Open Source Traffic Analyzer

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Abstract

Proper traffic analysis is crucial for the development of network systems, services and protocols. Traffic analysis equipment is often based on costly dedicated hardware, and uses proprietary software for traffic generation and analysis. The recent advances in open source packet processing, with the potential of generating and receiving packets using a regular Linux computer at 10 Gb/s speed, opens up very interesting possibilities in terms of implementing a traffic analysis system based on open-source Linux.

The pktgen software package for Linux is a popular tool in the networking community for generating traffic loads for network experiments. Pktgen is a high-speed packet generator, running in the Linux kernel very close to the hardware, thereby making it possible to generate packets with very little processing overhead. The packet generation can be controlled through a user interface with respect to packet size, IP and MAC addresses, port numbers, inter-packet delay, and so on.

Pktgen was originally designed with the main goal of generating packets at very high rate. However, when it comes to support for traffic analysis, pktgen has several limitations. One of the most important characteristics of a packet generator is the ability to generate traffic at a specified rate. Pktgen can only do this indirectly, by inserting delays between packets. Moreover, the timer granularity prevents precise control of the transmission rate, something which severely reduces pktgen's usefulness as an analysis tool. Furthermore, pktgen lacks support for receive-side analysis and statistics generation. This is a key issue in order to convert pktgen into a useful network analyser tool.

In this paper, improvements to pktgen are proposed, designed, implemented and evaluated, with the goal of evolving pktgen into a complete and efficient network analysis tool. The rate control is significantly improved, increasing the resolution and improving the usability by making it possible to specify exactly the sending rate. A receive-side tool is designed and implemented with support for measurement of number of packets, throughput, inter-arrival time, jitter and latency. The design of the receiver takes advantage of SMP systems and new features on modern network cards, in particular support for multiple receive queues and CPU scheduling. This makes it possible to use multiple CPUs to parallelize the work, improving the overall capacity of the traffic analyser.

A significant part of the work has been spent on investigating low-level details of Linux networking. From this work we draw some general conclusions related to high speed packet processing in SMP systems. In particular, we study how the packet processing capacity per CPU depends on the number of CPUs.

This work consists of minimal set of kernel patches to pktgen.

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Chapter 1

Introduction

Proper traffic analysis equipment is crucial for the development of network systems, services and protocols. Traffic analysis equipment is often based on costly dedicated hardware, and uses proprietary software for traffic generation and analysis. The recent advances in open source packet processing, with the potential of generating and receiving packets using a regular Linux PC at 10 Gb/s speed, opens up very interesting possibilities in terms of implementing a traffic analysis system based on an open-source Linux system.

Open source traffic analysers can be used in academic and research communities in order to understand better networks and systems. This can be used to create better hardware and operating systems for the future.

Processors manufactures are focusing their designs in systems with multiple processors, called SMP systems, instead of increasing the processor clock. Processors with up to 4 cores are becoming common in the commodity market. In order to take advantage of SMP systems, new feature such multiple queues are added to network cards. This allows multiple CPUs to work concurrently without any interference. Each CPU is in charge of one queue, making possible the parallelization of the packet processing of a single interface. This feature can be used to increase the performance of the tools that analyse high speed networks.

There are different options in the open source community of Linux to analyse network behaviour, but most of them are user-space applications (netperf, iperf ...). They have advantages in terms of usability but also drawbacks in terms of performance. Managing small packets in high speed networks requires a lot of process, and all the resources of the system are needed. In this case, user-space applications do not achieve higher rates. The main problem is that there is a high overhead due to the entire network stack.

The Pktgen software package for Linux is a popular tool in the networking community for generating traffic loads for network experiments. Pktgen is a high-speed packet generator, running in the Linux kernel very close to the hardware, thereby making it possible to generate packets with very little processing overhead. The packet generation can be controlled through the user interface with respect to packet size, IP and MAC addresses, port numbers, inter-packet delay, and so on.

There is currently no receive-side counterpart to Pktgen. That is, an application that receives packets on an interface, performs analysis on the packets received, and collects statistics. Pktgen have the advantage that is a kernel module, which can bypass entire network overhead, resulting in better performance. Also, because it is inside the kernel can use resources of the system more efficiently.

1.1 Goals

The goals of this master thesis can be described as follows:

- Investigate the current solutions for traffic analyses
- Understand how Pktgen works
- Investigate how design and implement a network analyser inside the Linux Kernel, taking advantage of the new features in the modern systems.
- Integrate the results in the current Pktgen module
- Evaluate and calibrate the behaviour of the module implemented

1.2 Thesis outline

This work is organized as follows:

- *Chapter 2* contains the background study. A study of the current network analysis tools and methodologies is done. Also, a brief introduction of the Linux Kernel is presented. Finally Pktgen is studied in depth in order to understand how it works.
- *Chapter 3* contains the requirements and the design of the traffic analyzer implemented with Pktgen. The design includes the architecture, the receiver metrics and the application interface. Also an overview of the operation is presented.
- *Chapter 4* contains some explanations of the modified code, as well as the new add-ons. Moreover some test are included in order to justify its choice. Also explains how the design proposed in *Chapter 3* is implemented.
- *Chapter 5* evaluates the behaviour and performance of the implemented solution using different real tests. Some conclusions about the results of the test are drawn.
- *Chapter 6* summarise the work and draws some conclusion of it. Moreover, some suggestions for the future work are provided.

Chapter 2

Background study

This chapter includes a study of the current network analysis tools and methodologies. Then, some of the used parameters of the network analysis tools are defined. Also, a brief introduction of the Linux Kernel is presented. Finally Pktgen is studied in depth in order to understand how it works, in order to add new features to Pktgen.

2.1 Network analysis

2.1.1 Methodologies

Traditionally two different approaches are taken in order to analyse the network and its performance. The first one is **custom hardware based** solutions which are usually very expensive but have a good performance. The second one is **software based** which it is cheaper and more flexible. It can run in general purpose systems, such as Personal Computers (PCs) but sometimes it has problems of performance at high speed networks. Also, in the recent years, a third solution based on network processors appears between both of them.

In the following section, different solutions of different types will be introduced with a brief overview.

2.1.2 Custom hardware based

Usually custom hardware based solutions are proprietary and very expensive due to its specialization. It is the most popular approach for the industrial environment. Such solutions are designed to minimize the delays and increase the performance. All the functionalities are developed near the hardware in order to adjust the delays introduced by the operating system (OS) in general purpose systems.

These tools are configurable, but due to its specialization it is difficult to change its behaviour. Normally, the testing equipment is located at the ends of the sections to be tested.

2.1.2.1 Ixia - IxNetwork

Ixia [1] is the former Agilent. Ixia's solutions are based on hardware and specialized equipment. Their products offer a wide range of testing tools for performance and compliance of communications equipment. Related with network analysis are IxNetwork and IxCharriot.

IxNetwork IxNetwork [2] is the solution for testing network equipment at its full capacity. It allows simulating and tracking millions of traffic flows. Also there is a wizard to customize the traffic

and is able to generate up to 4 million traceable flows due to its scalability. It is focused in L2 and L3 protocols.

The traffic measurements according with [2] are showed in Table 2.1.

Loss	Track Tx frames, Rx expected frames, Rx frames, Rx bytes frame delta loss
Rate	Tx frame rate, Rx frame rate, Rx rate (bps, Bps, Kbps, Mbps)
Latency	Store and forward, cut-through, MEF frame delay, forwarding delay
Delay Variation (Jitter)	Delay variation measurement (jitter) minimum, average, maximum
Inter-arrival time	Inter-arrival minimum, average, maximum
Sequence	Small error, big error, reverse error, last sequence number, duplicate frames, sequence gaps
Time Stamps	First and last timestamp per flow
Packet Loss Duration	Estimated time without received packets calculated by frames delta at the expected Rx rate
Misdirected Packets	Per-port based count of packets not expected on an Rx port

Table 2.1. Traffic measurements at IxNetwork

IxCharriot *IxCharriot* [3] is a tool for making network test between two endpoints. It is based on Windows. According to the manufacturer is a tool for simulating real-world applications to predict device and system performance under realistic load conditions.

2.1.2.2 Spirent SmartBits

Spirent SmartBits [4] (see Figure 2.1) is a hardware for generating and simulate high traffics in multiples ports. It has interfaces for the most common carrier and user ports. It is used for test, simulate, analyse, troubleshoot, develop, and certify network infrastructure. It consists of two parts: the chassis with specific module for the selected interface and the SmartBits Control station, which is in charge of setting up the hardware in the configuration and controlling the test. It allows manual and automation control. Depending on the selection of the correct control, it allows testing different layers from 2 to 7.

Depending on the module used, more or less capabilities are obtained. They are classified in traditional, SmartMetrics and TeraMetrics. Traditional capabilities include sending packet at wire speed, throughput, latency (delay), packet loss, variable packet length. SmartMetrics includes capabilities for advance traffic generation and tracking. TeraMetrics can also simultaneously correlate data plane tests with control plane traffic such as routing, to provide the most realistic performance measurements.

2.1.3 Software based

Software based solutions are cheaper and more flexible than hardware based but they have limitations on performance in high speed connections. Most of them, work well at low rates but they does not obtain high rates especially in small packets, as shown in [5].

There are libraries to make easier the applications programming, user space tools that use or not the features offered by the libraries, and kernel tools, which are closer to the hardware and allow

Figure 2.1. Spirent SmartBits

better performances. User tool are libraries rely on the kernel, because the kernel is the only element which has direct access to the hardware.

2.1.3.1 Libraries

Libraries contain codes that are used by other programs. It is the way of reusing code. Usually libraries are linked with the program at compilation time.

Pcap Libpcap [6] is a library which allows the user-space to capture network packets at low level. Also it provides filter engines. It was originally developed at the scope of Tcpdump [6] and later ported to a library. Many analyzing tools, protocol analyses, network monitors, traffic testers, traffic generators and network intrusion detectors use libpcap or the Windows version WinPcap. Some of the programs that use libpcap are: tcpdump, Wireshark (formerly Ethereal) [7], Snort [8], ssldump [9], Nmap [10], justniffer [11], Kismet [12], Mausezahn [13], ...)

Ncap Ncap [14] was proposed in [15]. Essentially it is a library that allows user space application to send and receive packets bypassing the kernel. It is designed for using in high speed networks. It is divided in two components: a driver module and a user space library. Only it is implemented in Intel cards drivers. It connects the user space library directly to the NIC firmware in order to reduce the overhead caused by the kernel. Only one application can use the network card when it is controlled by ncap. When is not used, the kernel has the control.

There is a modification of the libpcap library which allows using the features of ncap without porting the applications which use pcap. The only necessary thing is linking the application with the new library.

It is designed for commodity software and hardware.

Some of its drawback is its dependency to a specific kernel and network adapter. When it is implemented in a multi-processor / multi-core environment it has some limitations due to the lack of the ability to share a network adapter between multiple threads or processors.

It is distributed with a GNU GPL2 and a BSD license, but the code is not available. A fee is required in order to finance the research work.

Dashcap Dashcap was proposed in [16]. It is another library for capturing packets at high speed rate. It is multi-core aware. Also it is composed by two modules: a kernel module and a user-space library. Running multiple applications work in the same NIC is allowed.

Neither the source nor the binary is available.

2.1.3.2 User Space tools

User space tools are on the top of the system architecture and usually have lower performance and speed than kernel ones. They use system calls to use the resources of the system.

IPerf *IPerf* [17] is a classical Linux tool that allows testing the throughput of a network connection between two nodes at application level. It can operate with TCP and UDP and returns the network bandwidth of a given link with the given buffers. It makes some modifications in the buffers of the system in order to get the higher throughput. Also it allows setting customized values for the user.

A server is listening for incoming connection and the client starts the connection and measures the network bandwidth in a unidirectional way. It is possible to measure bidirectional traffic.

The statistics offered by *IPerf* are the amount of data transferred in a given interval, the average throughput, the jitter and the losses.

NetPerf *Netperf* [18] is a popular tool for benchmarking the network. It is created by IND Networking Performance Team of Hewlett-Packard. It provides tests for both unidirectional throughput, and end-to-end latency. It is focused on sending bulk data using either TCP or UDP.

The only statistic offered by *NetPerf* is the throughput of the test. The latency has to be obtained in an indirect way.

NetPIPE *NetPIPE* [19] is a benchmark tool for the network throughput. It sends messages with an incremental size in order to evaluate the throughput obtained with this message. It allows checking the OS parameters (socket buffer sizes, etc...) with messages of different size in order to optimize them. Also allows identifying drop-outs in networking hardware and drivers.

The result of the test is a series that contains the message length, the times that it is send, the throughput obtained and the time needed to send it. It generates a file with the output in order to represent it.

Mausezahn *Mausezahn* [13] is a free traffic generator which allows sending whatever type of packet because the packets can be customized. It allows measuring the jitter between two hosts. It is based in libpcap library (See 2.1.3.1).

The statistics obtained by Mausezahn are: timestamp, minimum jitter, average jitter, maximum jitter, estimated jitter, minimum delta RX, average delta RX, maximum delta RX, packet drop count (total) and packet disorder count (total).

Harpoon *Harpoon* [20] is a flow-level traffic generator. It can generate the distribution statistics extracted from Netflow traces to generate flows which contains real Internet packet behaviour.

TPtest *TPtest* [21] is a tool for measuring the throughput speed of an Internet connection to and from different servers. It was originally developed by the Swedish government. It is used for evaluate the quality of the service offered by the Internet Service Providers (ISP).

It allows measuring the TCP and UDP throughput (incoming and outgoing), UDP packet loss, UDP round trip times and UDP out-of-order packet reception.

ttcp *Ttcp* [22] is a command-line sockets-based benchmarking tool for measuring TCP and UDP performance between two systems. It was developed in the BSD operation system in 1984. The code is freely available.

nuttcp *Nuttcp*[23] is a tool for measuring the throughput of a network. It is a modification of ttcp. It allows adjusting the output throughput and the packet size. The results displayed are the throughput archived, the packets received and the packets lost. Also it includes the load of the receiver and the transmission node. Nuttcp can run as a server and pass all the results to the client side. Then, it is not necessary to have access to the server.

RUDE/CRUDE RUDE [24] stands for Real-time UDP Data Emitter and CRUDE for Collector for RUDE. RUDE is a traffic generator and measurement tool for UDP traffic. It allows selecting the rate, and the results displayed are delay, jitter and loss measurements.

D-ITG D-ITG (Distributed Internet Traffic Generator)[25] is a platform capable to produce traffic at packet level to simulate traffic according to both Inter Departure Time and packet size with different distributions (exponential, uniform, cauchy, normal, pareto, ...). D-ITG is capable to generate traffic at network, transport, and application layer.

It measures One Way Delay (OWD), Round Trip Time (RTT), packet loss, jitter, and throughput.

LMbench LMbench[26] is a set of tools for benchmarking for different elements of a system. It include network test for measuring the throughput and the latency.

BRUTE BRUTE [27] is the acronym of Brawny and RobUst Traffic Engine. It is a user space application running on the top Linux operating system designed to produce high load of customizable network traffic. According with the author, it allows generating up to 1.4 Mpps of 64 bytes in a common PC.

2.1.3.3 Kernel Space tools

Kernel space tools archived better performance than user-space tools because they are closer to the hardware and they have more priority. Also they bypass the network stack, which user-space tools need to pass and do not suffer from context switching.

Pktgen *Pktgen* [28] is a packet generator at kernel space. Its main goal is to send at the maximum speed allowed by the Network Interface Card (NIC) to test network elements. It was introduced in [29]. A deep analysis of Pktgen is done in Section 2.3.

KUTE *KUTE* [5] [30] (formerly known as UDPgen), stands for Kernel-based UDP Traffic Engine, is a packet generator and receiver that works inside the kernel. It is focused on measuring the throughput and the inter-packet time accuracy (jitter) in high speed networks. It allows sending at different rates. It is composed of two kernel modules which cannot communicate with the user space. When the transmission module is loaded, it starts to send packets according with the configuration. The transmission and the reception are controlled with scripts. It has two different routines for receive packets: using the UDP handler (replace the original UDP handler to its handler) or using a modification of the driver to get better performance. In this way, the network stack is bypassed. The results are displayed in the proc file system (See Section 2.2.2) and then are exported to */var/log/messages* when the module is unloaded.

