On the Development of IETF-based Network Monitoring Probes for High Speed Networks

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Abstract

In the recent years network managers have increasingly relied on monitoring tools to characterize and measure high-layer protocol traffic in order to (a) justify investments on network equipment acquisition, (b) identify most network-consuming users, (c) detect bottlenecks, to mention just a few reasons. The Internet Engineering Task Force (IETF), aware of the mentioned demand, has been making efforts to standardize management mechanisms that allow the characterization and measurement of both protocols and networked applications behavior. However, the development of IETF compliant probes so that they sustain the traffic generated in high speed networks is a current challenge, since communication links operating at 100Mbps or higher rates require efficient packet filtering and processing mechanisms so that probes do not discard packets. This paper reports the development, by our research group, of a RMON2 compliant SNMP agent. The paper focuses on the project decisions, including the architecture and data structures used (having in mind that the agent is supposed to be deployed in high speed network environments). The paper also presents a performance evaluation of the agent.

Keywords: High speed network, monitoring, RMON2, SNMP.

1 Introduction

The popularization of computer networks in the recent years brought about the appearance of a high number of distributed applications and high-layer protocols. Online games such as Quake, videoconferencing tools (e.g. NetMeeting and CUseeMe) and applications for message and file exchange, like ICQ and Kazaa, are some examples of the "new" menu of networked applications. These applications and many other have been increasingly incorporated by network users to their daily routine, which for the network manager means the need for constant changes in the network infrastructure to support the increasing traffic imposed by them. Such modifications involve costs and, therefore, they need to be justified. Due to the diversity and complexity of these applications, not only *capacity planning* has become a more challenging task, but also *traffic characterization* and *monitoring* as well as *network optimization*.

The Internet Engineering Task Force (IETF), aware of the mentioned problem, has been making an effort to standardize management mechanisms that allow the characterization and measurement of both protocols and networked applications behavior. Remote Network Monitoring MIB version 2 (RMON2) [1], Application Performance Measurement MIB (APM) [2] and Real-time Application QoS Monitoring MIB (RAQMON) [3] are examples of initiatives where the *rmonmib* working group has been working on since the end of the 90's.

The importance of these standards is unquestionable. By using standard MIBs to accomplish protocols and networked applications monitoring, it becomes possible to manage an heterogeneous infrastructure, with network devices and probes from different vendors, using both the same interface (e.g. RMON2, APM and RAQMON MIBs) and communication protocol (e.g. SNMP). Besides, in opposition to what happens to most of the proprietary monitoring tools, a management station can collect data from several probes. Therefore, it is possible to monitor several subnets from one central manager.

The development of IETF compliant probes so that they sustain the traffic generated in high speed networks is a current challenge. On the one hand, communication links operating at 100Mbps or higher rates require efficient packet filtering and processing mechanisms so that probes do not discard packets. On the other, the size and complexity of the supported MIBs do not help to make the monitoring process efficient. IETF MIBs, specially RMON2, are composed of several groups that provide the network manager with different views about the monitored traffic. Hence, regardless of the architecture and data model used, each observed packet in the network traffic requires one or more updates in the internal structures maintained by the probe (delaying the accounting process).

This paper reports the development, by our research group, of an RMON2 compliant SNMP agent. The paper focuses on the project decisions, including the architecture and data structures used (having in mind that the agent is supposed to be deployed in high speed network environments). The paper also presents a performance evaluation of the agent. Besides discussing the difficulties of, at the same time, developing probes in conformance with IETF standards and making them able to operate in high speed networks, it is also a major contribution of this work the release of an open and free software-based RMON2 agent, which is an extension to NET-SNMP [4], and that can be used as an alternative to the expensive probes as there are not many requirements to run it on Intel `x86` stations (e.g. PCs). The agent can be deployed in any institution at close to zero costs and be used as a base to other academic researches[1].

The paper is organized as follows: section 2 describes some related work. In section 3 we present the developed agent. The paper follows with a detailed presentation, in section 4, of the performance evaluation done with the agent. Section 5 concludes with some final considerations and prospects for future research.

