Worldwide Internet Performance Measurements Using Lightweight Measurement Platforms

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***Abstract*—We report on a study of the applicability of using a Raspberry Pi for monitoring the worldwide performance of the Internet. The low cost and power requirements of the Raspberry Pi are particularly attractive for deploying in places with limited funds or power. This includes developing regions such as are monitored by the PingER project. We evaluate various statistical methods to establish their applicability and to compare if and how the measurements made by a regular bare-metal data center server significantly differ with those from a Raspberry Pi. Using the results from the comparisons we determine the significance of the differences, decide if they are important and suggest how to partially mitigate.**

***Index Terms*—Internet monitoring, ping, PingER, network monitoring**

I. Introduction

There are various Internet performance monitoring platform such as Surveyor [1], Scamper [2], PerfSONAR framework [3], [4], and others, each with their own approach (active vs passive monitoring), scope (WAN, high speed network, etc) and target audiences. Internet monitoring is important and useful in order to ensure that the status of the connection and the performance is known at all time to ensure the service is not interrupted to the end users.

This is a project to build and validate a PingER [5] Measurement Agent (MA) based on an inexpensive Raspberry Pi [6] using a linux distribution called Raspbian as the Operating System. If successful one could consider using these in production: reducing the costs, power drain (they draw about 3W of 5V DC power compared to typically over 100W for a deskside computer or 20W for a laptop) and space (credit card size). This is the same type of power required for a smartphone, so appropriate off-the-shelf products including a battery and solar cells are becoming readily available. Thus, the Raspberry Pi could be very valuable for sites in developing countries where cost, power utilization and to a lesser extent space may be crucial. However, we need to ensure that the important metrics derived from the measurements made by the Raspberry Pi should not be significantly different from those made by a bare metal PingER MA, or if they are, then this needs to be understood and possibly mitigated. In this paper we show the measurement set up and the analysis of the measurements to compare the results for MAs on very different hosts.

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The paper is organized as follows: Section II provides discussion on related works, followed by discussion on the requirements to setup the PingER MA in Section III. We discuss about the methodology of the research and how PingER works in Section IV. The result of the experiments is discussed in Section V We briefly discuss on future work in Section VI. Finally we discuss future work in Section VI and conclude the paper in Section VII.

II. Related Work

The MA we are proposing to deploy on the Raspberry Pi is part of the PingER project [5] started in 1995. In 2009, as a joint project between SLAC and ICTP in Trieste Italy, a PingER MA was installed on a 6x6 board embedded Linux platform and deployed in Zambia [7]. Since then, the Raspberry Pi has been proposed as such a low cost network MA in 2013 [8]. Following this there have been many MA projects based on the Raspberry Pi. There is also a proposal to install a Raspberry Pi PingER host in remote Sarawak areas [9]. However, we can find no references to whether the MA results from the Raspberry Pi platform differ significantly from a bare-metal platform.

III. Requirement

Two major points need to be addressed before we can comfortably deploy Raspberry Pi PingER MAs.

1) The Raspberry Pi PingER MA must be robust and reliable. It needs to run for months to years with no need for intervention.
2) The important metrics derived from the measurements made by the Raspberry Pi should not be significantly different from those made by a bare metal PingER MA, or if they are then this needs to be understood.

In addition for some sites with power problems the MA will need to get its power from an alternate source such as solar.

In this paper we mainly address item 2. We define the important metrics measured by PingER as being the minimum, average, median and jitter of the Round Trip Times (RTTs), the packet loss, together with the reachability (i.e. a target host is unreachable when no ping requests are responded by the target host). These are the main metrics that impact applications such as: throughput; real time applications such as voice over IP, streaming video, haptics, gaming; and estimating the geolocation of a host by pinging it from well known landmarks. Such differences might result in significant discontinuities in the metric measurements if we were to change the monitoring host from a bare metal server to a Raspberry Pi.

The jitter can be represented in many ways including the standard deviation or Inter Quartile Range (IQR) of the RTT distributions, or the standard deviation or the Inter Packet Delay (IPD). PingER mainly uses the IQR of the IPD distribution to represent the jitter referring to this metric as the Inter Packet Delay Variability (IPDV) [10].