2.1.4 Mixed solution

2.1.4.1 Caldera Technologies - LANforge-FIRE Stateful Network Traffic Generator

LANForge Fire [31] is a network packet generator for testing the network. It is stateful and allows generating traffic of all types of protocols. Also the maximum and minimum rate can be chosen. The tool is based on software, concretely in a Linux with a private customized kernel. The vendor sells this software with different hardware since laptops for low traffic emulations (up to 45 Mbps) to high performance servers (for 10 Gigabit connections).

The software part can be downloaded and purchased individually. Also there are a Live CD and pre-compiled kernels for Fedora which can be download in the website of the vendor [31] after a free register. The user interface is based on Java; therefore it can run in any system which has a Java Virtual Machine.

The statistics offered at Level 3 by *LANForge Fire* are packet transmit rate, packet receive rate, packet receive drop, transmit bytes, receive bytes, latency, delay, duplicate packets, out of order packets (OOO), CRC fail and received bit errors.

2.1.4.2 TNT Pktgen

TNT Pktgen [32] [33] is a project of the TNT laboratory in University of Geneva. Its goal is to develop a packet generator based on software but using network processors. It is developed over the Intel IXP2400 Network Processor [34]. Currently it is only developed the generator part and is awaiting the generation of statistics.

2.1.4.3 BRUNO

BRUNO [35] stands for BRUte on Network prOcessor), is a traffic generator built on the Intel IXP2400 Network Processor and based on a modified BRUTE version. Its goal is to send packets according to different models. It uses network processors in order to have more accurate time departures. It is only a packet generator, therefore it doesn't obtain statistics on the receiver side.

2.1.5 Metrics used in network analysis

After the study of the current solutions it is necessary to explain the used parameters in these tools.

2.1.5.1 IETF recommendations

The Internet Engineering Task Force (IETF) had made some recommendations for the metrics and methodologies which are necessary to use in network analysis. RFC 2544 [36] defines the methodology to benchmark network interconnect elements. RFC 2889 [37] extends the benchmarking methodology defined in RFC 2544 for local area networks (LAN) switching devices. The defined benchmarking test, where the definitions of each element are in the RFC 1242 [38] and RFC 2285 [39], are:

- **Throughput:** *"The maximum rate at which none of the offered frames are dropped by the device."*. It is calculate as the fraction between the amount of data transferred during a certain time.
- **Latency:** *"The time interval starting when the last bit of the input frame reaches the input port and ending when the first bit of the output frame is seen on the output port"*. When a network is considered, is the total time for travelling from source to a destination. It includes the network delay and the processing delay in the interconnection network equipments.

- **Frame loss rate:** *"Percentage of frames that should have been forwarded by a network device under steady state (constant) load that were not forwarded due to lack of resources."*

- **Back-to-back frames:** *"Fixed length frames presented at a rate such that there is the minimum legal separation for a given medium between frames over a short to medium period of time, starting from an idle state."*

The test above explained has to be repeated for different frame sizes. According to RFC 2544, for Ethernet devices these sizes are: 64, 128, 256, 512, 1024, 1280 and 1518 Bytes.

2.1.5.2 Summary of parameters used in studied platforms

After analyzing the different tools, the most common parameters in software based solutions are: packets sent / received, packets loss, throughput, jitter and inter-arrival times. Otherwise, the hardware based solutions offers more detailed statistical, such latency, delays, evaluation of different flows and compliance with the recommendations of the IETF in the field of benchmarking test.

Some of the tools offer a jitter measurement. Jitter (and latency) is used to characterize the temporal performance of a network. RFC 4689 [40] defines **jitter** as *"the absolute value of the difference between the Forwarding Delay of two consecutive received packets belonging to the same stream"*. The jitter is important in real-time communications when the variation between delays can cause a negative impact to the server quality, such voice over IP services.

There are three common methodologies to obtain jitter. They are described in [41]. Basically, there are the inter-arrival method, the capture and post-process method and true real-time jitter method. Usually it needs 4 parameters to be calculated.

The inter-arrival method consists of transmitting the packets in a known constant interval. Only it is necessary to measure the inter-arrival time between packets because two of the both parameters are known. The difference between the inter-arrival times is the jitter. If the flow is not constant, this method cannot be used.

The capture and post-process method consist of capturing all the packets. In transmission a timestamp is sent when the packet is transmitted. After capturing all the packets, the jitter is calculated. Its drawback is the finite available buffers.

The true real-time jitter method is defined in MEF 10 specification released on 2004. It is not necessary to send the packets at a known interval and the traffic can be bursty. Also there is not restriction in test duration and it is loss and out-of order tolerant. If the packet is the first received in the stream, then the delay (latency) is calculated and stored. If a received packet is not the first packet in the stream then it is checked if it in the correct sequence. If not, the results of latency are discarded and this packet is the *new* first packet. If the packet is not the first and it is in sequence, then the delay is calculated and stored. Then, the delay variation (jitter) is calculated by taking the difference of the delay of the current packet and the delay of the previous packet. Maximum, minimum, and average jitter values are updated and stored.

One-way latency measurement requires time synchronization between the two nodes. A basic technique is sending probes across the network. (See [42]). This is intrusive with the traffic. A novel approached is proposed in [43], where a mechanism called LDA is presented. It consists in different timestamp accumulators in the sender and the receiver. The packets are hashed and then inserted in one accumulator. Also the packets in each accumulator are count. At the end, if both accumulators have the same number of packets, the desired statistics are extracted. This mechanism avoids the bias caused by the packets loss. The basic mechanism consists in subtracting the transmission time with the receiver time. The synchronization between nodes is critical.

2.1.6 Technologies

Traffic analysis at high speed in commodity equipment is still an open issue. However different technologies and methodologies appear in order to solve this.

One approach is using **network processors** (used in TNT Pktgen 2.1.4.2). Network processors are integrated circuits which are specialized in network task. In this way, the load of the main CPU is reduced. This approach is cheaper than all customized platform because these network processor can be installed in normal PCs. On the other hand, it is needed a specialized hardware.

Another approach used by Intel is using **multiple queues** in the NICs in order to take advantage of the multi-core architecture. This technique is available in the Ethernet Controllers Intel 82575 [44], Intel 82598 [45], Intel 82599 [46] and other new networking chipsets. The main features of this technology are in [47]. The driver has multiple queues which can be assigned to different CPUs. This allows sharing load of the incoming packets between different CPUs. The main technique used on the cards is called RSS (Receive Side Scaling). RSS distributes packet processing between several processor cores by assigning packets into different descriptor queues. The same flow always goes to the same queue in order to avoid packet re-ordering.

2.2 Linux Kernel

This section summary the main characteristics of the kernel in order to understand and design the module. Understanding all the Linux Kernel is out of the scope of this thesis. For farther information about how Linux works see *Understanding Linux Network Internals* [48] and *Linux Device Drivers, Third Edition* [49].

2.2.1 Linux overview

Linux Kernel is the core of Linux system. Technically, Linux is the kernel, and the rest of the system is a set of applications that it has not relation with the kernel. The kernel offers an interface for the hardware (with the system call functions) and it is the responsible of the control of all processes and resources on the machine.

The Linux kernel is divided in different subsystems, which are: process management, memory management, file systems, device control and networking. (See Figure 2.2).

Several processes are running in the same machine and the kernel has to control the use of the CPU for each process. This task is done by the process management subsystem. Also the physical memory has to be shared between the kernel and the applications. This subsystem in charge is the memory management. Linux is based on file system concept, almost everything can be treated as file. Here is where the file system appears. Also it is necessary to control all the devices in the system, such as network interfaces, USB devices, keyboard, ...). The device control is in charge of this part. Finally, the networking is in charge of the communications with different system across the network.

The code in the kernel can be compiled as built-in or as a module. Built-in means that the code is integrated in the kernel and cannot be disabled on runtime. Otherwise, when the code is compiled as a module it can be loaded and unloaded on runtime which offers more flexibility and granularity to the kernel. This feature allows having multiple drivers and only loading the required ones. Otherwise the kernel would be too big and consume lot of memory.

2.2.2 Communications between User-space to kernel

There are different interfaces to communicate the user-space programs with the kernel.

- **proc file system**: It is a virtual file system, usually under */proc* where modules can register one or more files, which are accessible in the user space, in order to export data. When the

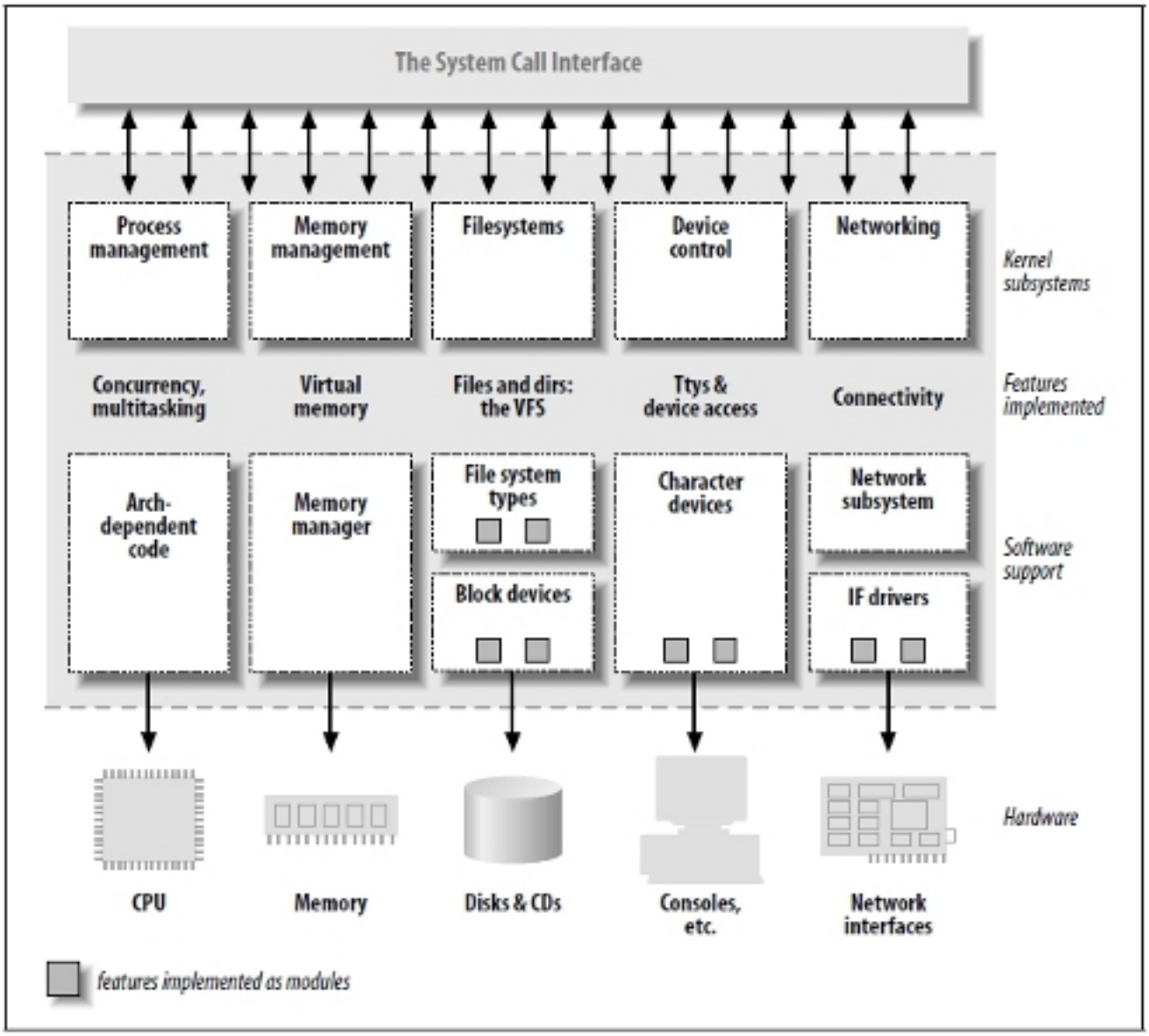


Figure 2.2. A split view of the kernel. Source [49]

user read, some functions of the module are called and the output is generated. It can only export read-only data.

- **sysctl**: It is a file system, usually under /proc/sys where it is possible to write data into the kernel, but only by the super user. Usually, in read-only data, the choice between proc and sysctl depends on how much data will be exported. For single variables is recommended sysctl and for complex structures proc.

- **sysfs**: It is a new file system for export plenty of information of the kernel. Proc and systcl have been abused over the years and this file system is trying to solve this. Some of the kernel's variables are migrated to this new file system.

- **ioctl system call**: The ioctl (input output control) system call is usually used to implement operations used by special drivers that are not provided by standard functions call.

- **Netlink**: It is the newest interface with the kernel. It is used like a socket and allows communicating directly with the kernel. It allows bidirectional communication but only in datagram mode.

2.2.3 Network subsystem

The Network subsystem is responsible of all the network communications of the system. Its stack is shown in Figure 2.3.

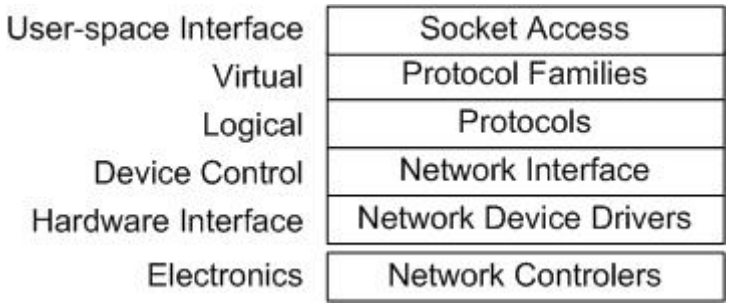


Figure 2.3. Network subsystem stack

The main data structures of the network subsystem are the socket buffer (Protocol Layer) and the netdevice structure (Network Interface Layer).

The **socket buffer** *(sk_buff)* is defined in *include/linux/skbuff.h* include file. This structure contains the packet and its meta-data associated available in the kernel, such as headers, pointers to different parts of the data and properties of the structure such as clone or the interface where it comes or goes. Therefore its field can be classified in: Layout, General, Feature-specific and Management functions.

The **net_device** structure is defined in *include/linux/netdevice.h* and store all the information related of the network device. The fields of the *net_device* structure can be classified in: Configuration, Statistics, Device Status, Traffic Management, Feature Specific, Generic and Function Pointers.

2.2.3.1 Packet Reception

There are two different techniques to get the packets from the network:

- **Interrupt driven**. When a packet is received an event interrupt is sent to the processor by the network device. When an interrupt is called, the CPU stores the process where it was and it executes a handler set by the network device in order to save the packet in a queue for its later processing. Usually the interrupt has to be quickly. If the traffic is high, and an interrupt is send for each received packet, causing a lot of overhead because they have higher priority than other processes in the kernel. In this case, the soft-irq (process in charge of processing the packets) is starved, and the kernel has no time to process the incoming packets.

- **Polling**. The kernel is constantly checking if a frame arrived in the device. It can be done reading a memory register in the device or when a timer expires. This causes a lot of overhead in low loads but it can be useful in high loads.

The first approached used in Linux was the interrupt driven, but this approach does not have a good behaviour at high rate. **NAPI** (New API) appeared to try to solve this. In NAPI the best of interrupts and polling is used. When a packet arrives, an interruption is sent and the interrupts are

disabled. After processing all the incoming packets the interrupts are enabled again. Meanwhile if a packet arrives when another packet is processed, it is stored in the reception ring of the device but no interruption is sent. This technique improves the performance of the system at high rates. Also, the delay and performance problems of the interruptions are partially solved.

In Figure 2.4 it is shown the path of a packet in the kernel from when it is received to when it is delivered to the protocol handler. When the packet arrives and receives the packet, the network driver sends an interrupt to the service routine, which enqueue the device to the network soft interrupts. When the CPU attends the softirq, all devices that have been received packets are polled and then the information of the new packet is sent via the `netif_receive_skb` to the protocol handlers associated with the packet protocol.