2 Related Work

Research works related to real time network traffic monitoring aim, in general, at proposing software architectures that are able to handle a large number of packets with the lowest possible discard rates. An approach to accomplish this objective is the use of efficient filtering and packet matching mechanisms. Monitoring tools proposed by Malan and Jahanian [5] and Anagnostakis et al. [6] take this aspect into account. Windmill is a passive network protocol performance measurement tool. The tool provides the underlying filtering mechanism as well as the ability to reconstruct the high-level protocol streams. It utilizes dynamic code generation for fast packet matching and is designed to demultiplex packets to a set of receivers (one-to-many). Through the combination of dynamic compilation and a fast matching algorithm, Windmill's WPF can match an incoming packet with five components in less than 350ns on a 200MHz Pentium-Pro. FLAME is a programmable packet monitoring system that provides a mechanism for loading code in the system kernel. It guarantees safety by using a type-safe language and run-time checks. Developers claim that the system sustains itself even under Gigabit per second traffic rates.

Other complementary and equally important approach to develop efficient real time traffic monitoring probes focuses on using data strucures that provide fast store and update procedures, since they are invoked at least once for every analyzed packet. In the case of ntop [7], an open-source web-based network usage monitor that enables users to track relevant network activities including network utilization, established connections, network protocol usage and traffic classification, hosts information is stored in a large hash table whose key is the 48 bit-long hardware (MAC) address that guarantees its uniqueness. Each entry contains several counters that keep track of the data sent/received by the host, sorted according to the supported network protocols. For each packet, the hash entry corresponding to packet source and destination is retrieved or created if not yet present. IPTraf is a network monitoring utility for IP networks that uses a similar approach [8]. The main data structures used by the various facilities are doubly-linked lists. This makes it easier to scroll forward and backward, and the maximum number of entries is limited only by available memory. Search operations on most facilities, are performed linearly, and have a mild hit [8]. The IP Traffic Monitor (part of IPTraf) though uses a hash table for better search efficiency, due to its propensity to grow quite rapidly.

Triticom, Network Harmoni, Cisco and Enterasys sell RMON2 probes that support 10 to 100Mbps traffic rates. However, information about packet filtering optimization and processing are not provided by these vendors. The RMON2 agent our research group has developed, as presented in the next sections, makes use of a user-level packet capture library and, therefore, tends to be less efficient than approaches that push this functionality into the kernel (e.g. FLAME). However, the station where our agent is installed can be used to run other applications concurrently. Regarding the data structures used to accomodate statistics provided by RMON2, we have mostly employed tables (implemented as vectors) indexed by *hash* functions. Besides, we have used additional mechanisms such as *caching* to improve agent efficiency (to support high-speed network traffic).

[1] It is important to highlight that there is no other open and free RMON2 agent implementation available.

3 Internals of the RMON2 Agent

In this section we describe the RMON2-compliant SNMP agent developed by our research group. The section starts with a brief review of the RMON2 MIB (sub-section 3.1), followed by a detailed description of the agent's architecture (sub-section 3.2). Then we present (a) the mechanisms used by the agent to store collected information (sub-section 3.3) and (b) relevant optimizations implemented (sub-section 3.4).

3.1 A Brief Review of the RMON2 Management Information Base

The works to extend RMON MIB and include mechanisms to monitor higher-layer protocols began in 1994. This initiative, called RMON2, resulted in the creation of RFC 2021 in January 1997 [1]. When monitoring high-layer protocols such as network and application-layer protocols, it is possible to visualize the whole corporate network instead of individual segments. Briefly, the groups defined in RMON2 MIB are:

- *protocol directory* (`protocolDir`): repository that indicates all the protocol encapsulations that the probe is capable to interpret; this group is composed of a single table;
- *protocol distribution* (`protocolDist`): provide statistics about the amount of traffic generated by each protocol encapsulation observed by the probe; it is composed of a control (`protocolDistControl`) and a data table (`protocolDistStats`);
- *address map* (`addressMap`): associates each network-layer address to the respective MAC address, storing it in a table;
- *network-layer host* (`nlHost`): collects statistics about the amount of input/output traffic of the hosts based on their network-layer addresses; composed of a control (`hlHostControl`) and a data table (`nlHost`);
- *network-layer matrix* (`nlMatrix`): provides statistics about the amount of traffic between host pairs based on their network-layer addresses; the network-layer matrix group is composed of two control tables (`hlMatrix-Control, nlMatrixTopNControl`) and three data tables (`nlMatrixDS, nlmatrixSD, nl-MatrixTopN`);
- *application-layer host* (`alHost`): collects statistics about the amount of input/output traffic of the hosts based on their application-layer addresses; it is composed of a data table (`alHost`) and is controlled by the network-layer host control table (`hlHostControl`);
- *application-layer matrix* (`alMatrix`): provides statistics about the amount of traffic between host pairs based on their application-layer addresses; the application-layer matrix is composed by three data tables (`alMatrixDS, alMatrixSD, alMatrixTopN`) and is controlled by the network-layer matrix control tables (`hlMatrixControl, hlMatrixTopNControl`);
- *user-history collection* (`usrHistory`): periodically samples objects specified by the user (manager) and stores the collected information in tables;
- *probe configuration*(`probeConfig`): controls the configuration of various operational parameters that are supported by the probe, software and hardware revision numbers of the probe, a trap destination table, and so on;
- *rmon conformance* (`rmonConformance`): describes the requirements for conformance to the RMON2 MIB.

The agent we have developed comprises the groups that provide statistical information: *protocol directory*, *protocol distribution*, *network-layer host*, *network-layer matrix*, *application-layer host* e *application-layer matrix*. Gaspary et al. describe in [9] the purpose of each of these tables in detail.

3.2 Architecture of the Agent

The agent runs on GNU/Linux stations and was developed as an extension to the Net-SNMP framework [4], using the C language, the POSIX thread library and the packet capture `libpcap` library [10]. Figure 1 shows the agent architecture. The `PM` (*Processing Module*) module is responsible for receiving and analyzing the captured packets (detailed in sub-sections 3.2.1 and 3.2.2). Essential information of the analyzed packets are identified and stored in an auxiliary data structure to be used later on by the `UM` (*Update Module*) module. The `UM` module, with the obtained information, updates the tables that store the statistics provided by the RMON2 MIB (sub-section 3.2.3). Finally, the `W` (Wrapper) module is an interface of the developed agent with the Net-SNMP daemon (sub-section 3.2.4).

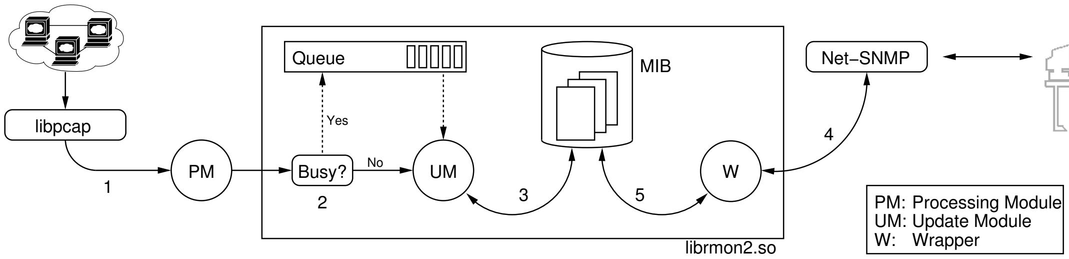


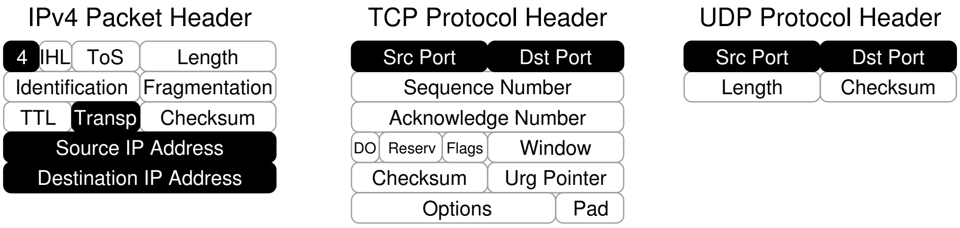
Figure 1: Internal organization of the agent