IV. Methodology

A. Pinger

The measurement tool was a PingER MA in all cases. PingER (Ping End-to-end Reporting) is the name given to the Internet End-to-end Performance Measurement (IEPM) project to monitor end-to-end performance of Internet links. Originally, in 1995 it was for the High Energy Physics community, however, this century it has been more focused on measuring the Digital Divide from an Internet Performance viewpoint. The project now involves measurements to over 700 sites in over 160 countries. It uses the ubiquitous ping facility so no special software has to be installed on the targets being measured by the MAs.

PingER measurements are made by 60 MAs in 23 countries. They make measurements to over 700 targets in about 160 countries containing more than 99% of the world's connected population. The measurement cycle is scheduled at roughly 30 minute intervals. At each measurement cycle, each MA issues a set of 100 Byte ping requests and a set of 1000 Byte ping requests to each target in the MAs list of targets, stopping when the MA receives 10 ping responses or it has issued 30 ping requests. The number of ping responses is referred to as N and is in the range 0 - 10. The data recorded for each set of pings consists of: the MA and target names and IP addresses; a time-stamp; the number of bytes in the ping request; the number of ping requests and responses (N); the minimum Round Trip Time (RTT) (Min_RTT), the average RTT (Avg_RTT) and maximum RTT (Max_RTT) of the N ping responses; followed by the N ping sequence numbers, followed by the N RTTs. From the N RTTs we derive various metrics including: the minimum RTT; average RTT; maximum RTT; standard deviation (stdev) of RTTs, 25% probability (first quartile) of RTT; 75% probability (third quartile) of RTT; Inter Quartile Range (IQR); loss; and reachability (host is unreachable if it gets 100% loss). We also derive the Inter Packet delay (IPD) and the IPDV.

The data is publicly available and since the online data goes back to January 1998, it currently provides 19 years of historical data on worldwide Internet performance.

B. PingER Architecture

The architecture of the PingER monitoring platform is shown in Figure 1.

The PingER monitoring platform consists of several different hosts. The first type of hosts are the ***remote hosts***, which are hosts that are being monitored by the monitoring hosts, usually a server with high and stable uptime such as a web server, within a particular organization. There is no software or setup required for a remote host and the only requirement is that the host must be ping-able (no firewall restriction on ping packets).

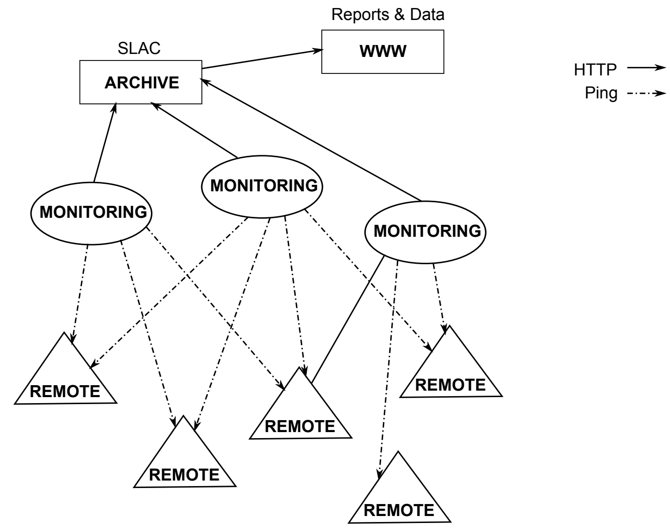

Fig. 1. PingER platform Architecture

The second type of host is the ***monitoring hosts*** whereby each of these hosts is a computer where the PingER monitoring software is being deployed. The computer where the PingER software is being deployed can be a server, a desktop, or laptop with minimal hardware requirement as low as Pentium III processor with 512 MB of RAM. As for the operating system, the computer needs to be installed with Linux-based operating system such as Ubuntu, CentOS, and other linux distribution. The computer also needs to be connected to the Internet with a public IP address which is accessible from outside the organization internal network. Optionally, rather than having a dedicated computer to deploy the PingER software, an existing server such as a web server can be use for the deployment.

Finally, the ***archive hosts*** gather data from the monitoring hosts and act as storage repository of the raw data. The main archive host is at SLAC, plus another two, each at FNAL (Fermi National Accelerator Laboratory) and at NUST[1] (National University of Sciences and Technology, Pakistan). The reports generated by various tools can be accessed from the PingER website[2] which serves as the front-end system to the end users.

