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                         Mobile Network Tracing

Status of this Memo

   This memo provides information for the Internet community. This memo
   does not specify an Internet standard of any kind. Distribution of
   this memo is unlimited.

Abstract

   Mobile networks are both poorly understood and difficult to
   experiment with. This RFC argues that mobile network tracing
   provides both tools to improve our understanding of wireless
   channels, as well as to build realistic, repeatable testbeds for
   mobile software and systems. The RFC is a status report on our work
   tracing mobile networks. Our goal is to begin discussion on a
   standard format for mobile network tracing as well as a testbed for
   mobile systems research. We present our format for collecting mobile
   network traces, and tools to produce from such traces analytical
   models of mobile network behavior.

   We also describe a set of tools to provide network modulation based
   on collected traces. Modulation allows the emulation of wireless
   channel latency, bandwidth, loss, and error rates on private, wired
   networks. This allows system designers to test systems in a
   realistic yet repeatable manner.

1. Introduction

   How does one accurately capture and reproduce the observed behavior
   of a network? This is an especially challenging problem in mobile
   computing because the network quality experienced by a mobile host
   can vary dramatically over time and space. Neither long-term average
   measures nor simple analytical models can capture the variations in
   bandwidth, latency, and signal degradation observed by such a host.
   In this RFC, we describe a solution based on network tracing. Our
   solution consists of two phases: trace recording and trace
   modulation.

   In the trace recording phase, an experimenter with an instrumented
   mobile host physically traverses a path of interest to him. During
   the traversal, packets from a known workload are generated from a
   static host. The mobile host records observations of both packets
   received from the known workload as well as the device
   characteristics during the workload. At the end of the traversal,
   the list of observations represents an accurate trace of the observed
   network behavior for this traversal. By performing multiple
   traversals of the same path, and by using different workloads, one
   can obtain a trace family that collectively characterizes network
   quality on that path.

   In the trace modulation phase, mobile system and application software
   is subjected to the network behavior observed in a recorded trace.
   The mobile software is run on a LAN-attached host whose kernel is
   modified to read a file containing the trace (possibly postprocessed
   for efficiency,) and to delay, drop or otherwise degrade packets in
   accordance with the behavior described by the trace. The mobile
   software thus experiences network quality indistinguishable from that
   recorded in the trace. It is important to note that trace modulation
   is fully transparent to mobile software --- no source or binary
   changes have to be made.

   Trace-based approaches have proved to be of great value in areas such
   as file system design [2, 10, 11] and computer architecture. [1, 5,
   13] Similarly, we anticipate that network tracing will prove valuable
   in many aspects of mobile system design and implementation. For
   example, detailed analyses of traces can provide insights into the
   behavior of mobile networks and validate predictive models. As
   another example, it can play an important role in stress testing and
   debugging by providing the opportunity to reproduce the network
   conditions under which a bug was originally uncovered. As a third
   example, it enables a system under development to be subjected to
   network conditions observed in distant real-life environments. As a
   final example, a set of traces can be used as a benchmark family for
   evaluating and comparing the adaptive capabilities of alternative

mobile system designs.

Our goal in writing this RFC is to encourage the development of a
widely-accepted standard format for network traces. Such
standardization will allow traces to be easily shared. It will also
foster the development and widespread use of trace-based benchmarks.
While wireless mobile networks are the primary motivation for this
work, we have made every effort to ensure that our work is applicable
to other types of networks. For example, the trace format and some
of the tools may be valuable in analyzing and modeling ATM networks.

The rest of this RFC is organized as follows. We begin by examining
the properties of wireless networks and substantiating the claim that
it is difficult to model such networks. Next, in Section 3, we
describe the factors that should be taken into account in designing a
trace format. We present the details of a proposed trace format
standard in Section 4. Section 5 presents a set of tools that we
have built for the collection, analysis and replay of traces.
Finally, we conclude with a discussion of related and future work.

2. Modeling Wireless Networks

Wireless channels are particularly complex to model, because of their
inherent dependence on the physical properties of radio waves (such
as reflections from "hard" surfaces, diffraction around corners, and
scattering caused by small objects) and the site specific geometries
in which the channel is formed. They are usually modeled as a time-
and distance-varying signal strength, capturing the statistical
nature of the interaction among reflected radio waves. The signal
strength can vary by several orders of magnitude (+ or - 20-30 dB)
within a short distance. While there have been many efforts to
obtain general models of radio propagation inside buildings and over
the wide area, these efforts have yielded inherently inaccurate
models that can vary from actual measurements by an order of
magnitude or more.

Signal-to-noise ratio, or SNR, is a measure of the received signal
quality. If the SNR is too low, the received signal will not be
detected at the receiver, yielding bit errors and packet losses. But
SNR is not the only effect that can lead to losses. Another is
inter-symbol interference caused by delay spread, that is, the
delayed arrival of an earlier transmitted symbol that took a
circuitous propagation path to arrive at the receiver, thereby
(partially) canceling out the current symbol. Yet another problem is
doppler shift, which causes frequency shifts in the arrived signal
due to relative velocities of the transmitter and the receiver,
thereby complicating the successful reception of the signal. If
coherent reception is being used, receiver synchronization can be

lost.

More empirically, it has been observed that wireless channels adhere
to a two state error model. In other words, channels are usually
well behaved but occasionally go into a bad state in which many burst
errors occur within a small time interval.