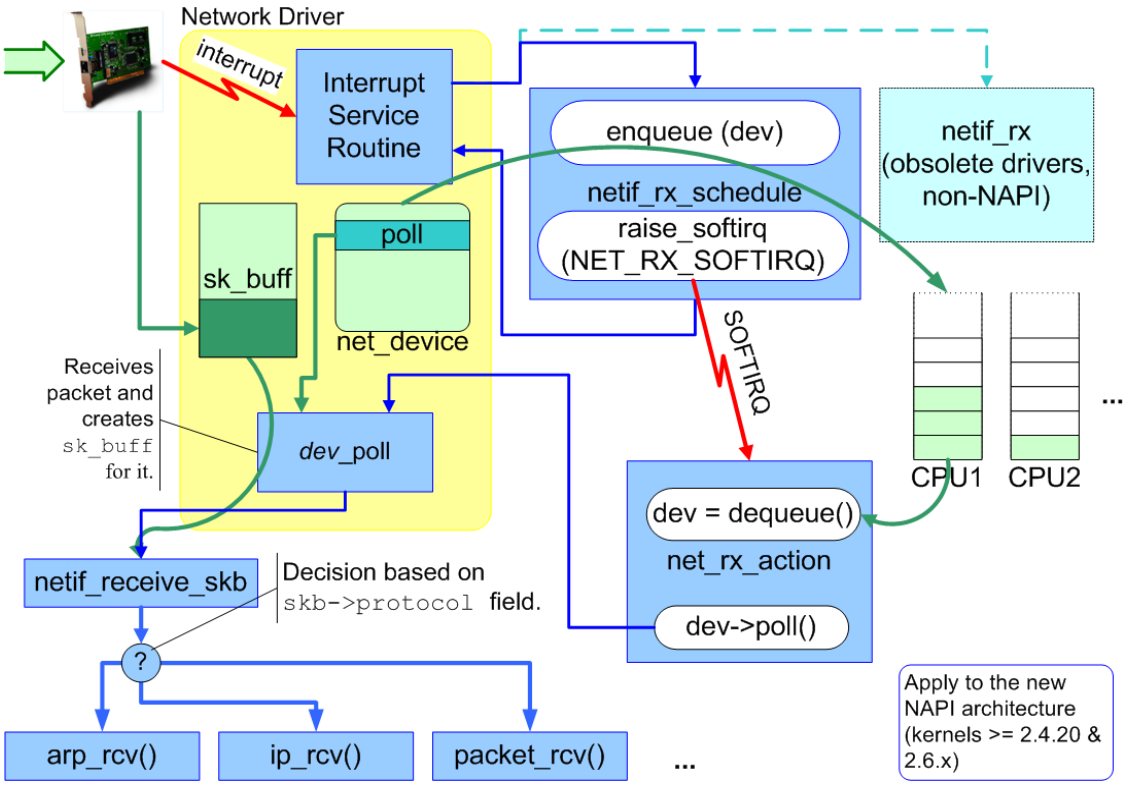


Figure 2.4. Packet path in the reception. Source [50]

2.3 Pktgen study

This section contains a study of the functions and the behaviour of Pktgen. This will be useful in the future chapters in order to understand how it works and the modifications on it.

2.3.1 About

Pktgen is a packet generator which allows sending to the network preconfigured packets as fast as the system supports. It is freely available in almost all current Linux Kernels.

It is a very powerful tool to generate traffic in either PC, and allow testing network devices such as router, switches, network drivers or network interfaces.

In order to increase its performance, it is implemented above the Linux Network drivers, which interacts with them with the API provided by the netdevice interface. Its idea is simple: push to the

NIC buffers as many packets as it can until they are full. Also enables to clone packets in order to reduce the time of creating and allocating new ones.

The latest implementation (version 2.73) has the following features:

- Support for MPLS, VLAN, IPSEC headers.
- Support for IP version 4 and 6.
- Customized the packets with multiples addresses
- Clone packets to improve performance
- Multi queue is implemented in the transmission. Different flows can be sent in the same interface from different queues.
- Control and show the results via the proc file systems.
- Control the delay between packets.
- It uses UDP application protocol to send its own information. The discard port is used in order that the IP layer discards the packet in the reception.

The application layer contains the following 4-byte fields (16 Bytes in total) which are:

- pgh_magic: packet identifier that belong to a Pktgen transmission.
- seq_num: sequence number of the packet. If the packets are clone, there are gaps in the numbering. The gaps have the size of the clone parameter.
- tv_sec: First part of the timestamp. The timestamp indicates when the packet is generated.
- tv_usec: Second part of the timestamp.

2.3.2 Pktgen Control and visualization

The control and the visualization of the results are implemented in three different proc file systems.

- **pgcrtl**: it is in charge of controlling the threads of Pktgen in order to *start*, *stop* or *reset* the tests.
- **Pktgen_if**: it is in charge of displaying the results and setting the parameters to the desired interface. The parameters available to change are: *min_pkt_size, max_pkt_size, pkt_size, debug, frags, delay, udp_src_min, udp_dst_min, udp_src_max, udp_dst_max, clone_skb, count, src_mac_count, dst_mac_count, flag, dst_min, dst_max, dst6, dst6_min, dst6_max, src6, src_min, src_max, dst_mac, src_mac, clear_counters, flows, flowlen, queue_map_min, queue_map_max, mpls, vlan_id, vlan_p, vlan_cfi, svlan_id, svlan_p, svlan_cfi, tos* and *traffic_class.*
- **Pktgen_thread**: it is in charge of setting the correct interfaces into the threads. The available commands are: *add_device* and *rem_device_all*

2.3.3 Pktgen operation

When the module is loaded (*pg_init*), Pktgen makes the following things:

- Creates the profs directory of Pktgen and pgctrl file.
- Register the module to receive the netdevice events.
- Creates a thread for each CPU and attached to it, which it will be the function *Pktgen_thread_worker*. Also a procfs for each thread is created. This thread will be in charge of sending the packets to the network interface.

When all the initializations and configuration via the procfs are done and the user sets start to pgcrtl, the control is changed to RUN in order to start the transmission. When RUN is set to the thread, the initial packet and the output device (odev) are initialized via the function *Pktgen_run()*.

The main flow of the thread worker is showed in Figure 2.5. In each loop an instance of the struct *pkt_dev* is obtained by the function *next_to_run()*. This struct is used in the function for sending packets which is *Pktgen_xmit()*. Also there are functions for stopping the transmission (*Pktgen_stop()*), removing all the interfaces from the thread (*Pktgen_rem_all_ifs()*) or removing only a specific interface (*Pktgen_rem_one_if()*). After each execution of the control functions, the control flags are reversed.

Pktgen_xmit() is the function in charge of sending the correct packets. Its flow graph is showed in Figure 2.6. First of all, the device is checked in order to know if there is link and it is running. Otherwise, the device is stopped with the *Pktgen_stop_function()*. After that, the delay is checked. Then, it is checked if there is not a previous packet or there are not more clones of packets to do. In this case, a new packet is generated.

If the user has configured some delay and the last packet was transmitted OK, the program waits for the next transmission, otherwise continue with the transmission. There are two different waiting behaviours which are implemented in the waiting function called *spin*. One is active (checking the condition in a loop) and the other is freeing the CPU and scheduling the task in the future (in the case of bigger waiting times). Once this is done, it is time to get the transmission queue from the *netdevice* and block it.

Then if it is not stopped or frozen, the packet is send with the *xmit* function, and some variables are updated depending on the result of the transmission. Finally, the transmission queue is unblocked. The last check is if the transmitted packets are the same or more than the expected packets to be send. In it is true, the device is stopped with the function *Pktgen_stop_function()*.

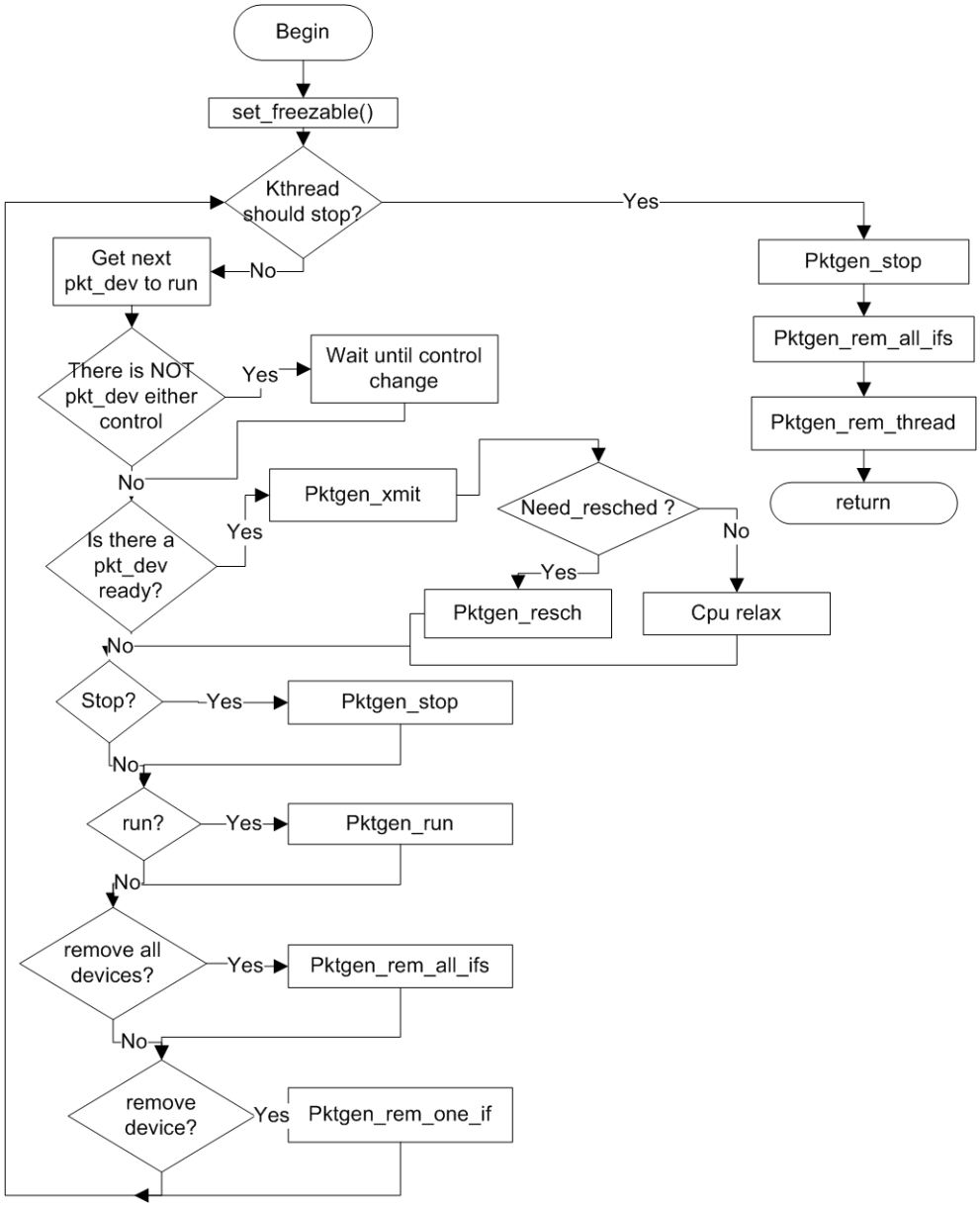


Figure 2.5. pktgen's thread main loop flow graph

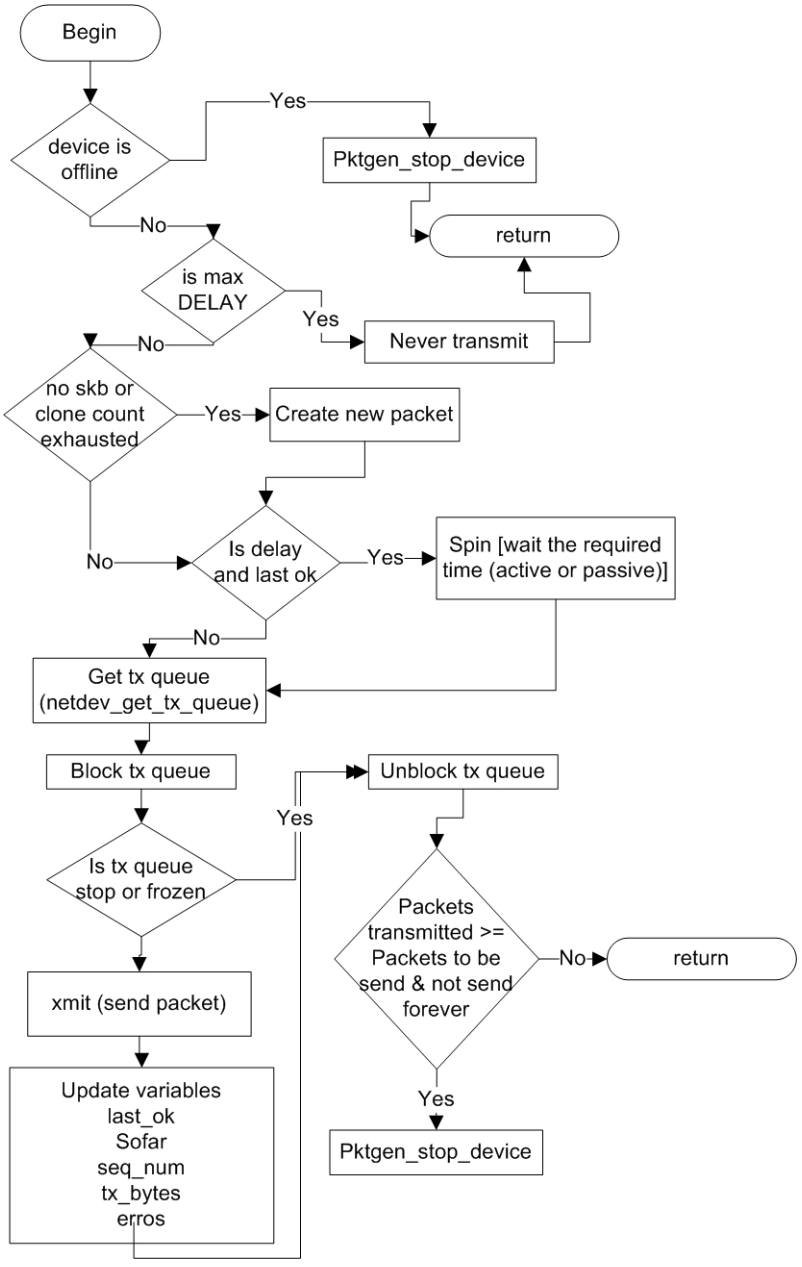


Figure 2.6. Pktgen_xmit() flow graph

Chapter 3

Design

This chapter contains the requirements and the design of the traffic analyzer implemented with pktgen. The design includes the architecture, the receiver metrics and the application interface. Also a overview of the operation is presented.

3.1 Requirements

The **goal** of this project is to implement an open-source software to analyze high speed networks. This software is based on pktgen module. The receiver modules is able to measure at high speed the basic parameters used in benchmarking tools. The parameters are:

- Num of packets / Bytes received from the transmitter.
- Num of packets / Bytes lost in the network or element under test.
- Percentage of packets / Bytes lost.
- Throughput received from the link. Also the output throughput of pktgen will be adjustable by the user.
- Latency between transmitter and receiver.
- Inter-arrival time
- Jitter

The only action that the user needs to do is enabling the reception and the desired statistics. A private protocol for allowing the auto-configuration of the receiver is designed. Basically the application tells to the receiver part, which parameters will be used in the test.

The data collected is processed on real-time because in high traffics it is not possible to save all the meta-data of the packets in memory and keep a high performance.

The receiver only process the packets coming from a pktgen packets generator.

It takes advantage of the multi-queue network devices in multi-core systems, if they are available.

3.1.1 Not used parameters

Some parameters used in different network analyzer tools that where studied in Chapter 2 or defined in standards are discarded in the final design of the module for several reasons.

The *inter packet gap* (Back to back frame, according with RFC 1242 [38]) is discarded because there is not direct way to know it. The kernel only can stamp the time after receiving the packet.

Also, there is some delay between when the packet is received and it is delivered to the kernel. Also due to interrupt mitigation, some packets will be processed together and will have the same time. Moreover, an estimation of the transmission time is needed because it is not known at kernel level when the NIC starts to receive the packet. Nowadays, only specialized hardware solutions are able to get this type of statistics.

TCP statistics are also exclude because pktgen does not use TCP stack to send the packets. Also out of order packets, CRC checks are excluded. Moreover advance traffic generator and analyzing distributions are excluded.

3.2 Architecture

In order to increase the performance, the sender and the receiver should be in different machines. Also, in order to reduce the time for getting the counter, each CPU has independent counters for the received packets. Different reception formats could be used without modification the code. In order to work properly, each network queue interrupt should be attached to a different processor. Multi-queue reception is available in the Linux Kernel since version 2.6.27.

