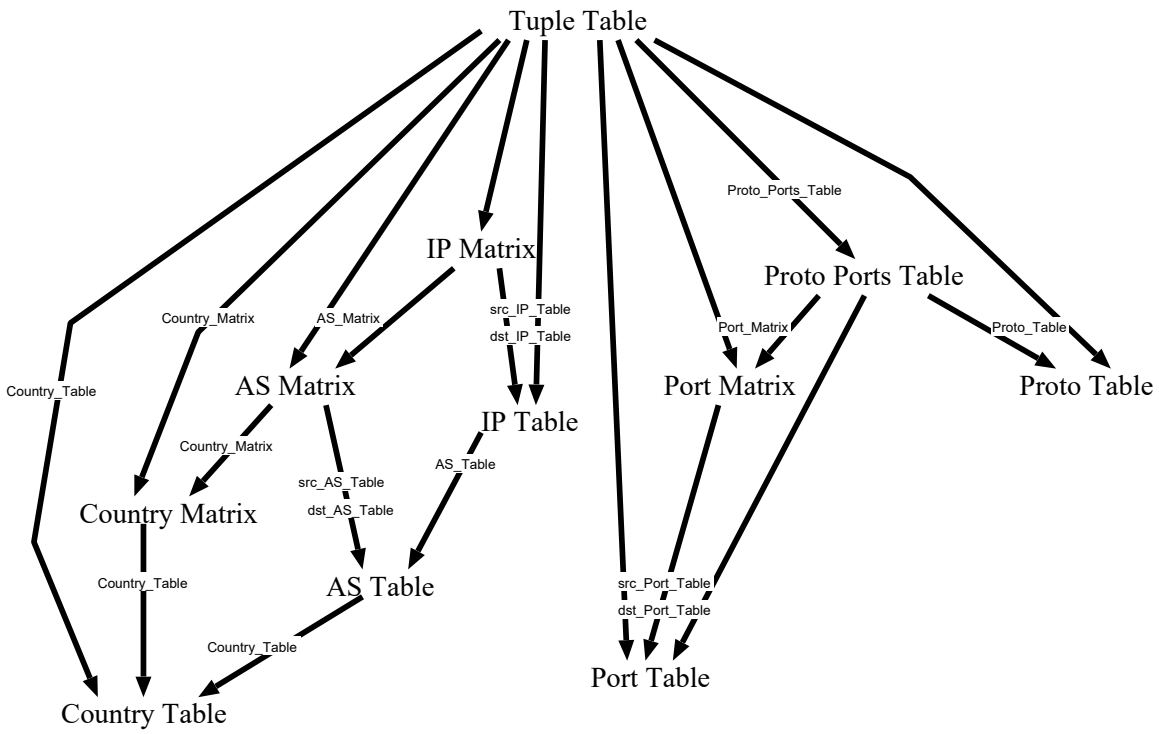

Fig. 3. Table conversion operations.

E. Using `t2_*` to find hosts talking to the most hosts

Normally, the flows column in each entry of the output table of `t2_convert` is the sum of the flows column of the input table entries with the same output keys. But with the `-F` option of `t2_convert`, the flows column in each output entry will be the *number* of input entries with the same output keys. For example, given this `IP_Matrix` table:

src	dst	pkts	bytes	flows
0.0.0.1	0.0.0.2	3	120	3
0.0.0.1	0.0.0.3	1	40	1
0.0.0.1	0.0.0.4	10	400	5

The command "`t2_convert src_IP_Table`" yields an `IP_Table` in which the flows column shows the number of 5-tuple flows with the given source address:

src	pkts	bytes	flows
0.0.0.1	14	560	9

but "`t2_convert -F src_IP_Table`" yields an `IP_Table` in which the flows column shows the number of IP pairs with the given source address:

src	pkts	bytes	flows
0.0.0.1	14	560	3

E.1 Goal: find the number of unique destination hosts for each source host

Command line:

```
crl_flow -I -b -Ci=10 if:fxp0 |
t2_convert IP_Matrix |
t2_convert -F src_IP_Table |
t2_top -Sf -n5
```