Developers of network protocols and mobility algorithms must
experiment with realistic channel parameters. It is highly desirable
that the wireless network be modeled in a thoroughly reproducible
fashion. This would allow an algorithm and its variations to be
evaluated in a controlled and repeatable way. Yet the above
discussion makes it clear that whether analytical models are used or
even actual experimentation with the network itself, the results will
be either inaccurate or unlikely to be reproducible. A trace-based
approach alleviates these problems.

3. Desirable Trace Format Properties

In designing our trace format, we have been guided by three
principles. First, the format should be extensible. Second, it
should be self-describing. Third, traces should be easy to manage.
This section describes how each of these principles has affected our
design.

Although we have found several interesting uses for network traces,
it is certain that more will evolve over time. As the traces are
used in new ways, it may be necessary to add new data to the trace
format. Rather than force the trace format to be redesigned, we have
structured the format to be extensible. There is a built-in
mechanism to add to the kinds of data that can be recorded in network
traces.

This extensibility is of little use if the tool set needs to change
as the trace format is extended. Recognizing this, we have made the
format -- particularly the extensible portions -- self-describing.
Thus, old versions of tools can continue to work with extended
traces, if perhaps in a less than optimal way.

In our experience with other tracing systems, management of trace
files is often difficult at best. Common problems include the need
to manage multiple trace files as a unit, not easily being able to
extract the salient features of large trace files, and having to use
dedicated trace management tools to perform even the simplest tasks.
To help cope with file management, we have designed the the traces to
be split or merged easily. To reduce dependence on specialized
tools, we've chosen to store some descriptive information as ASCII
strings, allowing minimal access to the standard UNIX tool suite.

4. Trace Format

   This section describes the format for network traces. We begin by
   presenting the basic abstractions that are key to the trace format:
   the record, and the track, a collection of related records. We then
   describe the records at the beginning and end of a trace, the header
   and footer. The bulk of the section describes the three kinds of
   record tracks: packet, device, and general. These also make up the
   bulk of the actual trace. We conclude the section with a discussion
   of two special purpose records: the annotation and the trace data
   loss records.

4.1. Basic Abstractions

4.1.1. Records

   A record is the smallest unit of trace data. There are several
   different types of records, each of which is discussed in Sections
   4.2 through 4.7. All of the records share several features in
   common; these features are described here.

   Records are composed of fields, which are stored in network order.
   Most of the fields in our records are word-sized. Although this may
   be wasteful in space, we chose to leave room to grow and keep trace
   management simple.

   The first field in each record is a magic word, a random 32 bit
   pattern that both identifies the record's type and lends some
   confidence that the record is well formed. Many record types have
   both required and optional fields; thus they can be of variable size.
   We place every record's size in its second field. By comparing the
   size of a record to the known constraints for the record's type, we
   can gain further confidence that a record is well-formed. This basic
   record structure is illustrated in Figure 1.

   All records also contain a two-word timestamp. This timestamp can
   take one of two formats: timeval or timespec. Only one of the two
   formats is used in any given trace, and the format is specified at
   the start of a trace file. The first word in either format is the
   number of seconds that have elapsed since midnight, January 1, 1970.
   The second word is the additional fractions of a second. In the
   timeval format, these fractions are expressed in microseconds, in the
   same way that many current operating systems express time. In the
   timespec format, these fractions are expressed in nanoseconds, the
   POSIX time standard. We've chosen these two values since they are
   convenient, cover most current and anticipated systems' notions of
   time, and offer appropriate granularity for measuring network events.

```
                    +------------------+
                    | Magic Number     |
                    | Size of Record   |
                    +------------------+
                    | Required Fields  |
                    |        ...       |
                    +------------------+
                    | Optional Fields  |
                    |        ...       |
                    +------------------+
```
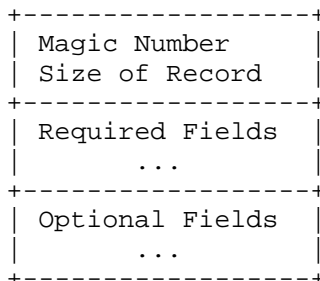
Figure 1: Record format

4.1.2. Tracks

   Many of the record types have both fixed, required fields, as well as
   a set of optional fields. It is these options that provide
   extensibility to our trace format. However, to provide a self-
   describing trace, we need some compact way of determining which
   optional fields are present in a given record. To do this, we group
   related sets of packets into tracks. For example, a set of records
   that captured packet activity for a single protocol between two
   machines might be put together into a track. A track is a header
   followed by some number of related records; the header completely
   describes the format of the individual records. Records from
   separate tracks can be interleaved with one another, so long as the
   header for each individual track appears before any of the track's
   records. Figure 2 shows an example of how records from different
   tracks might be interleaved.

   Track headers describe their records' content through property lists.
   An entry in a property list is a two-element tuple consisting of a
   name and a value. The name is a word which identifies the property
   defined by this entry. Some of these properties are measured only
   once for a track, for example, the address of a one-hop router in a
   track recording packets from that router. Others are measured once
   per record in that track, such as the signal strength of a device
   which changes over time. The former, which we call header-only
   properties, have their most significant name bit set. The value
   field of a header-only property holds the measured value of the
   property. Otherwise, the value field holds the number of words used
   in each of the track's records.

```
+----------++----------++----------++----------++----------+
| Track #1 || Track #1 || Track #2 || Track #1 || Track #2 |
| Header   || Entry    || Header   || Entry    || Entry    |
+----------++----------++----------++----------++----------+
```

                    Figure 2: Interleaved track records

Those properties measured in each record in the track are grouped
together in a value list at the end of each such record. They appear
in the same order that was specified in the track header's property
list so that tools can properly attribute data. Thus, even if a tool
doesn't know what property a particular name represents, it can
identify which parts of a trace record are measuring that property,
and ignore them.