3.2.1 Packet capture

Packets are captured using the `libpcap` (Packet Capture library) library, which provides the developer with a high-level interface to capture all the packets flowing on the network segment. When the agent requests the library to start capturing packets in a certain interface, it registers a call-back function that is invoked whenever a packet is captured, delivering it to the `PM` module (see flow 1 in figure 1). The agent explores the filtering mechanisms available in the library. Hence, only packets whose encapsulations are registered at `protocolDir` table are captured, minimizing the number of packets that would be unnecessarily processed otherwise. When packets are discarded, the number of dropped packets is measured and `protocolDistControl`, `hlHostControl` and `hlMatrixControl` tables are updated.

3.2.2 Packet processing

To speed up the process of updating the tables that compose the RMON2 MIB, each packet delivered by the `libpcap` to the `PM` module is analyzed and essential information are grouped in a PEDB (Packet Essential Data Block). If the `UM` module is not busy, the PEDB is directly dispatched to it. Otherwise it is inserted in a circular queue (as illustrated in flow 2 of figure 1). This queue leads to packet loss rate reduction (especially during network traffic peaks). Figure 2 shows the essential information that are extracted from each packet and grouped in a PEDB.



IPv4 Packet Header

4	IHL	ToS	Length
Identification		Fragmentation	
TTL		Transp	Checksum
Source IP Address			
Destination IP Address			

TCP Protocol Header

Src Port		Dst Port	
Sequence Number			
Acknowledge Number			
DO	Reserv	Flags	Window
Checksum		Urg Pointer	
Options			Pad

UDP Protocol Header

Src Port	Dst Port
Length	Checksum

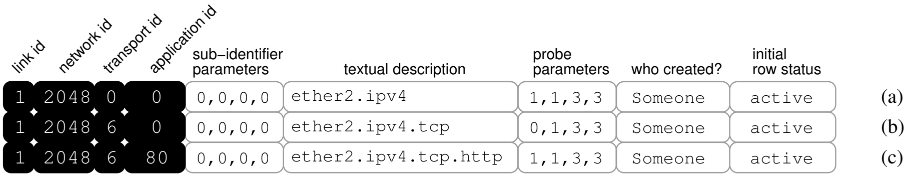
Figure 2: Essential information extracted from the captured packets

3.2.3 Update of the RMON2 tables

Concurrently to the process just mentioned, the `UM` module checks if there is any pending PEDB in the queue. If not, it is going to block until the `PM` module delivers new data. Whenever the `UM` module receives a new PEDB, it updates the RMON2 MIB tables executing the procedure described below. To illustrate it, consider an `http/tcp/ipv4/ether2` packet being processed by an agent configured to identify the encapsulations listed in figure 3.

- First, the `UM` module checks if there is an encapsulation registered at the `protocolDir` table that matches the encapsulation of the PEDB being processed, taking only **link** and **network** layers into account. If so, as occurs in figure 3 (a), then tables `protocolDistStats`, `nlHost` and `nlMatrix` must be updated.
- Second, the `UM` module checks if there is an encapsulation registered at the `protocolDir` table that matches the encapsulation of the PEDB being processed, taking only **link**, **network** and **transport** layers into account. If so, as occurs in figure 3 (b), then tables `protocolDistStats`, `nlHost`, `nlMatrix`, `alHost` and `alMatrix` must be updated.