C. Measurement Agents

Since we believed, both a priori and from observations, that the major impact on the measurements was the network and not the servers' hardware or OS, we chose to make detailed analysis of a small subset of the PingER measurements. We chose the two representative MAs at SLAC and two representative sites in Vancouver, Canada and Geneva Switzerland that are very reliable and well separated from SLAC, and hence with very different RTTs. The two MAs at SLAC were:

1) A 10 year old re-purposed Dell Poweredge 2650 3GHz with one physical processor

[1] http://pinger.seecs.edu.pk/
[2] http://www-iepm.slac.stanford.edu/pinger/

TABLE I
LOCATIONS OF THE PINGER MAS

Host, location	Latitude	Longitude	Great Circle distance	Min RTT	Directivity
pinger.slac.stanford.edu (pinger.SLAC)	37.4190 N	122.2085 W	0 km	0.0003 ms	0.001
pinger-raspberry.slac.stanford.edu (pinger-raspberry.SLAC	37.4190 N	122.2085 W	0 km	0.0003 ms	0.001
sitka.triumf.ca, Vancouver, Canada (TRIUMF)	49.2475 N	123.2308 W	1319.6 km	13.196 ms	0.6
pinger.cern.ch, Geneva Switzerland (CERN)	46.23 N	6.07 E	9390.6 km	93.90 ms	0.63

with 16GBytes RAM re-purposed bare metal pinger.slac.stanford.edu server running Red Hat Linux 2.6.32-504.8.1.el6.i686. More information can be found at https://confluence.slac.stanford.edu/display/IEPM/ePinger+Project+at+SLAC. Henceforth this MA is referred to as pinger.SLAC.

2) A Raspberry Pi Armv61 pinger-raspberry.slac.stanford.edu server running Gnu Linux. Henceforth this MA is referred to as pinger-raspberry.SLAC.
    a) The Raspberry Pi purchased is a version 1 of Raspberry Pi, model B. It has 512MB RAM, on a 700Mhz ARM CPU and a 32GB SD Card. It has 2 USB ports, 1 100Mb/s Ethernet interface and 1 HDMI port. For reasons of economy it does not have a Real Time Clock (RTC). Instead, the Raspberry Pi is intended to be connected to the Internet via Ethernet or WiFi, updating the time automatically from the global ntp (network time protocol) servers [11].
    b) The Voltage requirement for the power is 5V+-5%. Keep in mind that it is necessary to have a keyboard, a mouse and a HDMI monitor to do the installation process, but once PingER is working they are not necessary anymore. We measured the power (Wattage) during normal use and it is 2.7 Watts. When using the Dell mouse, with an LED, powered from the Raspberry Pi it crept up to 3.2 Watts.
    For applications in remote areas with limited power, the Raspberry Pi needs to be able to run 24 hours a day with only solar derived power. Let's say the power required is 3W at 5V or (3/5)A=0.6A. If we have a 10Ah battery, then at 0.6A it should have power for 10Ah/0.6A or 16.7 hours. Then we need a solar cell to be able to refill the battery in a few hours of sunlight. Let's take a 20W 5V solar panel = 20/5 = 4A solar panel. So initial guess to re-charge the 10Ah battery is 10Ah/4A = 2.5 hours. But inefficiencies [12] of say 2.5 extends this to 6.25 hours.

Both the SLAC MAs were in the same building at SLAC, i.e. roughly at latitude 37.4190 N, longitude 122.2085 W, but on different floors. The machines were about 30 metres apart or about 0.0003 ms based on the speed of light in a directly connected fibre.

Information on the various hosts involved is given in the table below. The Directivity in the table below provides a measure of how direct the route is between the MA and target.

The ***Directivity*** is given as:

$$Directivity = \frac{Great \quad Circle \quad Distance[km]}{RTT[ms] * 100[km/ms]}^{3}$$

The Directivity is <= 1, and a value of 1 means the RTT is the same as given by the speed of light in a fibre.

The measurements were made:
- between pinger.SLAC and pinger-raspberry.SLAC;
- from both pinger.SLAC and pinger-raspberry.SLAC to the targets at TRIUMF and CERN;
- from the two MAs at TRIUMF and CERN to pinger.SLAC and pinger-raspberry.SLAC

For each pair of hosts (MA and target) using the PingER measurements:
- for all the 30 minute measurement sets we plotted the Min_RTT, Avg_RTT and Max_RT and loss as a time series. For the Min_RTT and Avg_RTT we calculated the minimums, averages, the 25%, the median, the 75% and IQR.
- for all the individual ping response in all the sets we plotted the Inter Packet Delay (IPD) distributions and recorded the minimum IPD, average IPD, maximum IPD, standard deviation of IPD, 25% IPD, 75% IPD, Median IPD, IQR IPD and loss.