4.2. Trace Headers and Footers

   Trace files begin with a trace header, and end with a trace footer.
   The formats of these appear in Figure 3. The header specifies
   whether this trace was collected on a single machine, or was merged
   from several other traces. In the former case, the IP address and
   host name of the machine are recorded. In the latter, the IP address
   is taken from the family of Class E address, which are invalid. We
   use a family of invalid addresses so that even if we cannot identify
   a number of hosts participating in the trace we can still distinguish
   records from distinct hosts.

```
    #define TR_DATESZ   32
    #define TR_NAMESZ   64

    struct tr_header_t {
        u_int32_t       h_magic;
        u_int32_t       h_size;
        u_int32_t       h_time_fmt;         /* usec or nsec */
        struct tr_time_t h_ts;              /* starting time */
        char            h_date[TR_DATESZ];  /* Date collected */
        char            h_agent[TR_NAMESZ]; /* DNS name */
        u_int32_t       h_agent_ip;
        char            h_desc[0];          /* variable size */
    };

    struct tr_end_t {
        u_int32_t        e_magic;
        u_int32_t        e_size;
        struct tr_time_t e_ts;          /* end time */
        char             e_date[32];  /* Date end written */
    };
```

                 Figure 3: Trace header and footer records

   The trace header also specifies which time stamp format is used in
   the trace, and the time at which the trace begins. There is a
   variable-length description that is a string meant to provide details
   of how the trace was collected. The trace footer contains only the
   time at which the trace ended; it serves primarily as a marker to
   show the trace is complete.

   Unlike other kinds of records in the trace format, the header and
   footer records have several ASCII fields. This is to allow standard
   utilities some access to the contents of the trace, without resorting
   to specialized tools.

4.3. Packet Tracks

   Measuring packet activity is the main focus of the network tracing
   project. Packet activity is recorded in tracks, with a packet header
   and a set of packet entries. A single track is meant to capture the
   activity of a single protocol, traffic from a single router, or some
   other subset of the total traffic seen by a machine. The required
   portions of packet headers and entries are presented in Figure 4.

   Packet track headers identify which host generated the trace records
   for that track, as well as the time at which the track began. It
   records the device on which these packets are received or sent, and
   the protocol used to ship the packet; these allow interpretation of
   device-specific or protocol-specific options. The header concludes
   with the property list for the track.

```
    struct tr_pkt_hdr_t {
        u_int32_t             ph_magic;
        u_int32_t             ph_size;
        u_int32_t             ph_defines;  /* magic number defined */
        struct tr_time_t      ph_ts;
        u_int32_t             ph_ip;       /* host generating stream */
        u_int32_t             ph_dev_type; /* device collected from */
        u_int32_t             ph_protocol; /* protocol */
        struct tr_prop_lst_t  ph_plist[0]; /* variable size */
    };

    struct tr_pkt_ent_t {
        u_int32_t        pe_magic;
        u_int32_t        pe_size;
        struct tr_time_t pe_ts;
        u_int32_t        pe_psize;    /* packet size */
        u_int32_t        pe_vlist[0]; /* variable size */
    };
```

             Figure 4: Packet header and entry records

   A packet entry is generated for every traced packet. It contains the
   size of the traced packet, the time at which the packet was sent or
   received, and the list of property measurements as specified in the
   track header.

   The options we have defined to date are in Table 1. Several of these
   have played an important role in our early experiments. ADDR_PEER
   identifies the senders of traffic during the experiment. We can
   determine network performance using either PKT_SENTTIME for one-way
   traffic between two hosts with closely synchronized clocks, or round

   trip ICMP ECHO traffic and the ICMP_PINGTIME option. Tracking
   PKT_SEQUENCE numbers sheds light on both loss rates and patterns.
   Section 5 discusses how these measurements are used.

4.4. Device Tracks

   Our trace format records details of the devices which carry network
   traffic. To date, we've found this most useful for correlating lost
   packets with various signal parameters provided by wireless devices.
   The required portions of device header and entry records appear in
   Figure 5, and are quite simple. Device track headers identify the
   host generating the track's records, the time at which the
   observation starts, and the type of device that is being traced.
   Each entry contains the time of the observation, and the list of
   optional characteristics.

```
+---------------+-----------------------------------------------+
| ADDR_PEER     | Address of peer host                          |
| ADDR_LINK     | Address of one-hop router                     |
| BS_LOC_X      | One-hop router's X coordinate (header only)   |
| BS_LOC_Y      | One-hop router's Y coordinate (header only)   |
| PKT_SEQUENCE  | Sequence number of packet                     |
| PKT_SENTTIME  | Time packet was sent                          |
| PKT_HOPS      | Number of hops packet took                    |
| SOCK_PORTS    | Sending and receiving ports                   |
| IP_PROTO      | Protocol number of an IP packet               |
| ICMP_PINGTIME | Roundtrip time of an ICMP ECHO/REPLY pair     |
| ICMP_KIND     | Type and code of an ICMP packet               |
| ICMP_ID       | The id field of an ICMP packet                |
| PROTO_FLAGS   | Protocol-specific flags                       |
| PROTO_ERRLIST | Protocol-specific status/error words          |
+---------------+-----------------------------------------------+
        Table 1: Current optional fields for packet entries
```

```
    struct tr_dev_hdr_t {
        u_int32_t               dh_magic;
        u_int32_t               dh_size;
        u_int32_t               dh_defines;  /* Magic number defined */
        struct tr_time_t    dh_ts;
        u_int32_t               dh_ip;       /* host generating stream */
        u_int32_t               dh_dev_type; /* device described */
        struct tr_prop_lst_t dh_plist[0]; /* Variable size */
    };

    struct tr_dev_ent_t {
        u_int32_t         de_magic;
        u_int32_t         de_size;
        struct tr_time_t de_ts;
        u_int32_t         de_vlist[0]; /* Variable size */
    };
```