- Third, the UM module checks if there is an encapsulation registered at the protocolDir table that matches the encapsulation of the PEDB being processed, taking all **link**, **network**, **transport** and **application** layers into account. If so, as occurs in figure 3 (c), then tables protocolDistStats, nlHost, nlMatrix, alHost and alMatrix must be updated.



link id	network id	transport id	application id	sub–identifier parameters	textual description	probe parameters	who created?	initial row status	
1	2048	0	0	0,0,0,0	ether2.ipv4	1,1,3,3	Someone	active	(a)
1	2048	6	0	0,0,0,0	ether2.ipv4.tcp	0,1,3,3	Someone	active	(b)
1	2048	6	80	0,0,0,0	ether2.ipv4.tcp.http	1,1,3,3	Someone	active	(c)

Figure 3: Examples of encapsulations registered at the protocolDir table

3.2.4 Integration of the agent to the Net-SNMP framework

The integration between the RMON2 agent and Net-SNMP is done through a module (Wrapper) that registers several call-back functions. These functions are invoked whenever the Net-SNMP daemon receives a request (get, getnext or set) referring to RMON2 MIB objects (see flows 4 and 5 in figure 1). The Wrapper module had its basic structure created by a tool called mib2c (included in Net-SNMP distribution). The skeleton automatically generated has been populated with functions that (a) access the data structures developed (detailed in next subsection) and (b) retrieve/set the information being requested/informed.

3.3 Storing of Collected Information

This section describes how the statistics that comprise the RMON2 MIB are internally stored by the agent. Basically, three types of data structures have been used: direct access, hash function-based access and cache-based access (detailed in the following sub-sections).

3.3.1 Data structures with direct access

The protocolDir and control tables (protocolDistControl, hlHostControl, hlMatrixControl, hlHostControl and alMatrixControl) have been implemented as vectors with direct access. These tables consist of vectors of pointers, which are used to allocate specific records of each table. Due to the static nature of these data structures, table sizes must be configured before compiling the agent.

3.3.2 Data structures with hash function-based access

Data tables (protocolDistStats, nlHost, nlMatrix, alHost and alMatrix) have been implemented as vectors of pointers whose indexing is done through a hash function applied to a key. This approach provides fast data retrieval (in the first attempt in general). For each data table there is a particular way of generating the key that will be used to access or insert an entry in its respective storage slot. As an example, figure 4 shows both the composition of the key used to access or insert an entry in alHost and the process of collision resolution.

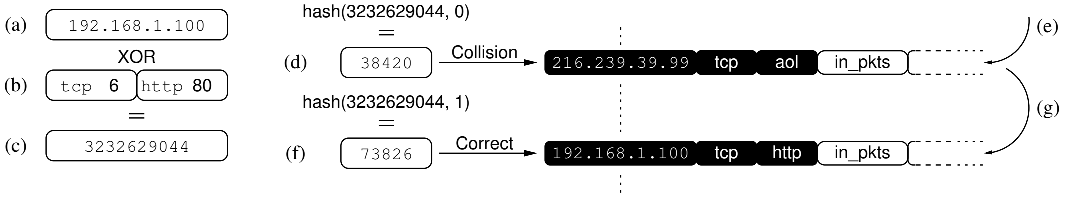


Figure 4: Key generation, access to the alHost table and conflict resolution

To generate the key, a XOR logical operation is performed on the source network-layer address, illustrated in figure 4(a), and the transport protocol identifier plus the destination application port (b), producing the key (c).

By applying the hash function to this key, one obtain the first vector access index (d), enabling the access to the table, illustrated in (e). In the example, one can observe that the entry in position (d) is not the one to be updated (network-layer addresses and application ports do not match), resulting an access collision. When it happens, it is necessary to calculate the second vector access index using the same key (c). By passing an offset of 1 as argument to the hash function, a skip (spacing between the keys) of 35406 slots has been added to the initial index (d), generating the second index (f). As one can see in the figure, this index will correctly point to the entry to be updated (g). It is worth mentioning that each key has a different spacing between keys reducing the probability of collisions.

Had other collision occurred, the previous step would be repeated using an offset of 2, and so on, until the corresponding entry had been found. After using all possible offsets, it means a new entry is supposed to be created and inserted in the table. Besides, the value for the maximum number of collisions must be updated, since the last entry inserted is located after the search limit the agent does.