V. RESULTS

Table II compares pinger.SLAC results with pinger-raspberry.SLAC results. It shows the more important aggregate metrics measured from an MA to a target. The columns are arranged in pairs. The first of each pair is for pinger.SLAC, the second for pinger-raspberry.SLAC. Each pair is measured over roughly the same time period identified in the Time period row. Different pairs are measured over different time periods.

The errors are estimated using standard deviations (stdev) and IQRs. The IPDV error is the standard deviation of the hourly IPDVs for the time period

We looked at various ways to estimate whether the probability of the ping distributions for pinger.SLAC differs significantly from those for pinger-raspberry.SLAC.

Figure 2 shows typical time series of the Min_RTT, Avg_RTT, Max_RTT and loss measured from the SLAC MAs

[3]between MA and target

TABLE II
RESULT COMPARISON BETWEEN PINGER.SLAC VS PINGER-RASPBERRY.SLAC

Monitor Target / Metric	**pinger[1] to pi**	**pi[2] to pinger[1]**	**pinger[1] to TRIUMF**	**pi[2] to TRIUMF**	**TRIUMF to pinger[1]**	**TRIUMF to pi[2]**	**pinger[1] to CERN**	**pi[2] to CERN**
Time period	Jun 17 to Jul 14	Jun 17 to Jul 14	Jun 17to Jul 14	Jun 17 to Jul 14	Jul 14 to Jul 27	Jul 14 to Jul 27	Jun 17 to Jul 14	Jun 17 to Jul 14
Samples	1361	1429	1362	1326	630	630	1283	1326
M=Min_RTT ms	0.476	0.465	23.382	22.333	22.337	22.807	150.935	151.398
S=error ms*	0.023	0.024	13.5	6.45	74.702	0.067	0.026	2.258
Z	0.331	-0.331	0.003	-0.003	-0.055	0.055	-0.205	0.205
M=Median(Min_RTT) ms	0.471	0.462	22.289	22.659	22.235	22.614	150.934	151.228
S=error ms**	0.028	0.034	0.57	0.08	0.057	0.082	0.026	0.0487
Z	0.204	-0.204	-0.643	0..643	-3.795	3.795	-5.236	5.326
M=Avg_RTT ms	0.542	0.526	24.041	23.855	22.857	23.203	151.06	151.512
S=error ms ***	0.038	0.117	18.764	9.236	7.085	6.838	0.392	2.267
Z	0.130	-0.130	0.009	-0.009	-0.035	0.035	-0.220	0.220
M=Median(Avg_RTT) ms	0.537	0.511	22.402	22.803	22.346	22.754	150.983	151.312
S=error ms +	0.029	0.03	0.104	0.109	0.109	0.132	0.031	0.044
Z	0.623	-0.623	-2.662	2.662	-2.383	2.383	-6.113	6.113
Samples	12810	13400	12820	13430	12820	12540	12480	12440
M=IPDV ms	0.061	0.051	0.19	0.21	0.21	0.19	0.01	0.01
S=error ms ****	0.003	0.22	0.039	0.025	0.25	0.039	0.075	0.028
Z	0.45	-0.045	0.432	0.432	0.191	-0.191	0.0	0.0
Loss %	0.07	0.00	0.01	0.01	0.00	0.00	0.02	0.00

*stdev(Min_RTT) **IQR(Min_RTT) ***stdev(Avg_RTT) ****IQR(IPDV) +IQR(Median(Avg_RTT))
[1]pinger.SLAC [2]pinger-raspberry.SLAC

to TRIUMF. It is seen that there are frequent spikes of high values of RTT, and that the minima hover around 25 msec. Also it is seen that there almost no losses.