              Figure 5: Device header and entry records

   These optional characteristics, listed in Table 2, are mostly
   concerned with the signal parameters of the wireless interfaces we
   have available. Interpreting these parameters is heavily device-
   dependent. We give examples of how we've used device observations in
   Section 5.

```
   +----------------+-------------------------------------------------+
   | DEV_ID         | Major and minor number of device (header only)  |
   | DEV_STATUS     | Device specific status registers                |
   | WVLN_SIGTONOISE | Signal to noise ratio reported by WaveLAN      |
   | WVLN_SIGQUALITY | Signal quality reported by WaveLAN             |
   | WVLN_SILENCELVL | WaveLAN silence level                          |
   +----------------+-------------------------------------------------+
         Table 2: Current optional fields for packet entries
```

4.5. Miscellaneous Tracks

   We use miscellaneous, or general, tracks to record things that don't
   fit clearly in either the packet or device model. At the moment,
   physical location of a mobile host is the only attribute tracked in
   general trace records. The required portion of the general header
   and entry records is shown in Figure 6, the two optional properties
   are in Table 3. In addition to the property list, general headers
   have only the IP address of the host generating the record and the
   time at which observations began. General entries have only a
   timestamp, and the optional fields.

4.6. Annotations

   An experimenter may occasionally want to embed arbitrary descriptive
   text into a trace. We include annotation records to provide for
   this. Such records are not part of a track; they stand alone. The
   structure of an annotation record is shown in Figure 7. Annotations
   include the time at which the annotation was inserted in the trace,
   the host which inserted the annotation, and the variable-sized text
   of the annotation itself.

```
    struct tr_gen_hdr_t {
        u_int32_t            gh_magic;
        u_int32_t            gh_size;
        u_int32_t            gh_defines;
        struct tr_time_t     gh_ts;
        u_int32_t            gh_ip;
        struct tr_prop_lst_t gh_plist[0]; /* Variable size */
    };

    struct tr_gen_ent_t {
        u_int32_t        ge_magic;
        u_int32_t        ge_size;
        struct tr_time_t ge_ts;
        u_int32_t        ge_vlist[0]; /* Variable size */
    };
```

              Figure 6: General header and entry records


```
      +------------+---------------------------------------------+
      | MH_LOC_X   | Mobile host's X coordinate (map-relative)   |
      | MH_LOC_Y   | Mobile host's Y coordinate (map-relative)   |
      | MH_LOC_LAT | Mobile host's GPS latitude                  |
      | MH_LOC_LON | Mobile host's GPS longitude                 |
      +------------+---------------------------------------------+
```
        Table 3: Current optional fields for general entries


```
    struct tr_annote_t {
        u_int32_t        a_magic;
        u_int32_t        a_size;
        struct tr_time_t a_ts;
        u_int32_t        a_ip;
        char             a_text[0]; /* variable size */
    };
```

                  Figure 7: Annotation records

4.7. Lost Trace Data

   It is possible that, during collection, some trace records may be
   lost due to trace buffer overflow or other reasons. Rather than
   throw such traces away, or worse, ignoring the lost data, we've
   included a loss record to count the types of other records which are
   lost in the course of trace collection. Loss records are shown in
   Figure 8.

```
   struct tr_loss_t {
       u_int32_t         l_magic;
       u_int32_t         l_size;
       struct tr_time_t l_ts;
       u_int32_t         l_ip;
       u_int32_t         l_pkthdr;
       u_int32_t         l_pktent;
       u_int32_t         l_devhdr;
       u_int32_t         l_devent;
       u_int32_t         l_annote;
   };
```

                        Figure 8: Loss records

5. Software Components

   In this section, we describe the set of tools that have been built to
   date for mobile network tracing. We believe many of these tools are
   widely applicable to network tracing tasks, but some have particular
   application to mobile network tracing. We begin with an overview of
   the tools, their applicability, and the platforms on which they are
   currently supported, as well as those they are being ported to. This
   information is summarized in Table 4.

   We have made every effort to minimize dependencies of our software on
   anything other than protocol and device specifications. As a result,
   we expect ports to other BSD-derived systems to be straightforward;
   ports to other UNIX systems may be more complicated, but feasible.

   There are three categories into which our tracing tools can be
   placed: trace collection, trace modulation, and trace analysis.
   Trace collection tools are used for generating new traces. They
   record information about the general networking facilities, as well
   as data specific to mobile situations: mobile host location, base
   station location, and wireless device characteristics. These tools
   are currently supported on BSDI, and are being ported to NetBSD. We
   describe these tools in Section 5.1.