There is one exception in the scenarios, which is when the latency is calculated. In this case, sender and receiver should be in the same machine. This gives a big advantage on measuring latency, because there are not problems of synchronization. At least two CPU are recommended because pktgen consumes all the resources of one CPU when it sends packets at high speed.

The receiver part is attached to the system at Level 3, just above the device driver. It is at the same level as IP. Both stacks receive the IP packets. In this way, the traffic on the network is not affected. Also it is transparent to the user. On the other hand, it has more overload because the IP stack process the incoming packet. Pktgen usually uses UDP packets with discard port, so when the packet arrives at UDP level, it is discarded.

3.3 Receiver metrics

This section describes how the data is processed to obtain the requirements.

3.3.1 Metrics computation

Num of packets and bytes received The variables containing the results of these two parameters increment its value in every reception of a packet. The bytes received do not include the CRC bytes (4bytes). This is done for legacy compatibility. The pktgen sender do not compute these bytes when it sends.

Num of packets / Bytes lost When the results are going to be displayed a subtract between the expected packets and the received packets is done. The expected packets are obtained with a configuration protocol which is explained in Section 3.5.1.1.

Percentage of packets / Bytes lost When the results are going to display a division between the packets or bytes lost and the packets or bytes expected is done.

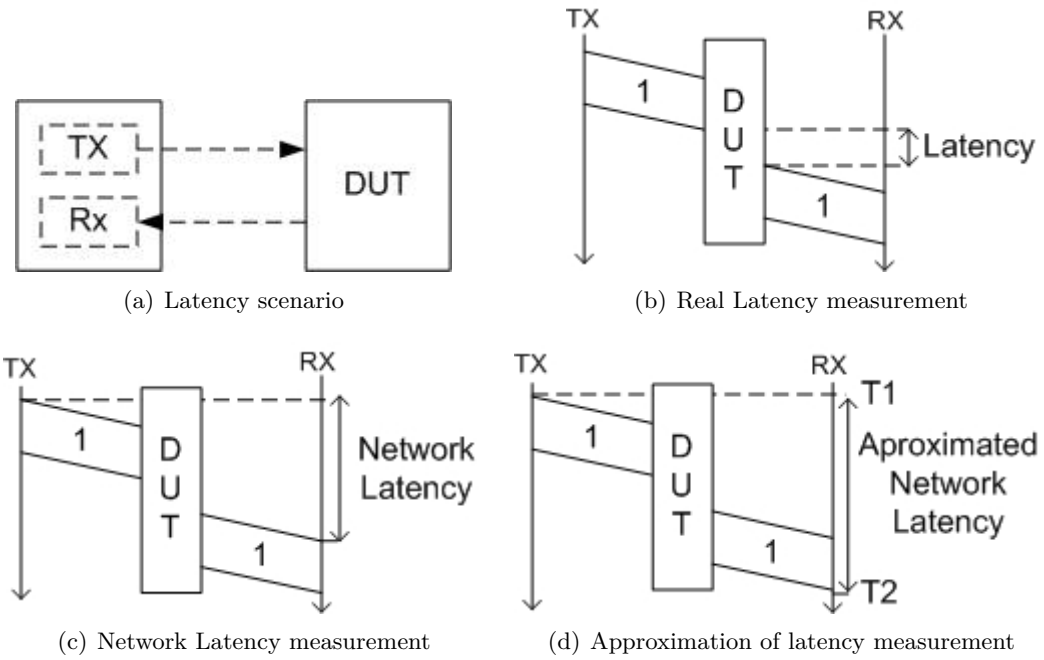
Throughput received When the first packet is received (when the counter of received packets is 0), the time is saved in a local variable. The time stamp for the last packet is update in each reception due to the possibility of losses in the last packets. Then the throughput is calculated when

the results are going to be displayed with Equation 3.2 and Equation 3.1.

$$\text{Throughput} = \frac{\text{packets received}}{\text{end time} - \text{start time}} \text{ (pps)} \tag{3.1}$$

$$\text{Throughput} = \frac{\text{bytes received} \times 8}{\text{end time} - \text{start time}} \text{ (bps)} \tag{3.2}$$

Latency In order to calculate latency the sender and the receiver must be in same machine in order to have the clock sources synchronized. (See Figure 3.1(a)). Otherwise the results will be wrong. According to the definition of the IETF, latency time is shown in Figure 3.1(b) and network latency is showed in Figure 3.1(c). Different approaches can be taken, in order to get the latency. A first approach used is shown in Figure 3.1(d). The reception time is too complex to obtain because hardware and scheduling aspects has to be considered. The drawback of this method is the latency change with the size of the packets due to the transmission time. Also there is some uncertainly due to delays caused in the transmission and in the packet processing. Latency is obtained with Equation 3.3. T1 is obtained from the received packet header. T2 is the time stamp when the packet arrives at the processing layer.



(a) Latency scenario

(b) Real Latency measurement

(c) Network Latency measurement

(d) Approximation of latency measurement

Figure 3.1. Latency

$$\text{Latency} = T2 - T1 \tag{3.3}$$

The latency calculation is made in the first packet of the clone series. The last transmission time is recorded and compared with the new one. If it is the same time, no calculation is done, otherwise the latency is processed using the transmission timestamp and the receiver time. Latency results are exported as average, variance, maximum and minimum.

Intel-arrival time When a packet arrives, its arrival time is saved. Then, when the next packet arrives, the current arrival time is subtracted from the last arrival time (See Equation 3.4). Finally,

the last packet arrival is saved. Then the results are exported as average, variance, maximum and minimum.

$$\text{Inter arrival time } = T_{current} - T_{last\,arrival} \tag{3.4}$$

Jitter In order to calculate jitter, the inter-arrival method is used(See Section 2.1.5.2). Sending in a constant rate is necessary, otherwise the results will be wrong and it will depend on the transmitter. In this case, the last inter-arrival time calculated is required. It is assumed that pktgen sends at constant rate. Jitter results are exported as average, variance, maximum and minimum.

3.3.2 Data collection

The timestamp is extracted from the system, when it is needed. The high-resolution timer API will be used to get the times in transmission and in the reception. The transmission timestamp is extracted from the packet headers.

The length of the packet is extracted from the socket buffer (skb) structure.

3.4 Application interface

The modification of pktgen uses proc file system in order to maintain backward compatibility. Both user control and measurement visualization will be implemented in proc file system.

3.4.1 User Control

The user control allows enabling the reception of packets and selecting the type and the format of the statistics generated. The user interface is in a new file called */proc/net/pktgen/pgrx*. The required data for generating the results is obtained with a configuration protocol and the receiver module.

The added commands are:

- **rx [device]**: command that reset the counters and enable the reception of new packets. If the device name is not valid, all the interfaces will process their input packets.
- **statistics [counters, basic or time]**: command for selecting the statistics. **Counter** statistics includes those one that the time is not required (packets received, bytes received, packets lost, bytes lost). **Basic statistics** adds the receiver throughput. **Time statistics** additionally includes statistics that need more overload of the reception of the CPU because their process (inter-packet arrival time, latency and jitter). The default value is basic.
- **rx_disable:** command for stopping the receiver side of pktgen.
- **rx_reset:** command for resetting the values of the receiver.
- **display [human, script]**. Two different ways of displaying the results. See Subsection 3.4.2 and 4.3.

3.4.2 Measurement visualization

The results are displayed in a new file called */proc/net/pktgen/pgrx*. It shows the receiver interface and the parameters defined in Section 3.1. Two different formats are used to display the results. The first one is for human reading and the second one for script reading.

The results are displayed per different CPU and then they are summarized for all the CPUs.

3.5 Operation

This section describes the operation of the main features of the modified pktgen.

3.5.1 Initialization

Pktgen can be controlled with a script which is in charge of passing the desired options to the kernel module. When the script calls *start* the test is initialized. The first packet is the configuration packet. Then after waiting a predefined time (in order that the receiver process the configuration), the bulk transmission is initialized.

3.5.1.1 Configuration protocol

The minimum size of an Ethernet frame is 64 Bytes. The available free space header in the current pktgen for inserting data is 64 - Ethernet Header (14 Bytes) - Ethernet CRC (4 Bytes)- IP Header (20 Bytes) - UDP Header (8 Bytes) - PKTGEN Header (16 Bytes) = 2 Bytes. This space is not enough for sending the configuration to the receiver side during the test, so it is necessary to send it before or after the test. It is necessary to create a new packet. The new header contains:

- Magic number (4 bytes). This field identifies a pktgen packet.
- Sequence number (4 bytes)
- Payload (Remaining space. Min 10 bytes)

The first packet (sequence number 0) sent is the configuration and it is not computed in the statistics. The configuration header includes in the payload area:

- Packets to send (8 bytes). If it is 0 means infinite, so the statistics on the receiver side do not know how many packets are transmitted. The sequence number is not a reliable source because it can have hops due to the clone skb parameter.
- Packet size (4 bytes)

The other packets on the payload will contain the timestamp when the packet is generated.

3.5.2 Packet transmission

The transmission mechanism available in the current pktgen module is used. Only some modifications are done, such as the packet header and the throughput adjustment. There are two different alternatives for generating a desired throughput: adjusting the delay between packets or sending a fixed number of packets in a given interval.

On one hand, the first approach obtains a constant bit rate (CBR) traffic but it requires high accuracy on high speed networks because the distance between packets is very small (ns). The gap between packets can be obtained with Equation 3.5, where P is the packet length of the packet in bits, R_t is the target throughput in bits per second and L_r is the link rate in bits per second. Also it is possible to calculate the interval between transmission packets, which required less resolution and it is shown in Equation 3.6.

$$\text{gap delay(s)} = \frac{P}{R_t} \times (1 - \frac{R_t}{L_r}) \tag{3.5}$$

$$\text{transmission delay(s)} = \frac{P}{R_t} \tag{3.6}$$

On the other hand, the second approach does not required high time accuracy but it generates bursty traffic. It consists on calculating how many packets must be sent to get a target throughput. When all the packets are sent in a period, the transmitter wait until the next interval, where the counter is initialized again. The number of packets to send is shown in Equation 3.7, where R_t is the target throughput in b/s and T_i is the interval selected in seconds. In this case, it is not necessary to know the speed of the link.

$$\text{packets in interval} = \frac{R_t \times T_i}{\text{Packet size (Bits)}} \tag{3.7}$$

The first alternative is used.

3.5.3 Packet reception

The program flow of the reception function depends on the statistics selected, which is selected when the user sets the type of statistics. The structure of the function is the same for each type, but adding extra functionalities. The whole flow is shown in Figure 3.2. If the statistics is not required the block function in skipped. The timestamp of the system is disabled. The packets are time stamped when being processed.

First, the read function checks if the received packet is a pktgen packet. If not, the packet is drop. Then, if it sequence number is 0 (pktgen test sequence number usually starts at 1) it means it is a configuration packet, so the *packets to send* and the *bytes to send* is obtained. After that, the packet is dropped because the configuration packet is not taken into account in the test.

The time is obtained when it is necessary to use it. Then, the inter-arrival time and the jitter is calculated. When the process arrives to the latency part, the transmission time is checked. If it is different than the previous one, it means that the packet is the first of a clone series. In this case, the latency is calculated. This allows to compute the latency during all the test.

In the throughput part, if the receiver packets variable is 0, the receiver gets the time stamp of the system and it is stored. Also, the last timestamp is saved as stop timestamp. Finally, the *packets received* and the *bytes received* variables are updated.

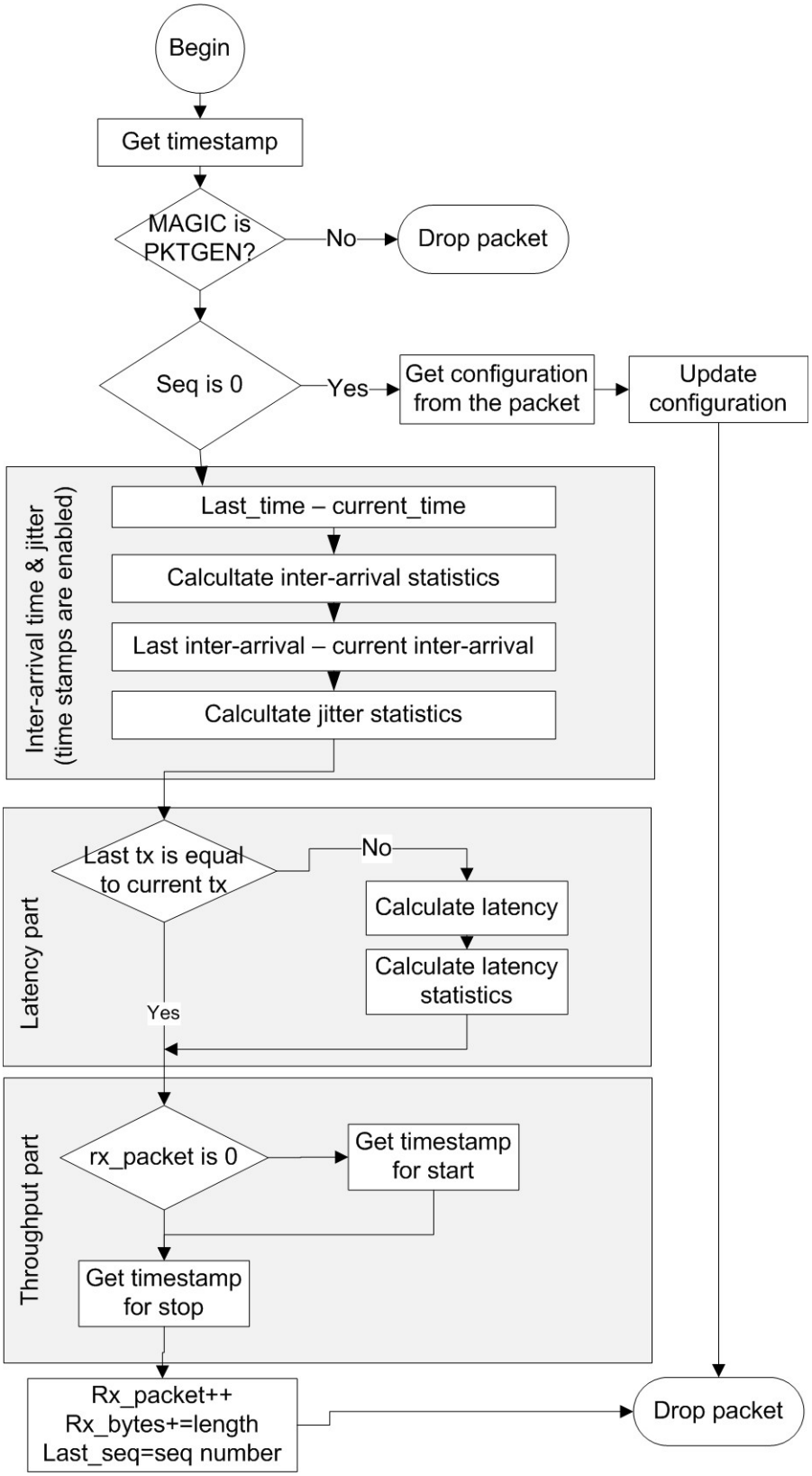


Figure 3.2. Flow chart of reception in time statistics.

Chapter 4

Implementation

This chapter includes some explanation of the implementation stage. Different steps were followed in order to obtain the code as optimized as possible. During the implementation stage, different test were done in order to evaluate which is the best way to write the code. The tests had different initial conditions but their finality is to compare a specific implementation in order to see the gain or loss of performance. The final tests are explained in the next Chapter. The small packet size is used because it requires more CPU resources.

This chapter explains different parts of the code and it justifies their election with some test. Also some concepts are introduced if they are necessary to understand the code.

4.1 Processing the incoming packet

Pktgen is modified in order to act as a L3 handler (sniffer) associated with IP packets and a specific device (input_device). Also it is possible to capture from all the devices in the system. At this level, the compatibility with other modules and kernel functions is guaranteed. Also it is driver independent and more generic. The drawback is that also IP has to process the packets. This can be avoided modifying the network kernel subsystem (See Section 4.4), but then it is necessary to recompile the entire kernel.