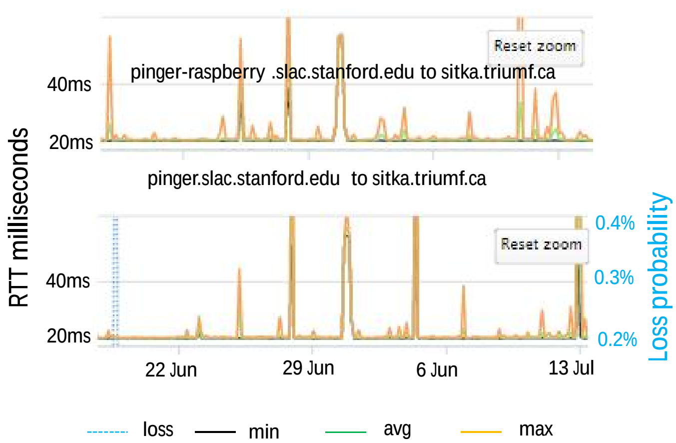

Fig. 2. Typical time series of the Min_RTT, Avg_RTT, Max_RTT and loss measured from the SLAC MAs to TRIUMF

A. Chi squared

Since the timestamps of measurements for one MA to a target are not synchronized with another MA to the same target, they are sampling the network at different times. Typically the difference in the time of a measurement from pinger.SLAC to TRIUMF versus pinger-raspberry.SLAC to TRIUMF averages at about 8 mins. Thus we decided not to use the residuals in the RTTs between one pair and another to generate Chi squared.

B. Z-test

We used the Z-test to find the probability of the distributions overlapping. For all the ms rows in the table below, we calculated $Z = (M1 - M2)/sqrt(S_1^2 - S_2^2)$ where M1 and M2 are the values, S_1 and S_2 are the errors. The subscripts 1 and 2 are those shown in the heading row. However the ping distributions are decidedly non-normal (see for example the Figure 3 below) have wide outliers, and are heavy tailed on the upper side [13]. This leads to large standard deviations (one to two orders of magnitude greater than the IQR) in the RTT values. As can be seen from the table this results in low values of the Z-test and a false probability of no significant statistical difference. As seen in the table, using the IQRs of the frequency distributions instead generally leads to much higher values of the Z-test and hence a higher probability that the distributions of RTTs between two pairs of hosts are significantly different.

Comparing the frequency distributions in Figure 3, it is seen that there is indeed a marked offset in the RTT values of the peak frequencies and a resultant difference in the cumulative RTT distributions. Using the non-parametric Kolomogorov

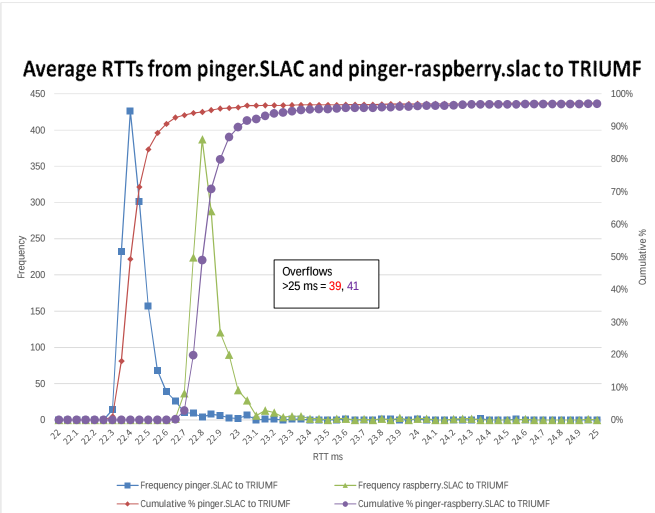

Fig. 3. Average RTTs from pinger.SLAC and pinger-raspberry.slac to TRIUMF

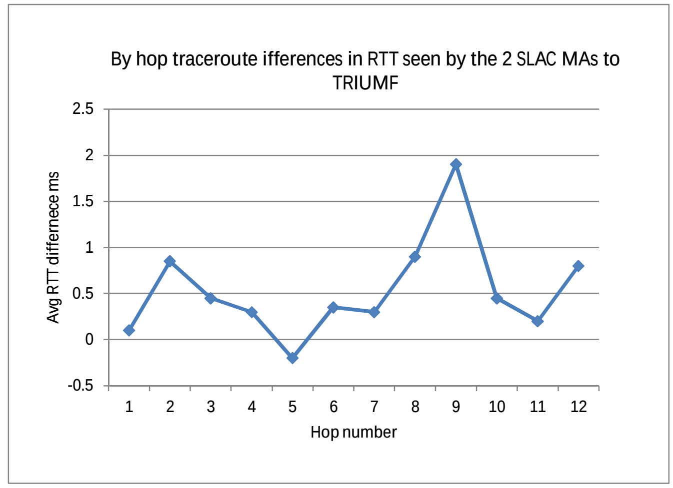

Fig. 4. By hop differences in RTT (pinger-Raspberry.SLAC - pinger.SLAC) seen by 2 SLAC MAs to TRIUMF. Note that routers typically give low priority responding to probes, rather focusing on transferring packets. Thus the delays measured can be caused by non network related causes and can fluctuate widely based on load.