Trace modulation tools emulate the performance of a traced wireless
network on a private wired network. The trace modulation tools,
discussed in Section 5.2, are currently supported on NetBSD
platforms. They are geared toward replaying low speed/quality
networks on faster and more reliable ones, and are thus most
applicable to reproducing mobile environments.

In Section 5.3, we conclude with a set of trace processing and
analysis tools, which are currently supported on both NetBSD and BSDI
platforms. Our analyses to date have focused on properties of
wireless networks, and are most directly applicable to mobile traces.
The processing tools, however, are of general utility.

```
            +--------------+--------------+--------------+
            | Collection   | Modulation   | Analysis     |
  +----------+--------------+--------------+--------------+
  | NetBSD   | In Progress  | Supported    | Supported    |
  | BSDI     | Supported    | Planned      | Supported    |
  +----------+--------------+--------------+--------------+
```
This table summarizes the currently supported platforms for the tracing
tool suites, and the platforms to which ports are underway.

                     Table 4: Tool Availability

5.1. Trace Collection Tools

   The network trace collection facility comprises two key components:
   the trace agent and the trace collector. They are shown in Figure 9.

   The trace agent resides in the kernel where it can obtain data that
   is either expensive to obtain or inaccessible from the user level.
   The agent collects and buffers data in kernel memory; the user-level
   trace collector periodically extracts data from this kernel buffer
   and writes it to disk. The buffer amortizes the fixed costs of data
   transfer across a large number of records, minimizing the impact of
   data transfer on system performance. The trace collector retrieves
   data through a pseudo-device, ensuring that only a single -- and
   therefore complete -- trace file is being generated from a single
   experiment. To provide simplicity and efficiency, the collector does
   not interpret extracted data; it is instead processed off-line by the
   post-processing and analysis tools described in Sections 5.2 and 5.3.

   There are three sorts of data collected by the tracing tools: network
   traffic, network device characteristics, and mobile host location.
   The first two are collected in much the same way; we describe the
   methodology in Section 5.1.1. The last is collected in two novel
   ways. These collection methods are addressed in Section 5.1.2.
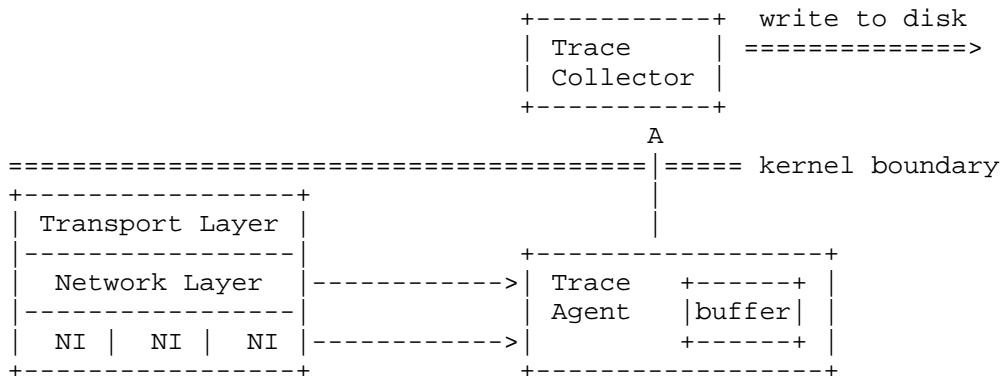
```
                                   +-----------+  write to disk
                                   | Trace     | ==============>
                                   | Collector |
                                   +-----------+
                                        A
      =================================|==== kernel boundary
      +-----------------+                |
      | Transport Layer |                |
      |-----------------|         +------------------+
      |  Network Layer  |-------->| Trace   +------+ |
      |-----------------|         | Agent   |buffer| |
      | NI | NI | NI |-------->|         +------+ |
      +-----------------+         +------------------+
```
This figure illustrates the components of trace collection. The NI's
                      are network interfaces.

              Figure 9: Components of trace collection

5.1.1. Traffic and Device Collection

   The trace agent exports a set of function calls for traffic and
   device data collection. Traffic data is collected on a per-packet
   basis. This is done via a function called from device drivers with
   the packet and a device identifier as arguments. For each packet,
   the trace record contains the source and destination address options.
   Since our trace format assembles related packets into tracks, common
   information, such as the destination address, is recorded in the
   track header to reduce the record size for each packet entry. We
   also record the size of each packet.

   Information beyond packet size and address information is typically
   protocol-dependent. For transport protocols such as UDP and TCP, for
   example, we record the source and destination port numbers; TCP
   packet records also contain the sequence number. For ICMP packets,
   we record their type, code and additional type-dependent data. As
   explained in Section 5.2.3, we record the identifier, sequence number
   and time stamp for ICMP ECHOREPLY packets.

   Before appending the record to the trace buffer, we check to see if
   it is the first record in a track. If so, we create a new packet
   track header, and write it to the buffer prior the packet entry.

   Our trace collection facility provides similar mechanisms to record
   device-specific data such as signal quality, signal level, and noise
   level. Hooks to these facilities can be easily added to the device
   drivers to invoke these tracing mechanisms. The extensible and
   self-describing features of our trace format allow us to capture a
   wide variety of data specific to particular network interfaces.

For wireless network devices, we record several signal quality
measurements that the interfaces provide. Although some interfaces,
such as NCR's WaveLAN, can supply this of information for every
packet received, most devices average their measurements over a
longer period of time. As a result, we only trace these measurements
periodically. It is up to the device drivers to determine the
frequency at which data is reported to the trace agent.