When the incoming packets are processed, after allocating the socket buffer (skb), they are sent to the different protocols that want to process the packets. In order to add a receive handler it is necessary to call the function (*dev_add_pack()*). This function need a parameter which is a packet type (Source 4.1). Basically it defines the handler function, the type of packets required and, also it is possible to specify the device (.dev). The handler is added when the user writes in the proc file system the option *rx* with the interface. If the interface is not valid, all the interfaces are used. The *.dev* field is changed in execution time in order to specify the correct listening device. This allows filtering the interface from where the traffic is processed. Also, the handler function is selected according with the statistics selected (counter, basic or time).

```
static struct packet_type pktgen_packet_type __read_mostly = {
        .type = __constant_htons(ETH_P_IP),
        .func = pktgen_rcv_basic,
        .dev  = NULL,
};
```

Source 4.1. struct pktgen_rx

4.1.1 Accessing data of the packet

When a packet arrives, the first thing to do is checking if it is a pktgen packet. But before that, it is necessary to obtain the pktgen header values from the packet. The packet data is stored in the socket buffer structure (skb). The network card has two possible ways to store the packet data: linear and non linear.

In the linear way, the entire packet is in a continuous space of memory which allows to access directly with an offset from the beginning of the packet. In the non-linear, the data is stored in different memory locations. The header is in the skb structure and the data is shared by all the references of the same packet and it is stored in *pages*.

A *page* is a structure of the kernel used to map different type of memory. The memory structure of the system is divided into different parts, usually protected between them. Mapping the packet data in a page is usually done in the transmission side. For instance, the *page* points to the buffer data of an UDP packet. This avoids copying the data from the user space buffer to the kernel space buffer. In this way, the data will be obtained directly from the original location and it will not be different copies inside the system. Some cards also use this feature in the receiver side in order to reduce the number of packets' copies. Then, both scenarios are possible and have to be taken into account. The way how the information is stored depends on how to access it.

There is a function in the kernel called *skb_header_pointer()* which allows to copy the split data into a local buffer. This requires a memory copy which reduces performance. Because it is only necessary to read the buffer, it is possible to map the real memory address to a kernel space address. This is implemented with the *kmap_atomic()*, which allows to map few memory addresses to each CPU. The network function for this operation is called *kmap_skb_frag*.

Figure 4.1 compares the two methods of accessing the data: using *skb_header_pointer* or *kmap_skb_frag*. With the second function is observed an improvement of around 7%. This is due to the fact that in the first case is necessary to allocate memory for the new local buffer and then it is necessary to free it. Also the performance without checks is plotted in order to compare the behaviours.

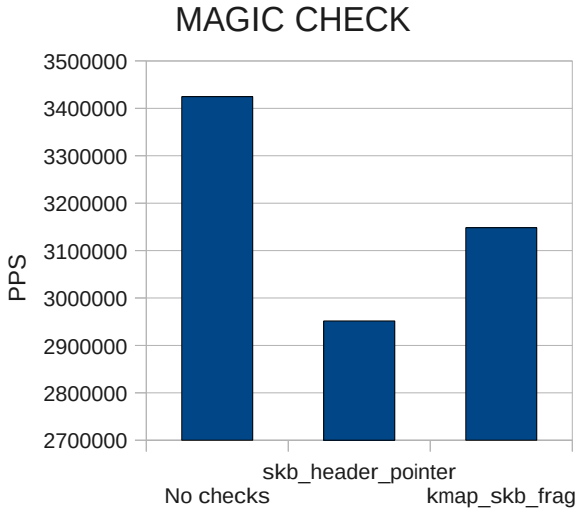


Figure 4.1. Reading parameters performance

Source 4.2 shows the code for getting the headers of a pktgen packet. After the processing it is necessary to unmap the assignment because virtual addresses are a limited resource. If it is not done, the performance drops.

```
(...)
void *vaddr;
if (skb_is_nonlinear(skb)) {
        vaddr = kmap_skb_frag(&skb_shinfo(skb)->frags[0]);
        pgh = (struct pktgen_hdr *)
                (vaddr+skb_shinfo(skb)->frags[0].page_offset);
} else {
        pgh = (struct pktgen_hdr *)(((char *)(iph)) + 28);
}
(...)
if (skb_is_nonlinear(skb))
        kunmap_skb_frag(vaddr);
```

Source 4.2. Reading pktgen's header

4.1.2 Saving the statistics

The variables can be allocated in different part of the system, such in the main memory, in the CPU, in a region with DMA ... For instance, network statistics gathered by the Linux stack uses per-CPU variables, which means each CPU has its own variables. When the results are going to be displayed, the variables are added in order to show the correct results.

The same approach is used in the pktgen receiver in order to count the packets and bytes. This avoids using locks between CPUs when accessing the variables and it increases the performance.

A new struct is created in order to allocate all the counters and the required variables (See Source 4.3). Also it is necessary to declare the variable as `PER_CPU`. This is done with the macro `DEFINE_PER_CPU`. This macro declares a variable with the given name and type to each CPU. The first argument is the type of the variable and the second the name. Also another struct called *pktgen_stats* it is used to save the values required by the time statistics.

```
struct pktgen_stats {
        u64     sum;
        u64     square_sum;
        u64     samples;
        u64     min;
        u64     max;
};
/*Receiver parameters per CPU*/
struct pktgen_rx {
        u64 rx_packets;                 /*packets arrived*/
        u64 rx_bytes;                   /*bytes arrived*/

        ktime_t start_time;             /*first time stamp of a packet*/
        ktime_t last_time;              /*last packet arrival */

        struct pktgen_stats inter_arrival;
        ktime_t last_time_ktime;
        u64     inter_arrival_last;

        struct pktgen_stats jitter;

        struct pktgen_stats latency;
        ktime_t latency_last_tx;
};
DEFINE_PER_CPU(struct pktgen_rx, pktgen_rx_data);
```

Source 4.3. struct pktgen_stats and struct pktgen_rx

There are two ways of accessing variables in a processor. If the variable is in the same processor, `get_cpu_var` is used. Otherwise, in order to access to the variable of a specific CPU, `per_cpu` is used. In Source 4.4 it is shown the two methods to access to the variables, concretely the packets received counter.

```
__get_cpu_var(pktgen_rx_data).rx_packets++;
per_cpu(pktgen_rx_data,cpu).rx_packets;
```

Source 4.4. Accessing data in per-CPU variable

4.1.3 Measuring time

The time reference is only obtained once, in order to avoid overhead. Pktgen will use the clock of the system obtained by *ktime_get()*.

Different approaches for getting the time stamp are evaluated. The first idea was to use the network time stamps enabling it with the function *net_enable_timestamp()*, but this option was discarded because the time resolution obtained was 1 millisecond.

The second option was using the Time Stamp Counter (TSC) clock. It is a 64 bit register present in the x86 systems. There is a TSC clock for each CPU. The TSC clock increases its value in each CPU cycle. The clock sources are not synchronized between the different CPUs. Also, if the different CPUs have different frequency (due to the saving energy, especially on laptops) it will be different increments for each CPU. Moreover, different types of processors increment the register in different ways. Read access to this clock is very fast, and in the current processors has a resolution of nanoseconds. In the other hand, it's architecture dependent.

The third option was using the hardware time stamps on the network card, but the accuracy was not good enough, because some packets had the same time, and others were not time stamped.

Because it is necessary a clock reference for the aggregated throughput of the different CPU, finally the TSC clock is discarded and the clock reference is provided by the kernel with the function *ktime_get()*. This functions gets the default clock of the system, which in the current scenario is a TSC clock of the 1st CPU. The available clocks can be listed with:

```
$cat /sys/devices/system/clocksource/clocksource0/available_clocksource
tsc hpet acpi_pm jiffies
```

After measuring the required parameters (inter-arrival time, jitter or latency), the data is processed and stored with the function in Source 4.5. Later, when the results are displayed, the current value for the average and the variance is calculated.

The latency is only calculated when the transmitter and receiver is in the same machine. In this case, the packet is sent out in one interface and it is received in the other interface.

```
void process_stats(u64 value, struct pktgen_stats *stats)
{
        stats->square_sum += value*value;
        stats->sum += value;

        stats->samples++;

        if(value > stats->max)
                stats->max = value;
        if(value < stats->min)
                stats->min = value;
}
```

Source 4.5. Processing statistics

4.2 Auto-configuration of the receiver

When the user adds the parameter *config 1* (NEW parameter) the sender will send a configuration packet. The legacy transmission system is modified to include the configuration data. Also a checking in the receiver side is done in order to know if the arrived packet is a configuration packet or not.

4.2.1 Sending

The pktgen function *fill_packet()* is modified in order to include the config packet. The configuration flag is only active before starting the transmission. When the flag is active, the configuration packet is created. It is necessary to change the size of the allocate packet. Also a new packet struct is created (See Source 4.6).

```
struct pktgen_hdr_config {
        __be32 pgh_magic;
        __be32 seq_num;
        __u64 pkt_to_send;
        __be16 pkt_size;
};
```

Source 4.6. struct pktgen_hdr_config

When the configuration flag is activated, after sending the first packet (config) the transmission waits a predefined time. This is done in order to give some time to the receiver to process the configuration packets and reset its counters. After that time, the configuration flag is set to 0, and the starting time of the test is reset. Also, a packet is discounted from the packets sent. Doing that, the configuration packets do not have any effect in the test.

4.2.2 Receiver

The receiver function checks for each packet if the sequence number is 0. It is possible to receive more than one configuration packet in each test. This is due to the fact that a configuration packet is generated for each pktgen thread. When the first packet is received, the counters are reset and the *packets to send* and the *bytes to sent* are set. In the next configuration packets, the values of the *packets and bytes to send* are updated. In order to know if it is a new test or the same one, the time when the configuration packets are received is saved. If the difference between the arrivals is less that the configuration delay time, it is considered the same test, otherwise a different one. (See Source 4.7)

```
static int is_configure_packet(void *header)
{
        struct pktgen_hdr *pgh = (struct pktgen_hdr *)header;

        if (likely(pgh->seq_num) != 0)
                return 0;
        else {
                struct pktgen_hdr_config *pghc =
                        (struct pktgen_hdr_config *) header;
                u64 pkts = ntohl(pghc->pkt_to_send);
                int pkt_size = ntohs(pghc->pkt_size);

                u64 time_from_last;
                ktime_t now;

                spin_lock(&(pg_rx_global->config_lock));
                now = ktime_now();
                time_from_last = ktime_to_us(ktime_sub(now,
```

```
                        pg_rx_global->last_config));

                if (time_from_last < TIME_CONFIG_US){
                        pg_rx_global->pkts_to_send += pkts;
                        pg_rx_global->bytes_to_send += pkt_size*pkts;
                } else {
                        pg_reset_rx();
                        pg_rx_global->pkts_to_send = pkts;
                        pg_rx_global->bytes_to_send = pkt_size*pkts;
                }
                pg_rx_global->last_config = now;
                spin_unlock(&(pg_rx_global->config_lock));
                return 1;
        }
}
```

Source 4.7. Receiving configuration packet

4.3 Displaying the results

The results are displayed in the *proc* file system. Two type of visualization are possible: human readable and script readable. Using the macro in Source 4.8 is it possible to display multiple formats with only one call. In order to choose between both formats, it is necessary to write *display human* or *display script* in the receiver proc file system. The default is *text*.

```
#define DISPLAY_RX(opt, seq, fmt, fmt1, args...)\
        if (opt == PG_DISPLAY_HUMAN)            \
                seq_printf(seq, fmt1 ,## args); \
        else                                    \
                seq_printf(seq, fmt ,## args);
```

Source 4.8. Macro for displaying results

Two different statistics are displayed. First, there is the statistics per CPU, where the time statistics are displayed if the option is enabled. Second, there is a summary of the test. If the configuration packet is sent, it also includes the expected packets and bytes and the losses. The percentage of losses is not possible to display because float operations are not allowed inside the kernel. The throughput is always displayed.

Source 4.9 is an example of a time reception statistics in a gigabit link. It is shown the details of each parameter measured. The latency appears only if the sender and receiver are in the same machine.

```
                RECEPTION STATISTICS
        PER-CPU Stats
CPU 0:  Rx packets: 0     Rx bytes: 0
CPU 1:  Rx packets: 0     Rx bytes: 0
CPU 2:  Rx packets: 10000000      Rx bytes: 600000000
        Work time 6719014 us
        Rate:  1488313pps 714Mb/sec (714390534bps)
        Inter-arrival
                Average: 671 ns Variance 381245 ns2
                Max: 10108 ns Min:: 404 ns
                Samples: 9999999
        Jitter
                Average: 360 ns Variance 665018 ns2
                Max: 9404 ns Min:: 0 ns
                Samples: 9999998
        Latency
```

```
                Average: 470578 ns Variance 216731083 ns2
                Max: 545217 ns Min:: 60345 ns
                Samples: 1000000
CPU 3:  Rx packets: 0    Rx bytes: 0
CPU 4:  Rx packets: 0    Rx bytes: 0
CPU 5:  Rx packets: 0    Rx bytes: 0
CPU 6:  Rx packets: 0    Rx bytes: 0
CPU 7:  Rx packets: 0    Rx bytes: 0

        Global Statistics
Packets Rx: 10000000     Bytes Rx: 600000000
Packets Ex: 10000000     Bytes Ex: 600000000
Packets Lost: 0  Bytes Lost: 0
        Work time 6719014 us
        Rate:  1488313pps 714Mb/sec (714390534bps)
```

Source 4.9. Time statistics in one CPU

Source 4.10 and Source 4.11 are examples of the human and script readable formats.

```
cat /proc/net/pktgen/pgrx
                RECEPTION STATISTICS
        PER-CPU Stats
CPU 0:  Rx packets: 0    Rx bytes: 0
CPU 1:  Rx packets: 0    Rx bytes: 0
CPU 2:  Rx packets: 9385641      Rx bytes: 563138460
        Work time 13483820 us
        Rate:  696066pps 334Mb/sec (334112119bps)
CPU 3:  Rx packets: 9490524      Rx bytes: 569431440
        Work time 13483381 us
        Rate:  703868pps 337Mb/sec (337856767bps)
CPU 4:  Rx packets: 8949667      Rx bytes: 536980020
        Work time 13483488 us
        Rate:  663750pps 318Mb/sec (318600065bps)
CPU 5:  Rx packets: 9030598      Rx bytes: 541835880
        Work time 13483509 us
        Rate:  669751pps 321Mb/sec (321480635bps)
CPU 6:  Rx packets: 9085660      Rx bytes: 545139600
        Work time 13483696 us
        Rate:  673825pps 323Mb/sec (323436304bps)
CPU 7:  Rx packets: 9009976      Rx bytes: 540598560
        Work time 13483359 us
        Rate:  668229pps 320Mb/sec (320750080bps)

        Global Statistics
Packets Rx: 54952066     Bytes Rx: 3297123960
Work time  13483828 us
 4075405pps 1956Mb/sec (1956194611bps)
```

Source 4.10. Displaying human readable

```
# cat /proc/net/pktgen/pgrx
0 0 0 0 0 0
1 0 0 0 0 0
2 9569752 574185120 13667949 700160 336 336076829
3 9591125 575467500 13667867 701728 336 336829440
4 9109725 546583500 13667629 666518 319 319928789
5 9159094 549545640 13668004 670112 321 321653777
6 9163423 549805380 13667956 670431 321 321806935
7 9123356 547401360 13667953 667499 320 320399907
G 55716475 3342988500 13668064 4076398 1956 1956671259
```

Source 4.11. Displaying script readable

4.4 Increasing the performance modifying the network subsystem

The receiver is not able to process all the incoming packets when the rate is too high. This is due to the fact, that the packets are also processed by the IP stack. A hook in the kernel, concretely at the network core (dev.c), is done in order to skip the process in IP.

Before sending the packet to the different packets handlers, the packet is redirected to a pktgen function. This function checks if the packet is a pktgen packet. If it is, the packets is processed and dropped. Otherwise, the packet continues its path. This avoids the process of the pktgen packets for upper layers when the received packet is a test packet.

Figure 4.2 shows the relation between the packets sent and received with the pktgen version using the packet handler and the version using the hook explained in this section. The test was done using a 10 Gigabit Link. It is shown an improvement of the reception rate around 15%.

The drawback of this technique is that is more intrusive and requires a modification of the network core. For this reason, requires a kernel compilation. The solution based on the packet handler, only requires the compilation of the module and it is transparent to the other protocols.