Sample output:

```
#KEYS           pkts    bytes   flows
# (top 5 sorted by flows)
0.1.0.120       1059   135597     159
0.1.0.5         1224   149885     143
0.4.1.16         188    13280     110
0.4.0.7         1239   140900      87
0.1.0.1          799    67787      78
# end of text table
```

```
#KEYS           pkts    bytes   flows
# (top 5 sorted by flows)
0.1.0.120       1159    93601     167
0.1.0.5         1553   119823     157
0.4.0.7         1042   109109      79
0.1.0.1          884    75684      71
0.1.0.65         941   106510      65
# end of text table
```

Explanation: Remember, since the `-F` option was used on the second `t2_convert`, the flows column is actually the number of corresponding entries in the `IP_Matrix` input table, i.e. the number of IP pairs with the given source address. So, in the first 10 second interval, host 0.1.0.120 sent traffic to 159 different destination hosts, totaling 135597 bytes.

E.2 Goal: find the top 5 web servers by number of clients

Command line:

```
crl_flow -I -b -Ci=10 -C'filter tcp src port 80' if:fxp0 |
t2_convert IP_Matrix |
t2_convert -F src_IP_Table |
t2_top -Sf -n5
```

Sample output:

```
#KEYS           pkts    bytes   flows
# (top 5 sorted by flows)
0.1.0.52         180    78166      11
0.1.0.108        102    52397       6
0.1.0.62          33    33203       4
0.1.0.182         24     1713       4
0.1.0.231         40    33100       3
# end of text table
```

```
#KEYS           pkts    bytes   flows
# (top 5 sorted by flows)
0.1.0.108        192    80733      11
0.1.2.135         66    72221       5
0.1.0.182         20     7135       4
0.3.0.77         131   119220       2
0.1.1.7          145    39893       2
# end of text table
```

Explanation: This example is similar to the previous one, except that we first filter the traffic to measure only packets sent by HTTP servers. So, in the first 10 second interval, host 0.1.0.52 sent HTTP traffic to 11 different destination hosts, totaling 78166 bytes.

E.3 Goal: find hosts on your internal network trying to spread the CodeRed worm

Command line:

```
crl_flow -I -b -Ci=60 -Csource=if:fxp0 \
    -C'filter tcp dst port 80 and src net 10.0.0.0/8' |
t2_convert IP_Matrix |
t2_convert -F src_IP_Table |
t2_top -Sf -n5
```

Sample output:

```
#KEYS          pkts    bytes   flows
# (top 5 sorted by flows)
10.0.39.61      7680  460800    7680
10.0.198.103    8960  358400    6144
10.0.39.60      6144  368640    6144
10.0.0.190      7168  299008    4864
10.0.19.1      12544  602112    4608
# end of text table
#KEYS          pkts    bytes   flows
# (top 5 sorted by flows)
10.0.39.61      8448  506880    8448
10.0.39.60      7424  445440    7424
10.0.198.103    7680  307200    6656
10.0.0.141      6144  256000    4352
10.0.213.103    4352  188416    3584
# end of text table
```

Explanation: Hosts infected with the CodeRed worm try to infect large numbers of other hosts by attempting to open an HTTP connection to random IP addresses (which may or may not actually exist or be running a web server)[18]. With the exception of web caches, most hosts do not open HTTP connections to more than a few different servers per second, so we should be suspicious of any host that tries to connect to significantly more servers. In particular, hosts infected with CodeRed attempt to open HTTP connections to many tens or hundreds of hosts per second. By using a filter that selects only packets from the internal network (10.0.0.0/8 in this example) to HTTP servers, and by seeing which of the hosts sending those packets are attempting to communicate with the most servers, we produce a list of internal hosts that are behaving suspiciously.