When devices support it, we also trace status and error events. The
types of errors, such as CRC or buffer overflow, allow us to
determine causes for some observed packet losses. For example, we
can attribute loss to either the wireless channel or the network
interface.

5.1.2. Location Tracing

At first thought, recording the position of a mobile host seems
straightforward. It can be approximated by recording the base
station (BS) with which the mobile host is communicating. However,
due to the large coverage area provided by most radio interfaces,
this information provides a loose approximation at best. In
commercial deployments, we may not be able to reliably record the
base station with which a mobile host communicates. This section
outlines our collection strategy for location information in both
outdoor and indoor environments.

The solution that we have considered for wide-area, outdoor
environments makes use of the Global Positioning System (GPS). The
longitude and latitude information provided by the GPS device is
recorded in a general track.

Indoor environments require a different approach because the
satellite signals cannot reach a GPS device inside a building. We
considered deploying an infrared network similar to the Active Badge
[14] or the ParcTab [12]; however, this significant addition to the
wireless infrastructure is not an option for most research groups.

As an alternative, we have developed a graphical tool that displays
the image of a building map and expects the user to "click" their
location as they move; the coordinates on the map are recorded in one
or more general tracks. The header of such tracks can also record
the coordinates of the base stations if they are known.

An extension can be easily added to this tool to permit multiple
maps. As the user requests that a new map be loaded into the
graphical tracing tool, a new location track is created along with an
annotation record that captures the file name of that image.
Locations of new base stations can be recorded in this new track

header. Each location track should represent a different physical
and wireless environment.

5.2. Trace Modulation Tools

A key tool we have built around our trace format is PaM, the Packet
Modulator. The idea behind PaM is to take traces that were collected
by a mobile host and distill them into modulation traces. These
modulation traces capture the networking environment seen by the
traced host, and are used by a PaM kernel to delay, drop, or corrupt
incoming and outgoing packets. With PaM, we've built a testbed that
can repeatably, reliably mimic live systems under certain mobile
scenarios.

There are three main components to PaM. First, we've built a kernel
capable of delaying, dropping, and corrupting packets to match the
characteristics of some observed network. Second, we've defined a
modulation trace format to describe how such a kernel should modulate
packets. Third, we've built a tool to generate modulation traces
from certain classes of raw traces collected by mobile hosts.

5.2.1. Packet Modulation

The PaM modulation tool has been placed in the kernel between the IP
layer and the underlying interfaces. The tool intercepts incoming
and outgoing packets, and may choose to drop it, corrupt it, or delay
it. Dropping an incoming or outgoing packet is easy, simply don't
forward it along. Similarly, we can corrupt a packet by flipping
some bits in the packet before forwarding it.

Correctly delaying a packet is slightly more complicated. We model
the delay a packet experiences as the time it takes the sender to put
the packet onto the network interface plus the time it takes for the
last byte to propagate to the receiver. The former, the transmission
time, is the size of the packet divided by the available bandwidth;
the latter is latency.

Our approach at delay modulation is simple -- we assume that the
actual network over which packets travel is much faster and of better
quality than the one we are trying to emulate, and can thus ignore
it. We delay the packet according to our latency and bandwidth
targets, and then decide whether to drop or corrupt it. We take care
to ensure that packet modulation does not unduly penalize other
system activity, using the internal system clock to schedule packets.
Since this clock is at a large granularity compared to delay
resolution, we try to keep the average error in scheduling to a
minimum, rather than scheduling each packet at exactly the right
time.

5.2.2. Modulation Traces

   To tell the PaM kernel how the modulation parameters change over
   time, we provide it with a series of modulation-trace entries. Each
   of these entries sets loss and corruption percentages, as well as
   network latency and inter-byte time, which is 1/bandwidth. These
   entries are stored in a trace file, the format of which is much
   simpler than record-format traces, and is designed for efficiency in
   playback. The format of modulation traces is shown in Figure 10.

```
    struct tr_rep_hdr_t {
        u_int32_t         rh_magic;
        u_int32_t         rh_size;
        u_int32_t         rh_time_fmt;          /* nsec or used */
        struct tr_time_t rh_ts;
        char              rh_date[TR_DATESZ];
        char              rh_agent[TR_NAMESZ];
        u_int32_t         rh_ip;
        u_int32_t         rh_ibt_ticks;         /* units/sec, ibt */
        u_int32_t         rh_lat_ticks;         /* units/sec, lat */
        u_int32_t         rh_loss_max;          /* max loss rate */
        u_int32_t         rh_crpt_max;          /* max corrupt rate */
        char              rh_desc[0];           /* variable size */
    };

    struct tr_rep_ent_t {
        u_int32_t          re_magic;
        struct tr_time_t  re_dur;            /* duration of entry */
        u_int32_t          re_lat;            /* latency */
        u_int32_t          re_ibt;            /* inter-byte time */
        u_int32_t          re_loss;           /* loss rate */
        u_int32_t          re_crpt;           /* corrupt rate */
    };
```

                    Figure 10: Modulation trace format

   Modulation traces begin with a header that is much like that found in
   record-format trace headers. Modulation headers additionally carry
   the units in which latency and inter-byte time are expressed, and the
   maximum values for loss and corruption rates. Individual entries
   contain the length of time for which the entry applies as well as the
   latency, inter-byte time, loss rate, and corruption rate.