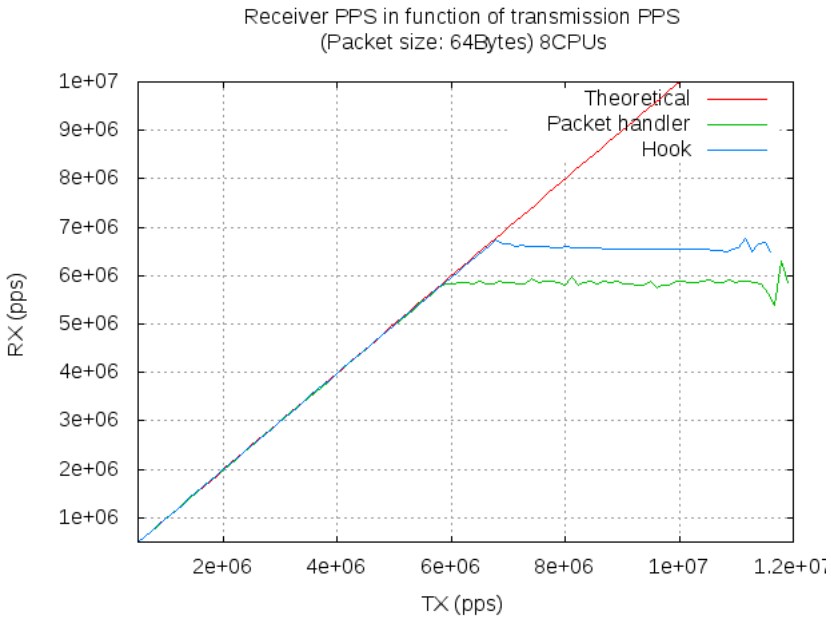


Figure 4.2. Comparison between packet handler and hook

4.5 Adjusting the transmission throughput

Pktgen has an indirect way for controlling the output throughput: changing the delay between packets. The original function that adjusts the delay (spin) used micro-second resolution. This resolution has not enough precision to adjust the delays between the transmissions of the packets. This fact produces a step behaviour in the transmission rates that causes that not all the rates are available.

The spin function (function in charge of waiting the delay time between transmissions) has been changed to use nanosecond resolution (*ktime_to_ns()* and *ndelay()*). This allows 1000 times the old resolution and increases the rate granularity of pktgen.

In Figure 4.3 is shown the output rate, in function of the theoretical delay, the original and the modified version in an Ethernet Gigabit Link. The theoretical rate in function of delay is shown in Equation 4.1. The configuration is done in a way that the sender send at its maximal speed using one CPU and one transmission queue. In Figure 4.4 it is shown the same test with the 10Gigabit card. In this case, only one queue and one CPU are used. This Figure shows that when the system is able to send at the required speed, there is sent matching the theoretical.

$$\text{Throughput (Mb/s)} = \frac{\text{Packet size (Bytes)} \times 8 \times 1000}{\text{delay (ns)}} \tag{4.1}$$

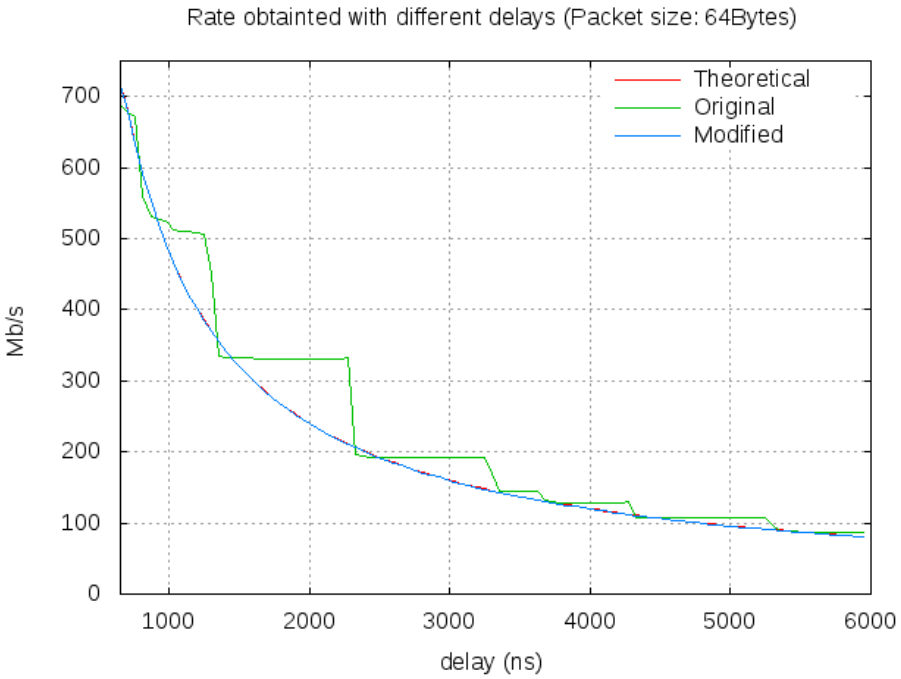


Figure 4.3. Throughput with delays. Gigabit Link

After the improvement of the delay, a new input parameter is added in order to simplify the configuration. The user can add directly the rate in Mb/s or in packets per second (PPS). This command is added in the normal control configuration via the proc file system. The options are *rate* (in Mb/s) and *ratep* (in pps).

Also, the call order of the delay and the creation of the packet is changed, inside pktgen. In the original version, first the packet was created and later delayed. This introduces a delay when the latency was measured because the time stamp was written in the packet in the creation, so the transmission delay was added to the latency test.

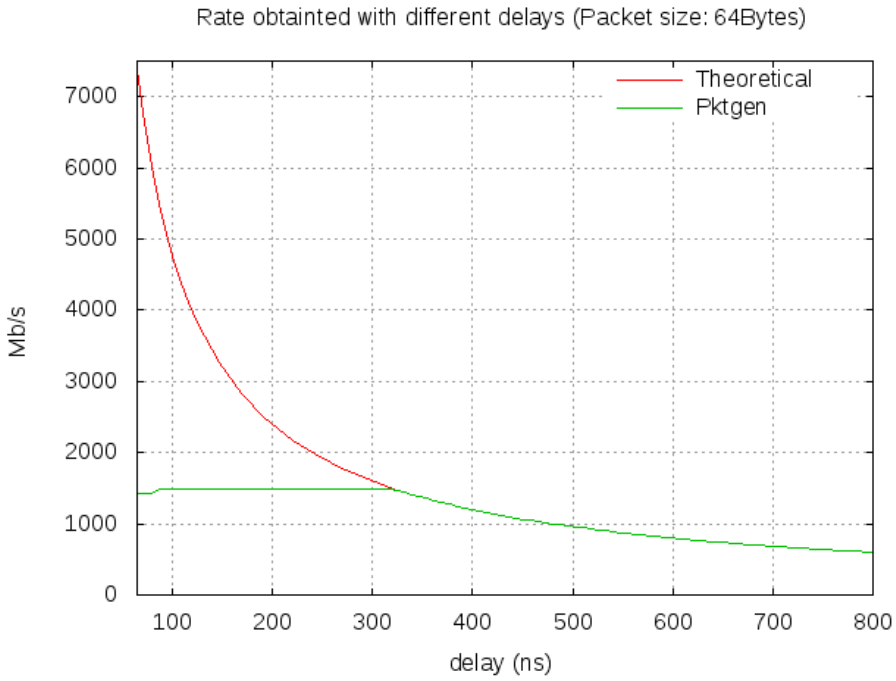


Figure 4.4. Throughput with delays. 10 Gigabit Link

Chapter 5

Evaluation

This chapter includes some test in order to calibrate the implementation. Because the reception of the packets is directly related with the network subsystem, also the behaviour of the Linux receiver is shown. Moreover, additional tests related with the performance are done.

5.1 Equipment and scenario

There are two machines with the characteristics described in the next subsections. Different scenarios were used in order to do the test.

5.1.1 Hardware

The motherboard is a TYAN S7002. The processors of the test machine are: Intel(R) Xeon(R) CPU E5520 at 2.27GHz. It is a Quad-Core processor with Hyperthreading [51], which in practice gives 8 available CPUs. The system has 3 Gigabyte (3x1Gigabyte) of DDR3 (1333MHz) RAM.

The available network cards on the system are:

- 2 Intel 82574L Gigabit Network (2 built in Copper Port): eth0, eth1
- 4 Intel 82576 Gigabit Network (2 x Dual Copper Port): eth2, eth3, eth4, eth5
- 2 Intel 82599EB 10-Gigabit Network (1 x Dual Fibre Port): eth6, eth7

There are two test machines available (host1 and host2).

5.1.2 Software

The operating system running on the test machines is Linux with Bifrost Distribution [52]. The kernel was obtained from net-next repository [53] in the 8th April of 2010. The version is 2.6.34-rc2.

Bifrost distribution is a Linux distribution focus on networking. It is used in open source routers. Net-next repository is the kernel development repository where are the latest features for the network subsystem. It runs on a USB memory stick.

5.1.3 Scenarios

Different scenarios were tested in order to evaluate the different features introduced in the pktgen modification. Almost all the tests were done with a direct connection between the two hosts. This avoids any interference between sender and receiver, and it allows higher rates in the 10 Gigabit environments. The only exception was the latency test, where a local loop between the interfaces

was done. In the Gigabit environment, two different physical cards were used. In the 10 Gigabit environments, one CPU is used for sending, and two for receiving. Table 5.1 shows the interfaces used in the tested scenarios.

Scenario Name	TX interface (Host)	RX interface (Host)	Speed
A	eth7 (host1)	eth7 (host2)	10G
B	eth4 (host1)	eth4 (host2)	1G
C	eth5 (host2)	eth3 (host2)	1G
D	eth6 (host2)	eth7 (host2)	10G

Table 5.1. Test scenarios

5.1.4 Parameters under study

Several parameters were monitored in order to evaluate the system.

- Throughput received: the units are in packets per second. The maximal theoretical number of packets per second in Gigabit links is 1,48 Mpps and for the 10 Gigabit links is 14,8Mpps. This value is obtained with the minimal Ethernet packet size (64 Bytes) plus the Ethernet preamble (14 bytes) and the inter packet gap (6 bytes).
- Time statistics: the results of the defined parameters in the previous chapters. They are expressed in nanoseconds.
- Interrupts: number of interrupt per second caused by the network device. This can help to understand some of the behaviours.

5.2 Validation and Calibration

This section includes the test of the received throughput with different CPUs and the validation and calibration of the different statistics collected by the pktgen module.

5.2.1 Receiver throughput

The maximal received throughput was tested. Scenario A and B were used, but the main interest is focus on scenario A because of the higher rates.

First, how much traffic was able to send the transmitter with the 10G card with the small packet size was tested. It was able to send up to 11,5 Mpps. In order to archive the maximal speed, it is necessary to send at least with 4 CPUs. One CPU does not have enough processing power to create and sent all the packets. Nevertheless, the wire speed is not archived. This is a hardware limitation and is produced for architecture limitations, such as the bus capacity in terms on transaction per second. The results are shown in Figure 5.1.

The receiver test was done changing the number of queues on the receiver. Each queue is attached to different processors. Each CPU has to have the same number of queues, otherwise the load is not balanced and their performance is reduced. The objective of this test is to check the amount of traffic that the system is able to process using different queues and CPUs. Also different flows are simulated because a single flow always goes to the same queue in order to avoid packet reordering. The parameters used by the pktgen sender are shown in Table 5.2.

The results of the test are plotted in Figure 5.2(a). It is shown that from 1 to 4, there is an increment of the maximal received throughput. With 5 CPUs there is a drop in the received

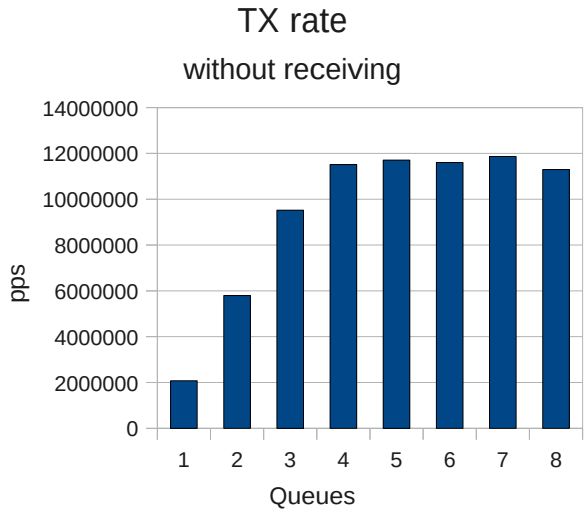


Figure 5.1. Maximal transmission rate

Parameter	Value
Device	eth7 (Intel 82599)
Number of RX queues	1 to 8
Clone packets	10
Packet size	64 Bytes
Test time	60s
Number of flows	1024
Packets per flow	8

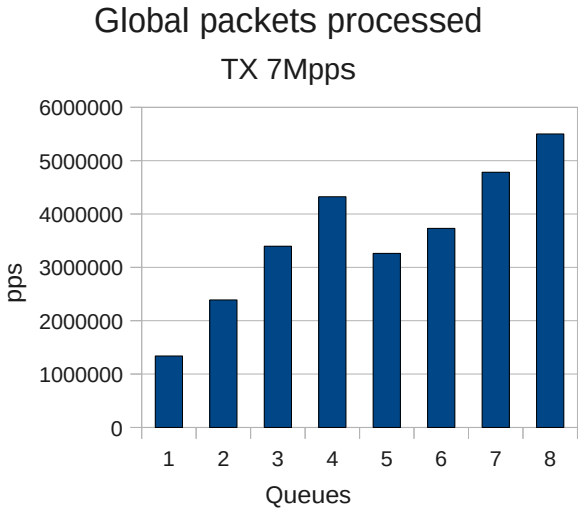
Table 5.2. Test parameters. Different number of CPUs

capacity. With 6 CPUs the performance is also less the same than with four. With 7 and 8 the results are better, but the increment is not the same that in the first case.

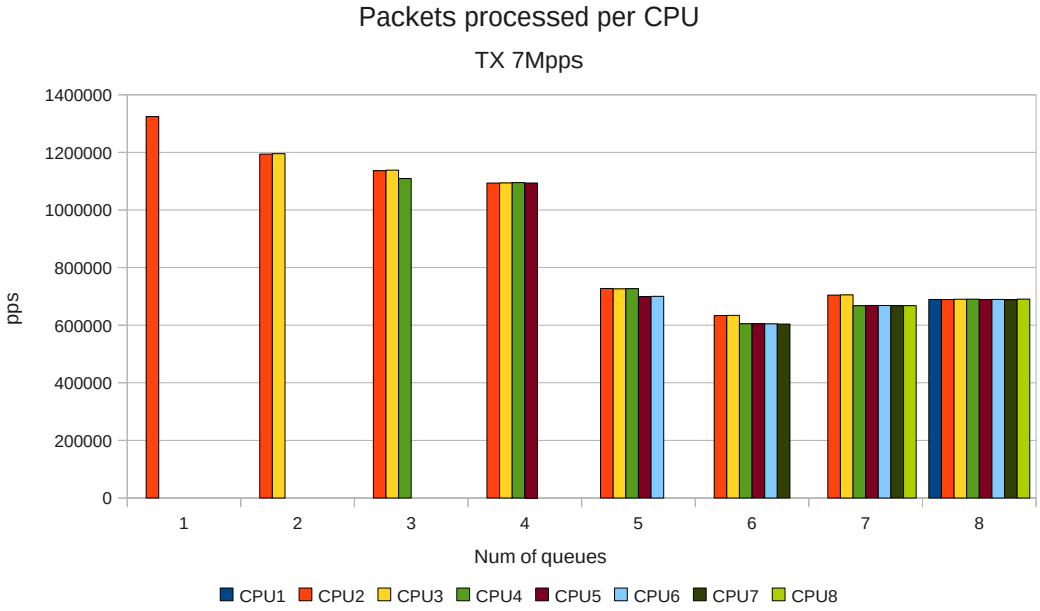
In order to understand the global behaviour, it is necessary to look at the details of each CPU. This is shown in Figure 5.2(b). It is visible, that each time that a queue is added, the individual performance drops. This is especially dramatic when 5 queues are used. In this case, the gain of the additional queue is less than the drop of performance. The drop of performance it is produced when at least one processor is using Hyperthreading. So, it is possible that the internal architecture of the processor have some influence on the results.

The results show that some resources are shared between the CPUs, and the time of synchronization and the use of common resources it is a key factor in the performance.