3.3.3 Data structures with cash-based access

The `protocolDir` table, besides being directly accessed, has an auxiliary structure that provides the functionality of a cache. As some encapsulations are identified more than others in the network traffic, they are promoted and are moved to the header of a doubly-linked list. Hence, encapsulations that occur more frequently are located in the `protocolDir` table in a shorter time (and with lower computational cost). To speed up the search for encapsulations even more, the table uses three caches, one for each encapsulation level (network, transport and application).

3.4 Optimizations

During the development of the agent we have put efforts into increasing the processor cache hit rates (in an attempt to maximize the number of operations that are retrieved from the processor cache memory). The data structures have been designed aiming at obtaining a better usage of the new features and resources provided by current processors. For example, current `i686` processors have multiple parallel execution units, allowing anticipated instruction decoding. Hence, while an instruction is being executed, the next is decoded, reducing the time the processor has to wait for instruction decoding. There are also special parallel execution channels that allow operations on integer and float point numbers to be executed in parallel.

4 Performance Analysis of the Agent

In this section we describe the performance analysis we have carried out to determine the sustained capacity of the agent. The experimental setup used to run the experiments is presented in sub-section 4.1. Then we present in sub-section 4.2 the measurements performed (using both homogeneous and realistic network traffic) to figure out the performance of the agent.

4.1 Experimental Setup

To analyse the performance of the agent we have used a simple setup, consisting of two PCs connected through a category 5e UTP crossover cable at 100Mbps. The source host has a 333MHz Intel Celeron (Mendocino) CPU and 64MB RAM. Its Ethernet controller is the 100Mbps 3COM 3c905B Cyclone. The operating system used in the source host is the GNU/Linux (Slackware Linux 8.0, kernel 2.4.20). The destination host (where the RMON2 agent is installed) has a 1.7GHz Intel Pentium 4 CPU, 512MB RAM, an Intel i845 (Brookdale) chipset host bridge, a 100 Mbps 3COM 3c905C-TX/TX-M Tornado network interface card and runs GNU/Linux (Slackware Linux 8.1, kernel 2.4.20).

4.2 Measurements

The first experiment consisted of transmitting 1,000,000 UDP packets (with the same protocol header) from source to destination, at 100Mbps, using the packet generator module provided by the Linux kernel. This transmission has been repeated 43 times varying the size of the packets generated, to achieve different packets per second (pps) rates. The purpose of this experiment was to obtain the maximum number of packets per second the agent is able to process and to identify the interference of the operating system on the agent monitoring capacity.

In this first experiment, 64 to 1472 byte-long packets have been used. From 64 to 224 bytes, the packet sizes have been increased of eight bytes in each run so that we could identify the maximum agent capacity. From 256 to 1472 bytes the packet sizes have been enlarged 64 bytes in each run. In figure 5 one can observe that the agent capacity is highly affected by the heavy system load. From 208-byte long packets on, the system load allowed the agent to process 58,900pps with a 8.68% loss rate. It is worth noticing that, although when using 216 byte-long or larger packets the system has already some free CPU time, the agent still lose some packets. It occurs because there is a bottleneck when delivering captured packets by the libpcap to the RMON2 agent, evidenced by the fact that with 960-byte long packets there was a 0% loss rate (at 12,700pps), while with 1472-byte long packets (at 8,355pps) the loss rate reached 0.0015%.