5.2.3. Trace Transformation

   How can we generate these descriptive modulation traces from the
   recorded observational traces described in Section 4? To ensure a
   high-quality modulation trace, we limit ourselves to a very narrow
   set of source traces. As our experience with modulation traces is
   limited, we use a simple but tunable algorithm to generate them.

   Our basic strategy for determining latency and bandwidth is tied
   closely to our model of packet delays: delay is equal to
   transmission time plus latency. We further assume that packets which
   traversed the network near one another in time experienced the same
   latency and bandwidth during transit. Given this, we look for two
   packets of different size that were sent close to one another along
   the same path; from the transit times and sizes of these packets, we
   can determine the near-instantaneous bandwidth and latency of the
   end-to-end path covered by those packets. If traced packet traffic
   contains sequence numbers, loss rates are fairly easy to calculate.
   Likewise, if the protocol is capable of marking corrupt packets,
   corruption information can be stored and then extracted from recorded
   traces.

   Using timestamped packet observations to derive network latency and
   bandwidth requires very accurate timing. Unfortunately, the laptops
   we have on hand have clocks that drift non-negligibly. We have
   chosen not to use protocols such as NTP [9] for two reasons. First,
   they produce network traffic above and beyond that in the known
   traced workload. Second, and perhaps more importantly, they can
   cause the clock to speed up or slow down during adjustment. Such
   clock movements can play havoc with careful measurement.

   As a result, we can only depend on the timestamps of a single machine
   to determine packet transit times. So, we use the ICMP ECHO service
   to provide workloads on traced machines; the ECHO request is
   timestamped on it's way out, and the corresponding ECHOREPLY is
   traced. We have modified the ping program to alternate between small
   and large packets. Traces that capture such altered ping traffic can
   then be subject to our transformation tool.

   The tool itself uses a simple sliding window scheme to generate
   modulation entries. For each window position in the recorded trace,
   we determine the loss rate, and the average latency and bandwidth
   experienced by pairs of ICMP ECHO packets. The size and granularity
   of the sliding window are parameters of the transformation; as we
   gain experience both in analysis and modulation of wireless traces,
   we expect to be able to recommend good window sizes.

Unfortunately, our wireless devices do not report corrupt packets;
they are dropped by the hardware without operating system
notification. However, our modulation system will also coerce any
such corruptions to an increased loss rate, duplicating the behavior
in the original network.

5.3. Trace Analysis Tools

A trace is only as useful as its processing tools. The requirements
for such tools tools include robustness, flexibility, and
portability. Having an extensible trace format places additional
emphasis on the ability to work with future versions. To this end,
we provide a general processing library as a framework for users to
easily develop customized processing tools; this library is designed
to provide both high portability and good performance.

In this section, we first present the trace library. We then
describe a set of tools for simple post-processing and preparing the
trace for further analyses. We conclude with a brief description of
our analysis tools that are applied to this minimally processed data.

5.3.1. Trace Library

The trace library provides an interface that applications can use to
simplify interaction with network traces, including functions to
read, write, and print trace records. The trace reading and writing
functions manage byte swapping as well as optional integrity checking
of the trace as it is read or written. The library employs a
buffering strategy that is optimized to trace I/O. Trace printing
facilities are provided for both debugging and parsing purposes.

5.3.2. Processing Tools

The processing tools are generally the simplest set of tools we have
built around the trace format. By far the most complicated one is
the modulation-trace transformation tool described in Section 5.2.3;
the remainder are quite simple in comparison. The first such tool is
a parser that prints the content of an entire trace. With the trace
library, it is less than a single page of C code. For each record,
it prints the known data fields along with their textual names,
followed by all the optional properties and values.

Since many analysis tasks tend to work with records of the same type,
an enhanced version of the parser can split the trace data by tracks
into many files, one per track. Each line of the output text files
contains a time stamp followed by the integer values of all the
optional data in a track entry; in this form traces are amenable to
further analysis be scripts written in an interpreted language such

as perl.

We have developed a small suite of tools providing simple functions
such as listing all the track headers and changing the trace
description as they have been needed. With the trace library, each
such tool is trivial to construct.

5.3.3. Analysis Tools

Analysis tools depend greatly on the kind of information an
experimenter wants to extract from the trace; our tools show our own
biases in experimentation. Most analyses derive common statistical
descriptions of traces, or establish some correlation between the
trace data sets.

As early users of the trace format and collection tools, we have
developed a few analysis tools to study the behavior of the wireless
networks at our disposal. We have been particularly interested in
loss characteristics of wireless channels and their relation to
signal quality and the position of the mobile host. In this section,
we briefly present some of these tools to hint at the kind of
experimentation possible with our trace format.

Loss characteristics are among the most interesting aspects of
wireless networks, and certainly among the least well understood. To
shed light on this area, we have created tools to extract the loss
information from collected traces; in addition to calculating the
standard parameters such as the packet loss rate, the tool also
derives transitional probabilities for a two-state error model.

This has proven to be a simple yet powerful model for capturing the
burstiness observed in wireless loss rates due to fading signals. To
help visualize the channel behavior in the presence of mobility, our
tool can replay the movement of the mobile host while plotting the
loss rate as it changes with time. It also allows us to zoom in the
locations along the path and obtain detailed statistics over
arbitrary time intervals.

Our traces can be further analyzed to understand the relationship
between channel behavior and the signal quality. For wireless
devices like the NCR WaveLAN, we can easily obtain measurements of
signal quality, signal strength, and noise level. We have developed
a simple statistical tool to test the correlation between measured
signal and the loss characteristics. Variations of this test are
also possible using different combinations of the three signal
measurements and the movement of the host.