V. Report Generator

The `CoralReef` report generator provides a web interface to continuously updated link usage reports. The report generator (`t2_report`) is a Perl application, using C backends for speed, which receives (via a pipe) either live data or traces taken from `crl_flow`. `t2_report` collects and displays timeseries information by using `RRDtool` [19].

The report generator utilizes many of the features of the `CoralReef` suite and thus illustrates some of the capabilities of the suite. At configurable intervals (e.g. every 5 minutes), `t2_report` produces pie charts and tables of traffic data from the most recent sample interval, and timeseries graphs of data over the last hour, day, week, month, and year. All three report forms present data as bytes, packets, and flows. The pie charts and tables show protocol breakdown, applications, flows, source/destination hosts, unknown TCP and UDP, and source/destination ASes and countries. The timeseries graphs show absolute counts and percentages for protocol breakdown and applications. There are two sets of application timeseries graphs. One shows only the applications specified in the `t2_report` configuration file, and the other shows the applications with the most traffic in each interval.

To report traffic by AS number, countries, and application names, `t2_report` must use external data not present in the packets themselves. `t2_report` uses a library called `ASFinder` and a routing table, as output by `parse_bgp_*`, to map IP addresses to AS numbers. To get countries and AS names from AS numbers, `t2_report` uses NetGeo[20]. Application names are found by the `AppPorts` library, which uses a prioritized ruleset to map protocol and port numbers to applications. Users can add or modify application rules by editing a simple text file.

Figure 4 shows an example of a timeseries plot of application breakdown by bytes. Figure 5 shows an example of the top source ASes by bytes in a 5 minute period. The `CoralReef` web site has a live demonstration of the report generator monitoring the commodity traffic link for the U. C. San Diego.

VI. Conclusion

`CoralReef` provides a suite of tools to aid network administrators in monitoring and diagnosing changes in network behavior. `CoralReef` provides a unified platform to a wide range of capture devices and a collection of tools that can be applied at multiple levels of the network. Its components provide measures on a wide range of real-world network traffic flow applications, including validation and monitoring of hardware performance for saturation and diagnosis of network flow constraints. `CoralReef` can be used to produce standalone results or produce data for analysis by other programs. `CoralReef` reporting applications can output in text formats that can be easily manipulated with common UNIX data-reduction utilities (e.g. `grep`), providing enormous flexibility for customization in an operational setting.

`CoralReef` provides a balanced collection of features for network administrators seeking to monitor their network and diagnose trouble spots. It serves as a useful bridge between higher level monitoring tools which only work at a coarse level of aggregation and "dump" utilities which may overwhelm the administrator with detail. By covering the range from raw packet capture to real-time HTML report generation, `CoralReef` provides a viable toolkit for wide range of network administration needs.

VII. Acknowledgments

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VIII. Availability

The `CoralReef` software package is available for non-commercial use from `http://www.caida.org/tools/measurement/coralreef/`. Questions about `CoralReef` can be e-mailed to `coral-info@caida.org`.