In the scenario B (Gigabit), the maximal rate is archived in most of the cases. The results are shown in Table 5.3. There are two exceptions, when the CPU in charge of the packet processing is CPU 0 or 4. This is due to the fact that the system timer and services are running in the first processor. So, in order to process all the packets without losses, it is necessary to have a complete idle CPU. In the case of CPU 4, the drop is due to the fact that is the same physical processor than CPU0 because of the hyperthreading.



(a) Receiver with different number of RSS queues



(b) Packets processed per CPU

Figure 5.2. Test results. Different CPU receiving

5.2.2 Inter-arrival time and jitter

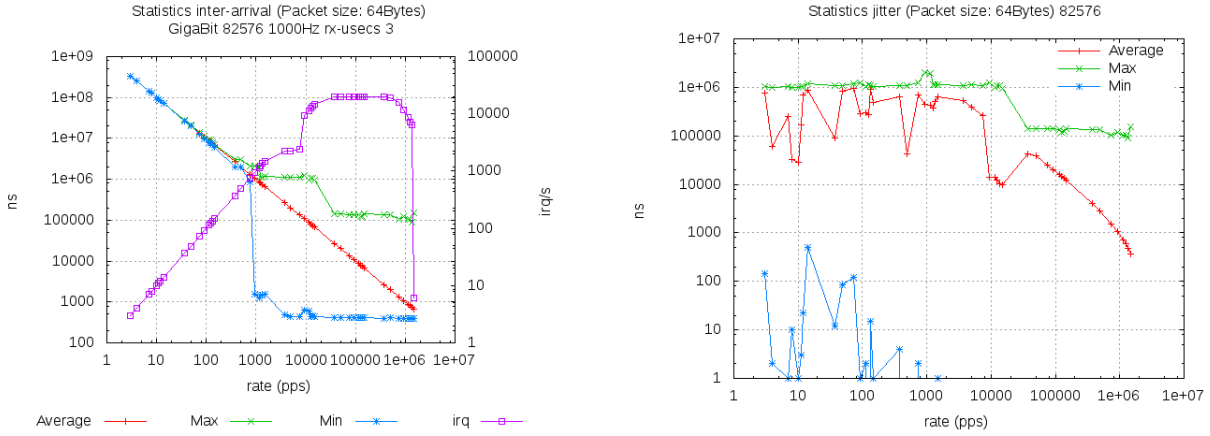
The inter-arrival time was calibrated in order to know its reliability. The sender and the receiver were in different machines. The scenario B is used. The 82576 Gigabit card was used. Both parameters (inter-arrival time and jitter) were studied together because their dependence, due to the fact that jitters is calculated with the inter-arrival times. It is been observed that there is a large dependency between the sender and the receiver, so it is not possible to isolate one of the elements. Because a constant rate is desired, the ideal maximal and minimal values of inter-arrival should be as close as possible to the average.

The first results of the inter-arrival test is displayed in Figure 5.3(a) and the jitter is displayed in Figure 5.3(b). In both graph, maximal, minimal and average values are displayed. The test was

Used CPU	Rate Received	%of wire speed (1.48Mpps)
0	1.01 Mpps	68
1,2,3,5,6 and 7	1.48 Mpps	100
4	1.38 Mpps	93

Table 5.3. Test results. Different CPU receiving

done with different packet size, and the resulting shape was always the same but with less packet rate. For this reason, and also because it implies more load, the test analysed is with a packet size of 64 bytes.



(a) Inter-arrival time results

(b) Jitter results

Figure 5.3. Inter-arrival and Jitter with default values

At low rate (less than 1kpps), in the inter-arrival time the maximal and the minimal are similar than the average. At this point, the minimal value drops to the minimal value and remains constant. The rate of the drop depends on the transmitter, which sends the packets with small inter-departure time. In this case, polling starts to work. The average value is exactly the expected. In order to obtain the expected inter-arrival time Equation 5.1 is used, where R_t is the rate in packets per second

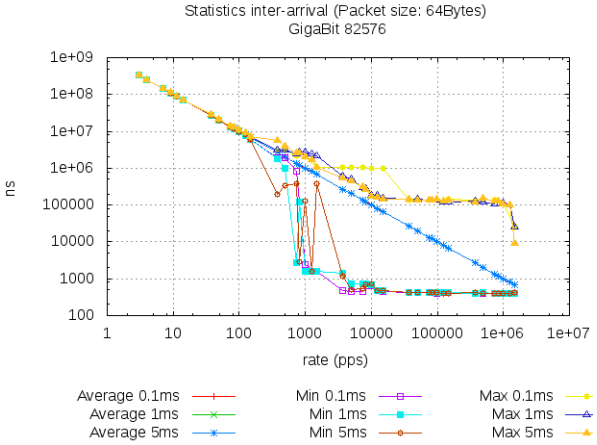
$$\text{Expected inter arrival} = \frac{1}{R_t} \tag{5.1}$$

Also it is observed that there are two steps in the maximal. The first one is due to the transmission side and it is caused by the timer frequency, which is responsible of the scheduling time. The second one is due to the NAPI. Both steps are explained later.

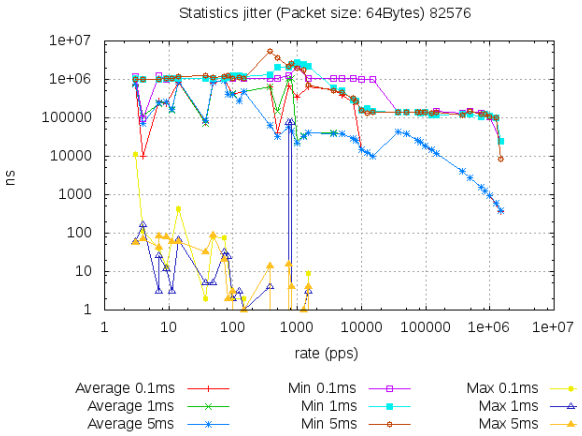
In the jitter graph at higher rates, the average is reduced, because the packets are processed in a burst (due to NAPI). Because of that, most of the packets are processed consecutively, and they have similar process time, which is the inter-arrival time calculated. Consequently, its jitter is around 0.

It was observed that some shape of the graph is due to the transmitter. In order to prove that, the spin time (See Section 4.5) was changed to different values. The results are shown in Figure 5.4. It is demonstrated that the first step disappear with higher values of the spin. Otherwise, the jitter in this interval is increased. The optimal value of the spin is the period of the timer frequency, because in this case the maximal is more close to the average in the range affected by this parameter. The factor between the maximal and the average in the different cases is plotted in Figure 5.4(c).

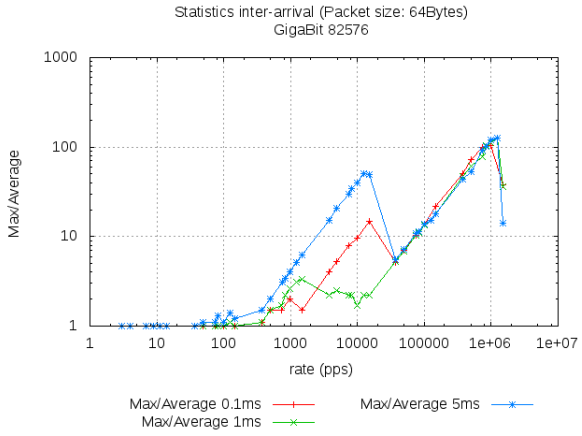
Also it is been observed that the drop of the minimal value around 1000pps is correlated with the system timer frequency of the system. In order to prove that, the timer frequency was changed



(a) Inter-arrival time results



(b) Jitter results



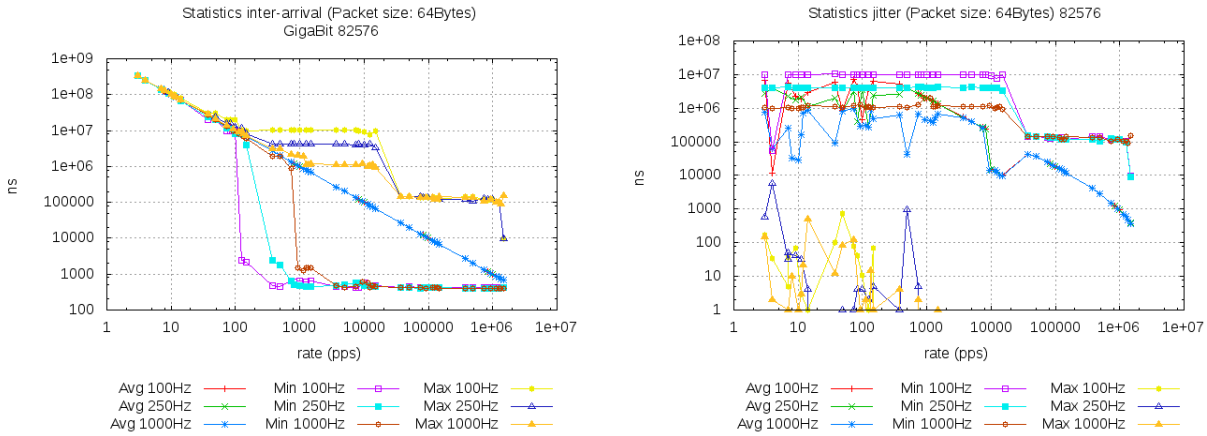
(c) Inter-arrival relation between maximal and average

Figure 5.4. Inter-arrival and Jitter with different spin time

to 100 Hz, 250 Hz and 1000 Hz. The result is plotted in Figure 5.5. It is demonstrated that there is a clear relation between the system timer frequency and the drop. The root of this behaviour is in the scheduler of the transmitter. In order to maintain an average rate, sometimes two consecutive packets are sent. In this case, the inter-arrival time is small. Also, the maximal jitter depends on the timer frequency on the transmission. The maximal jitter is the period of the system timer.

Finally, the original transmission pktgen module was tested (it used microsecond resolution, instead of nanosecond). The result is shown in Figure 5.6. It is shown that the transmitter is not able to send at all the speeds (different sample of the same rate) and also the minimal value is low than in the other cases. Moreover, also the jitter at low speeds is higher than in the improved version.

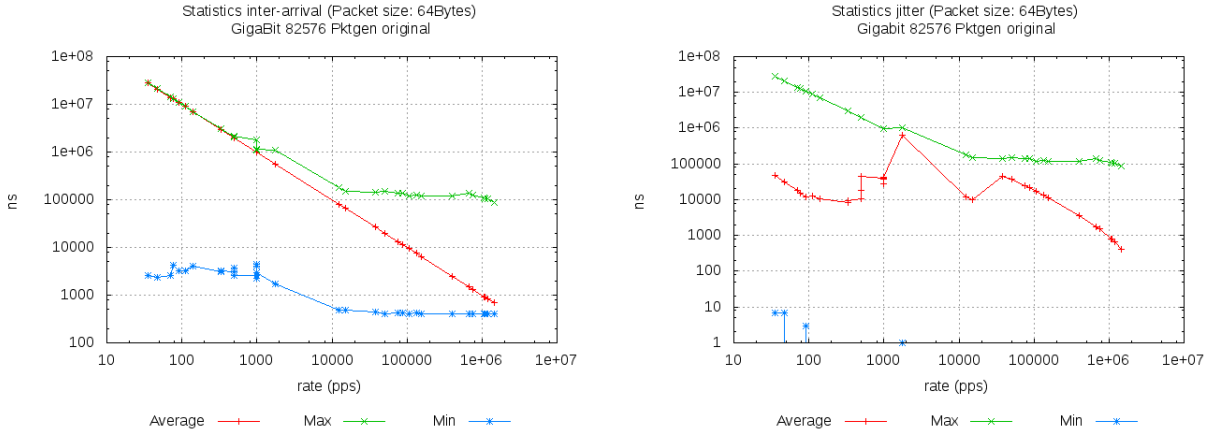
In conclusion, the modifications of the transmission of pktgen as well as the implementation of the pktgen receiver allow improving the flow sent by pktgen and also they allow extracting some basic statistics.



(a) Inter-arrival time results

(b) Jitter results

Figure 5.5. Inter-arrival and Jitter with different frequency



(a) Inter-arrival time results

(b) Jitter results

Figure 5.6. Inter-arrival and Jitter for the original module

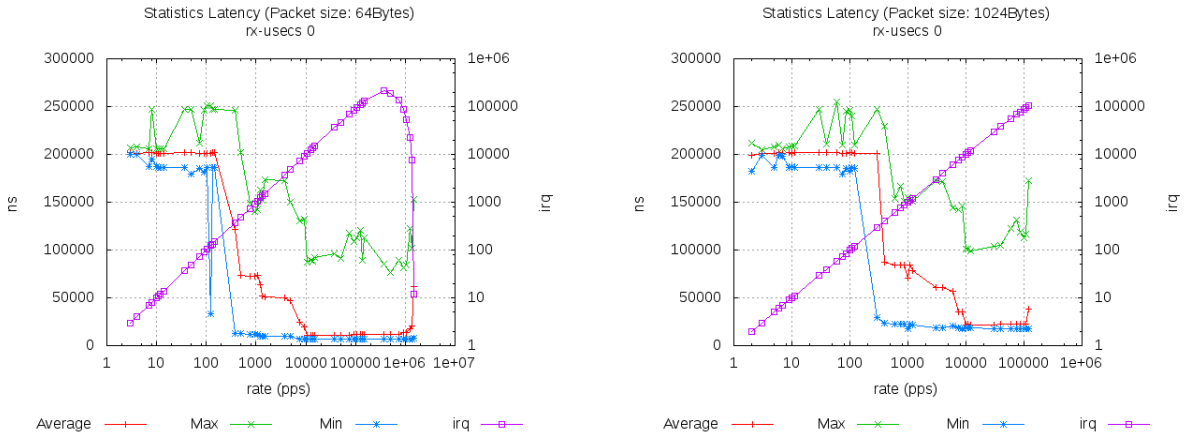
5.2.3 Latency

The latency measurement implemented in this project has the limitation that the transmitter and the receiver have to be in the same machine in order to avoid time synchronization problems.

Figure 5.7 shows the latency obtained with the default configuration in the scenario C with different packet size.

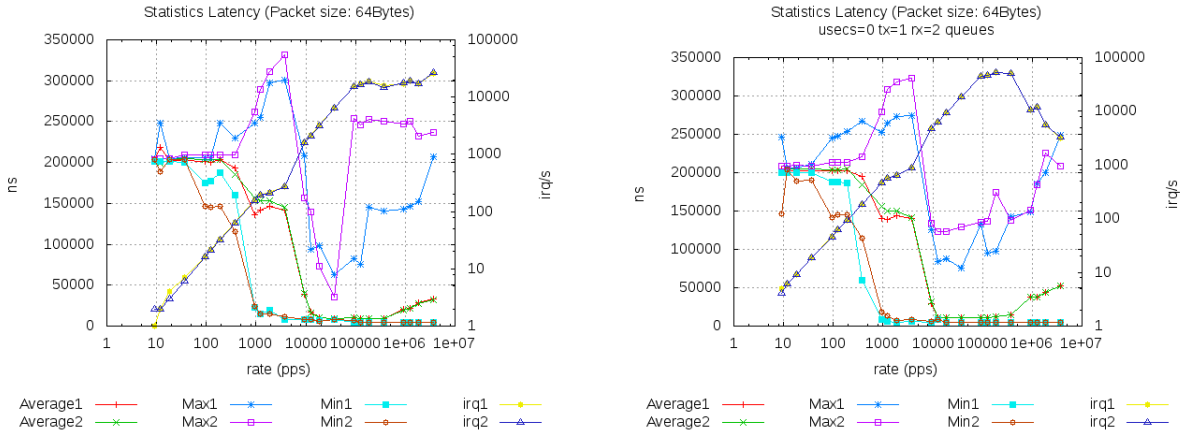
An unexpected behaviour is observed: at very low rate the latency is higher than in the rate in the middle of the capacity. This shape has to be investigated in future works. Nevertheless, the graph has the same shape with different packet size, with the only difference on the rate. The reason of this behaviour has to be founded on the driver module or in the hardware, because pktgen uses the public function offered by the driver API.

Also the 10 Gigabit interface was tested with the latency. The latency is calculated in each CPU, a flow was sent from one processor and it was received with two. The results are shown in Figure 5.8. Two scenarios were tested in order to evaluate the interrupt mitigation scheme but not visible effects on the delay were observed. The only visible effect is the reduction of interrupts at higher rates. The shape of the graph is similar with the gigabit interface. So, the same conclusions are extracted.