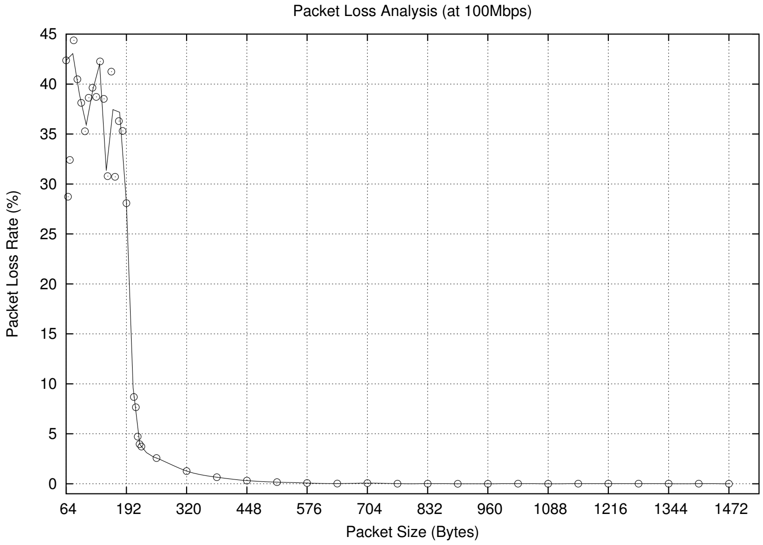


Figure 5: Packet loss rate at 100Mbps

To accomplish the realistic traffic test, a faster machine was necessary to substitute the one used as the source. The employed machined as the new sender is identical to the receiver, capable of retransmitting the traffic at the rate it was collected. Its characterization is shown in figure 6, containing 97.6482% of IPv4 packets from which 96.4051% are TCP packets (over the total of 1,000,000 packets) and 0.8486 are UDP packets. The remaining packets were not analysed by the RMON2 agent.

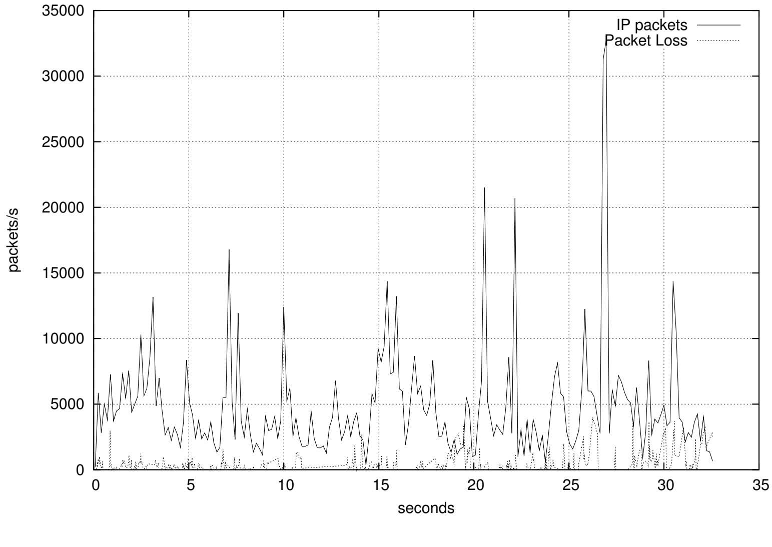


Figure 6: Characterization of the realistic traffic used to analyse the agent performance

The average packet loss in the carried out experiments was of 23.9608%. During the experiments, it was verified that the peaks of CPU use are directly related with packet dropping. A more refined analysis indicated that the protocolDir table cache mechanism presents deficiencies when submitted to very diversified traffic, as occurs in the carried out experiments, forcing the agent to discard packets.

5 Conclusions and Future Work

The RMON2 MIB, as happens with others MIBs standardized by the IETF, has a large number of objects, offering different views of the network traffic being monitored. To keep these views real-time updated, each captured packet requires a numerous set of tables to be updated. For example, when a http/tcp/ipv4/ether2 packet is captured (assuming the agent is setup to analyse this encapsulation), it is necessary to update statistics related to the network, transport and application protocols. This demands high computacional effort, directly affecting the tool's performance (as shown in figure 5).

The mechanisms chosen to support network monitoring (and to keep MIB objects up to date) are critical to achieve the necessary scalability to cope with high-speed networks. On passive network monitoring, intensively used by our agent, having a capture library on user-space becomes an inadequate approach to meet the imposed requirements to monitor networks whose rates are close to and higher than 100Mbps. Our research group believes that one strategy to adopt is the development of a Linux kernel module with similar functionalities to the libpcap library, aiming the agent specific needs. Other identified optimization points relate to a better CPU use, as suggested in [11].

Our experiments point that the cache mechanism, used to improve protocolDir table access performance, showed itself improper to specific conditions (traffic with a large variety of protocols). These observations lead us to the redesign of its internal structure, replacing the actual cache with a hash table (work in progress).

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