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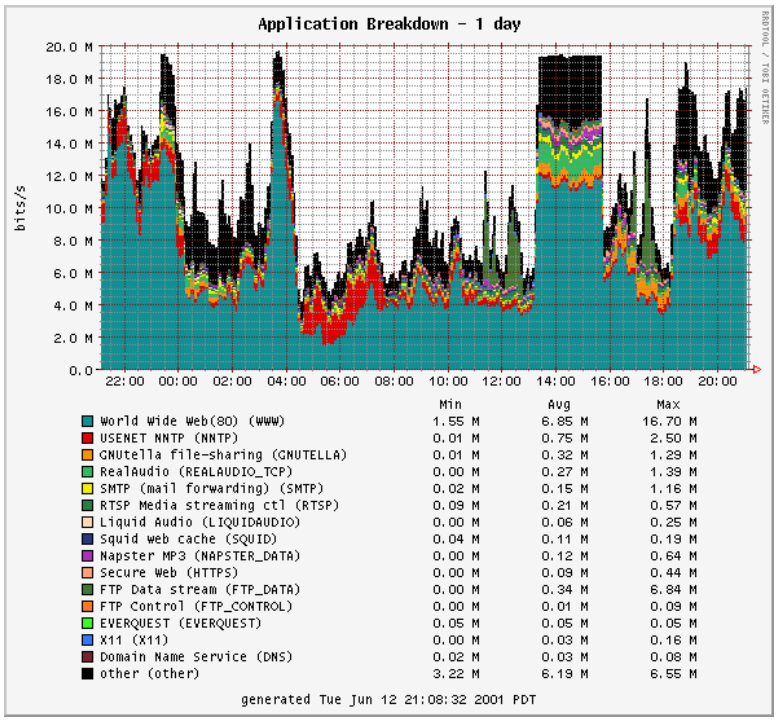
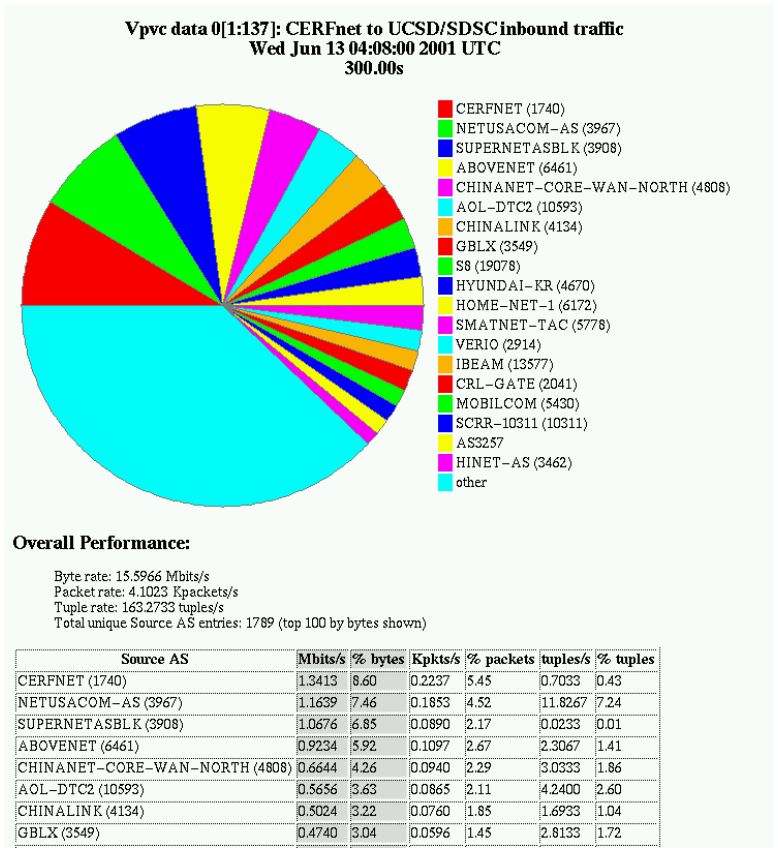


Fig. 4. Example of a timeseries plot of application breakdown by bytes



Source AS	Mbits/s	% bytes	Kpkts/s	% packets	tuples/s	% tuples
CERFNET (1740)	1.3413	8.60	0.2237	5.45	0.7033	0.43
NETUSACOM-AS (3967)	1.1639	7.46	0.1853	4.52	11.8267	7.24
SUPERNETASBLK (3908)	1.0676	6.85	0.0890	2.17	0.0233	0.01
ABOVENET (6461)	0.9234	5.92	0.1097	2.67	2.3067	1.41
CHINANET-CORE-WAN-NORTH (4808)	0.6644	4.26	0.0940	2.29	3.0333	1.86
AOL-DTC2 (10593)	0.5656	3.63	0.0865	2.11	4.2400	2.60
CHINALINK (4134)	0.5024	3.22	0.0760	1.85	1.6933	1.04
GBLX (3549)	0.4740	3.04	0.0596	1.45	2.8133	1.72

Fig. 5. Example of top source ASes by bytes in a 5 minute period

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