(a) Packet size 64 Bytes (b) Packet size 1024 Bytes

Figure 5.7. Latency test with 1G network card



(a) Latency test with interrupt mitigation (Default) (b) Latency test without interrupt mitigation

Figure 5.8. Latency test with 10G network card

5.3 Performance

This section includes some additional test in order to measure the performance of the implemented system.

5.3.1 Comparison between the different methods of collecting statistics

The three methods implemented (counters, basic and time) have different performance in terms of packets processed. This is because the number of instructions differs. Therefore, comparing the impact of the methods is interested in order to choose, which is better for the system. The parameter of the results used to compare them is the packets received, because it is the only collected for all the configurations.

The test lasted a duration of 20 seconds, using the 8 queues of the reception and the 10 Gigabit card. Because at each rate it is sent different number of packets, after obtaining the results of the test, the relative losses are calculated. The result is shown is Figure 5.9.

Counter statistics has better performance than the others because it has less operations and the

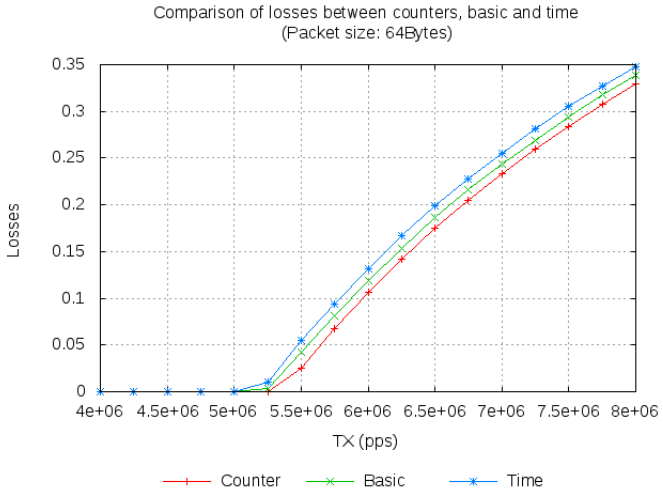


Figure 5.9. Comparison of losses of the three different types of statistics

time stamp of the system is not obtained. The result has the expected behaviour because as more process per packet, fewer packets processed. These results can be improved, removing the checking of the pktgen magic in order to know if it is a pktgen packet. But if this is done, packets that are not coming from pktgen will be counted in the test.

5.3.2 Header split or not split

The two mechanisms of reading the headers were evaluated with the same network card. The default option of the *ixgbe* driver (Intel 82599EB) is split the packet between header and data. In order to do the test without splitting the packet, an option of the driver was changed. The constant `IXGBE_RING_RX_PS_ENABLE` was set to 0. Table 5.4 shows some of the parameters used in the test.

Parameter	Value
Number of RX queues	8
Clone	10
Number of packets	80M packets

Table 5.4. Test parameters. Header split test

Table 5.5 shows the results of the test. An improvement of around 12% is archived. This is the expected result, because with splitting more operations are required. It is necessary to map the memory, read it and unmap it. When the packets are not split, there only required reading operation is an offset of a memory address.

Test	Received Rate
Split headers	5.8 Mpps
NO Split	6.5 Mpps

Table 5.5. Test Results. Header Split

5.3.2.1 Header splitting + hook

Also, the driver without the header splitter was tested with the kernel with the hook (See Section 4.4). The same parameters were used. The results are shown in Table 5.6. It is shown that only an increase of 100 kpps is archived (around 1.5%) in this environment. Also, it is shown that, if the header splitting is not working, the improvement is lower than when it is active.

Test	Received Rate	Hook Improvement
Split headers	6.64 Mpps	+14%
NO Split	6.74 Mpps	+4%

Table 5.6. Test Results. Header Split in hook kernel

Also it is shown that when the header splitter is disabled, the improvement is small. It is possible to deduce that the main overhead is caused by the IP stack instead of the pktgen, and when only the pktgen packets are processed, not such difference is between the two methods. With this test, it is possible to conclude that the overhead caused by the split headers in the pktgen receiver is around 1.5%

5.3.3 Trade-offs between single-system and dual-system implementations

When the transmitter and the receiver are in the same machine, there are some limitations in the 10G environment (Scenario D). The same physical network card is used, but with two different ports.

When the same CPU is used for sending and receiving, the performance is reduced an order of magnitude (from around 2.2 Mpps to 0.1Mpps). So, it is necessary to send and receive with different CPUs. In this case, the header split in the driver was disabled in order to increase the performance.

Some combinations of senders and receivers were tested. The results are show in Table 5.7. In the case of transmitting from 2 and receiving with 6, the limitation is on the transmission, which is not able to send more packets. In the case of sending with 3 and receiving with 5, the limitation is on the receiver, which is not able to process the amount of packets sent.

num TX	num RX	TX Rate (Mpps)	RX Rate (Mpps)
2	6	4.68	4.68
3	6	4.78	**4.78**
3	5	6.2	3.98
4	5	6.7	3.96

Table 5.7. Results of TX/RX in the same machine

In conclusion, in the analysed scenario the main limitation is the availability of CPUs for the transmission and the reception. It is shown that, the rate obtained is similar when not all the processors are used for receive the packets. Because as more CPUs, more packets processed, if some CPUs are used for sending, the receiver has less capacity to receive the packets.

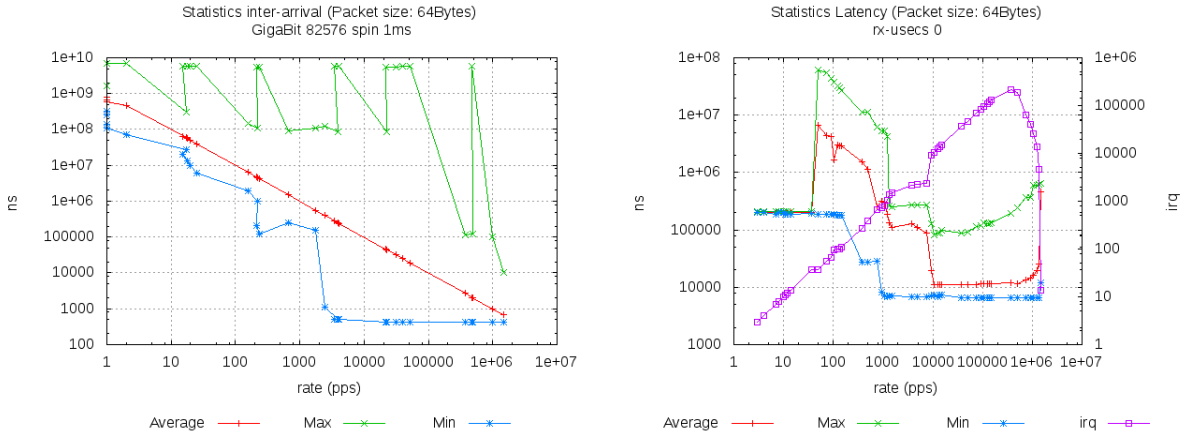
The only way to increase the throughput in terms of Mbps is increasing the packet size, which reduced the number of packets processed.

5.3.4 Implications of low performance

The more clear effect of a low performance is the packets drops. For instance, if the queues are not distributed to different CPUs, the performance drops at is shown in Subsection 5.2.1. The receiver is usually more sensible.

Also if the transmitter and the receiver have low performance, and it is not correctly calibrated, the results of the test can be not valid. For instance, if there are losses on the test will be not possible to know where these losses are produced. For this reason, it is very important to calibrate the transmitter and the receiver without any device in between in order to know the real capacities of the test machine. When this is done, the device under test (DUT) can be tested. If the results are worse than the calibrate system the problem is on the device under test. If not, the problem is in the system where the pktgen is loaded.

Also, if the conditions of the test are not well controlled, for instance, some extra load on the generator or receiver, the time measurements can be interfered at is shown in Figure 5.10.



(a) Inter-arrival time

(b) Latency measurement

Figure 5.10. Invalid tests due to bad performance

Chapter 6

Conclusions

In this thesis, some improvements to Pktgen are proposed, designed, implemented and evaluated in order to convert Pktgen into a network analyser tool. The design was done having in mind the performance and new features of commodity PCs are used, such as taking advantage of SMP systems and multiple queues in the network cards. In this work is demonstrated, that multiple queues allows processing the packets in parallel, increasing the scalability of the system. Also, it allows receiving at higher speed if one CPU is not power enough to process all the incoming traffic.

The granularity of Pktgen's transmission was improved, as well as the way how the user can introduce the parameters, in order to improve the usability. With the new version, it is possible to specify a rate in terms of megabits per second or packets per second. Also, the granularity improvement introduces a more accurate inter-arrival time between packets at low rates, making the flow more constant.

The receiver side statistics, specially the receiver throughput is a powerful tool to evaluate the performance of the network when it is saturated. The experiments showed that SMP system can receive and process more packets than a single CPU. On the other hand, the overall performance is not the sum of the packets processed with single CPU. For each CPU that process packets, less performance is achieved per CPU. The overall performance is better, except when Hyperthreading starts to work. In this case, the drop does not compensate the additional CPU. But if all CPUs with Hyperthreading are processing packets, the result is higher than without it. Additionally, some features of the cards have a direct impact on the received rate. For instance, the header split (available in Intel 10G card 82599) reduces the performance of routing capability on the system.

The different type of levels of statistics (Counter, Basic and Time) implemented allow adapting the application to different systems with performance limitations. The time statistics (inter-arrival times, jitter and latency) is a powerful tool to understand how the Linux kernel behave, and also it allows monitoring the behaviour of the network. With the inter-arrival statistics has been discovered that the transmission pattern depends on the configuration of the system. Moreover, an unexpected behaviour is observed in the latency of the network: lower rate has higher latency than higher rates. Usually, the lower latencies should be achieved in lower rates.

Also, it is possible to display the results in two different formats in order to adapt the results to the reader. First, the human display includes text description of the parameters. Second, script display allows to easily creating scripts to automate tests.

All of the new and modified features are integrated in the current Pktgen module, in order to add new features to this network tool inside the Linux Kernel. Some of the results open new fields of research, and it will allow designing better drivers and operating systems under Linux.

The tools have already tried in different environments and test with satisfactory results at the Telecommunications System Laboratory (TSlab) in the ICT School of KTH. At the time of writing, the result of this thesis is used in four research projects. Moreover, some parts of the code have been

sent to the Bifrost [52] and net-next [53] mailing list in order to incorporate the features to the main Linux Kernel.

6.1 Future work

New applications and new studies can be started with the Pktgen receiver. For instance, the change of latency with different rates does not follow the traditional curve of network delay. The delay in lower rates should be lower than in higher rates, but this is not the case.

Another aspect discovered was that how the delay is used in the Pktgen sender influence the inter-arrival times of the packets. A study of the optimal values for the delay is required to obtain a more constant traffic (CBR).

Moreover, implementing a latency test with some synchronization in order to test the end-to-end latency can be considered.

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Appendix A

Source code and scripts

A.1 Kernel patching and compiling

This sections includes a how-to for compiling a Linux kernel from the net-next repository and with the pktgen patch.

The first necessary thing is donwload the required packatges to build the kernel. In Ubuntu, using pktgen the following command is used:

```
apt-get install build-essential ncurses-dev git-core kernel-package
```

Clone the git repository of net-next. It will take some time.

```
git clone git://git.kernel.org/pub/scm/linux/kernel/git/davem/net-next-2.6.git
```

Apply the pktgen patch

```
patch -p1 < [path]/pktgen.patch
```

Configure the kernel with and compile the kernel.

```
make menuconfig
make
make modules_install
make install
```

Usually is a good idea to create a initramfs in order to load the required modules. In order to do that type:

```
update-initramfs -c -k [kernel_version]
```

After the compilation, reboot the system. Finally in order to test the module

```
modprobe pktgen
```

A.2 Summary of the new commands added in pktgen

This section includes a summary of the new commands added in pktgen. Some examples of scripts can be found in Section A.3

A.2.1 Transmitter

The improvment of granularity of pktgen can be controled with the folowing commands.

- rate [rate in Mbps]
- ratep [rate in pps]
- config [0 or 1] Enables or disables the configuration packet, which reset the statistics and allows to calculate the losses.

A.2.2 Receiver

It is controled by the proc file system. A new file is created: /proc/net/pktgen/pgrx The commands for controling are:

- rx [device] to enable the receiver part for an specific device. If it is wrong, all the devices are used.
- rx_reset: to reset the counters
- rx_disable: to disable the receiver
- display [human or script]
- statistics [counter, basic or time]

In order to see the results, the following command is used:

```
cat /proc/net/pktgen/pgrx
```

A.3 Examples of pktgen configuration scripts

The next script is used to configure the receiver. The first argument is the type of statistics and the second the interface.

```
#! /bin/sh
# $1 type of statistics
# $2 interface
function pgset() {
    local result
    echo $1 > $PGDEV
}

# Reception configuration
PGDEV=/proc/net/pktgen/pgrx
  echo "Removing old config"
 pgset "rx_reset"
  echo "Adding rx $2"
 pgset "rx $2
  echo "Setting statistics $1"
 pgset "statistics $1"
```

Source A.1. Receiver Script

This script is used to configure the transmitter to send with a specific rate. Also the configuration packet is enabled. The system has 8 CPUs and the CPU1 is used for sending the packets.

```
#! /bin/sh
function pgset() {
    local result
    echo $1 > $PGDEV
}
# Config Start Here -----------------------------------------------------------
CLONE_SKB="clone_skb 0"
PKT_SIZE=60
COUNT="count 10000000"
RATEP="ratep 100000"
MAC="dst_mac 00:1B:21:5A:8C:45"

#CLEANING
for processor in {0..7}
do
PGDEV=/proc/net/pktgen/kpktgend_$processor
  echo "Removing all devices"
 pgset "rem_device_all"
done

PGDEV=/proc/net/pktgen/kpktgend_1
echo "Adding eth3"
 pgset "add_device eth3"

PGDEV=/proc/net/pktgen/eth3
  echo "Configuring $PGDEV"
 pgset "$COUNT"
 pgset "$CLONE_SKB"
 pgset "$PKT_SIZE"
 pgset "$RATEP"
 pgset "dst 10.0.0.2"
 pgset "$MAC"
 pgset "config 1"

# Time to run
PGDEV=/proc/net/pktgen/pgctrl

 echo "Running... ctrl^C to stop"
 pgset "start"
 echo "Done"

# Display the results
grep pps /proc/net/pktgen/eth*
```

Source A.2. Trasmitter Script

The next script send with the speficied number of CPU (argument 2) and specific rate (argument 1).

```
#! /bin/sh
function pgset() {
    local result
    echo $1 > $PGDEV
}

# Config Start Here -----------------------------------------------------------
CPUS=$2
PKTS=`echo "scale=0; 100000000/$CPUS" | bc`
CLONE_SKB="clone_skb 10"
PKT_SIZE="pkt_size 60"
COUNT="count $PKTS"
```

```
DELAY="delay 0"
MAC="00:1B:21:57:ED:85"
#MAC="00:1B:21:5D:01:D1"
ETH="eth7"
RATEP=`echo "scale=0; $1/$CPUS" | bc`

for processor in {0..7}
do
PGDEV=/proc/net/pktgen/kpktgend_$processor
#  echo "Removing all devices"
 pgset "rem_device_all"
done

for ((processor=0;processor<$CPUS;processor++))
do
PGDEV=/proc/net/pktgen/kpktgend_$processor
#  echo "Adding $ETH"
 pgset "add_device $ETH@$processor"

PGDEV=/proc/net/pktgen/$ETH@$processor
#  echo "Configuring $PGDEV"
 pgset "$COUNT"
 pgset "flag QUEUE_MAP_CPU"
 pgset "$CLONE_SKB"
 pgset "$PKT_SIZE"
 pgset "$DELAY"
 pgset "ratep $RATEP"
 pgset "dst 10.0.0.1"
 pgset "dst_mac $MAC"
# pgset "config 1"
PORT=$((10000+processor))
 pgset "udp_dst_min $PORT"
 pgset "udp_dst_max $PORT"
done

# Time to run
PGDEV=/proc/net/pktgen/pgctrl

 echo "Running... ctrl^C to stop"
 pgset "start"
 echo "Done"

grep -h pps /proc/net/pktgen/eth*
```

Source A.3. Trasmitter Script

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