The question of just how mobile such mobile hosts are can also be
investigated through our traces. Position data are provided by
traces that either involved GPS or user-supplied positions with our
trace collection tools. This data is valuable for comparing and
validating various mobility prediction algorithms. Given adequate
network infrastructure and good signal measurements, we can determine
the mobile location within a region that is significantly smaller
than the cell size. We are developing a tool to combine position
information and signal measurement from many traces to identify the
"signal quality" signature for different regions inside a building.
Once this signature database is completed and validated, it can be
used to generate position information for other traces that contain
only the signal quality information.

6. Related Work

   The previous work most relevant to mobile network tracing falls into
   two camps. The first, chiefly exemplified by tcpdump [7] and the BSD
   Packet Filter, or BPF [8], collect network traffic data. The second,
   notably Delayline [6], and the later Probe/Fault Injection Tool [4],
   and the University of Lancaster's netowrk emulator [3], provide
   network modulation similar to PaM.

   There are many systems that record network packet traffic; the de
   facto standard is tcpdump, which works in concert with a packet
   filter such as BPF. The packet filter is given a small piece of code
   that describes packets of interest, and the first several bytes of
   each packet found to be interesting is copied to a buffer for tcpdump
   to consume. This architecture is efficient, flexible, and has
   rightly found great favor with the networking community.

   However, tcpdump cpatures only traffic data. It records neither
   information concerning mobile networking devices nor mobile host
   location. Rather than adding seperate software components to a host
   running tcpdump to capture this additional data, we have chosen to
   follow an integrative approach to ease trace file administration. We
   have kept the lessons of tcpdump and BPF to heart; namely copying
   only the information necessary, and transferring data up to user
   level in batches. It may well pay to investigate either
   incorporating device and location information directly into BPF, or
   taking the flexible filtering mechanism of BPF and including it in
   our trace collection software. For the moment, we do not know
   exactly what data we will need to explore the properties of mobile
   networks, and therefore do not exclude any data.

   There are three notable systems that provide packet modulation
   similar to PaM. The earliest such work is Delayline, a system
   designed to emulate wide-area networks atop local-area ones; a goal

   similar to PaM's. The most striking difference between Delayline and
   PaM is that Delayline's emulation takes place entirely at the user-
   level, and requires applications to be recompiled against a library
   emulating the BSD socket system and library calls. While this is a
   portable approach that works well in the absence of kernel-level
   source access, it has the disadvantage that not all network traffic
   passes through the emulation layer; such traffic may have a profound
   impact on the performance of the final system. Delayline also
   differs from PaM in that the emulated network uses a single set of
   parameters for each emulated connection; performance remains fairly
   constant, and cannot change much over time.

   The Lancaster network emulator was designed explicitly to model
   mobile networks. Rather than providing per-host modulation, it uses
   a single, central server through which all network traffic from
   instrumented applications passes. While this system also does not
   capture all traffic into and out of a particular host, it does allow
   modulation based on multiple hosts sharing a single emulated medium.
   There is a mechanism to change the parameters of emulation between
   hosts, though it is fairly cumbersome. The system uses a
   configuration file that can be changed and re-read while the system
   is running.

   The system closest in spirit to PaM is the Probe/Fault Injection
   Tool. This system's design philosophy allows an arbitrary protocol
   layer -- including device drivers -- to be encapsulated by a layer
   below to modulate existing traffic, and a layer above to generate
   test traffic. The parameters of modulation are provided by a script
   in an interpreted language, presently Tcl, providing considerable
   flexibility. However, there is no mechanism to synthesize such
   scripts -- they must be explicitly designed. Furthermore, the use of
   an interpreted language such as Tcl limits the use of PFI to user-
   level implementations of network drivers, and may have performance
   implications.

7. Future Work

   This work is very much in its infancy; we have only begun to explore
   the possible uses for mobile network traces. We have uncovered
   several areas of further work.

   The trace format as it stands is very IP-centric. While one could
   imagine using unknown IP addresses for non-IP hosts, while using
   header-only properties to encode other addressing schemes, this is
   cumbersome at best. We are looking into ways to more conveniently
   encode other addressing schemes, but are content to focus on IP
   networks for the moment.

Two obvious questions concerning wireless media are the following.
How does a group of machines perform when sharing the same bandwidth?
How asymmetric is the performance of real-world wireless channels?
While we do have tools for merging traces taken from multiple hosts
into a single trace file, we've not yet begun to examine such
multiple-host scenarios in depth. We are also looking into
instrumenting wireless base stations as well as end-point hosts.

Much of our planned work involves the PaM testbed. First and
foremost, many wireless channels are known to be asymmetric;
splitting the replay trace into incoming and outgoing modulation
entries is of paramount importance. We would like to extend PaM to
handle multiple emulated interfaces as well as applying different
modulation parameters to packets from or to different destinations.
One could also imagine tracing performance from several different
networking environments, and switching between such environments
under application control. For example, consider a set of traces
showing radio performance at various altitudes; an airplane simulator
in a dive would switch from high-altitude modulation traces to low-
altitude ones.

Finally, we are anxious to begin exploring the properties of real-
world mobile networks, and subjecting our own mobile system designs
to PaM to see how they perform. We hope others can make use of our
tools to do the same.

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Security Considerations

    This RFC raises no security considerations.

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