Smirnoff test (KS test) also indicated significant differences in the distributions.

C. KS-test

The Kolmogorov-Smirnov test (KS-test) tries to determine if two datasets differ significantly [14]. The KS-test has the advantage of making no assumption about the distribution of data. Basically it compares the difference of the cumulative distributions. As can be seen in Figure 3 there is a huge difference in the cumulative distributions around 22.5 ms leading KS to indicate the two distributions are significantly different.

D. Partial cause of the differences

The RTT measurements made from pinger.SLAC and pinger-raspberry.SLAC to TRIUMF and CERN average around 23ms and 151ms respectively. Despite this large difference in average RTTs, comparing the average RTTs from pinger.SLAC with those from pinger-raspberry.SLAC yields a difference of only 0.35ms for both TRIUMF and CERN.

Using Matt's traceroute [15] to measure the RTT to each hop, indicates that this difference starts at the first hop and persists for later hops as shown in Figure 4. We therefore made ping measurements from each SLAC MA to its loopback network interface. The measurements were made at the same times to facilitate comparisons. They indicate that the pinger-raspberry.SLAC is about 0.13ms slower in responding than the pinger.SLAC MA. Thus approximately 1/3rd of the difference in average RTS to TRIUMF measured by the two SLAC MAs is due to the MA platform itself. This may be partially due to pinger.SLAC running on a 3GHz host while the Raspberry Pi is only 700MHz host.

E. Results from IPDV

PingER's main metric for measuring jitter is the IPDV. A typical IPD distribution from which the IPD is derived is shown in Figure 5.

IPD distributions are centered on 0 ms and have very wide tails. The one in the figure is cut off below the 2% and above the 98% percentile. The number of outliers not shown is given in the figure, as are the maximum and minimum values of IPD. The distribution is thus seen to have very positive and negative tails. Also as illustrated in the figure a typical IPD distribution has a very sharp peak. To derive the IPDV we take the IQR of the IPD distribution. The values for the IPDV for the various measurements are shown in Table II. The errors(S) in the IPD are taken from the IQR for the hourly PingER IPDVs observed for the same period. It is seen that the Z-Test in this indicates a value of < 2.0. Assuming the Z-Test is relevant for the non-normal IPD distributions if one uses the IQRs instead of the standard deviation, a value of < 2 for the Z-test statistics indicates the two samples are the same [16].

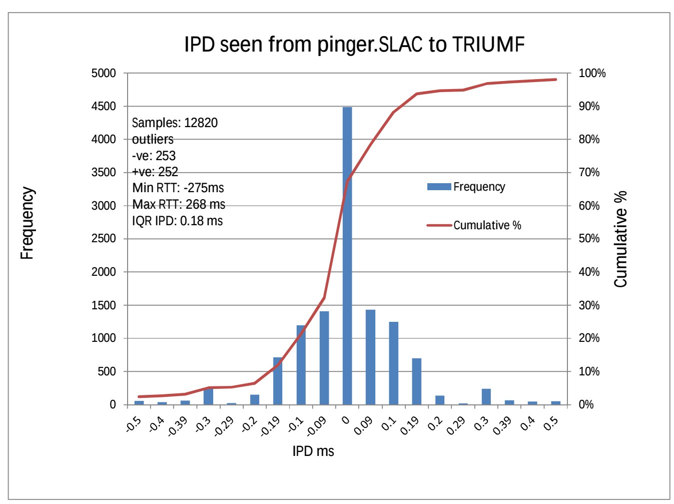

Fig. 5. Average RTTs from pinger.SLAC and pinger-raspberry.slac to TRIUMF

VI. Future Work

We have added continuous measurements of the loopback interfaces. When there is sufficient data we will analyze and compare the loopback IPDV frequency distributions for pinger.SLAC versus pinger-raspberry. We are also considering partially mitigating the differences in RTTs by subtracting the loopback RTTs.

The robustness of the Raspberry Pi for this application still needs to be demonstrated in the field. We also need to more fully understand the solar power requirements.

The installation procedures for a PingER MA are relatively simple, but do require a Unix knowledgeable person to do the install and it typically takes a couple hours and may require a few corrections pointed out by the central PingER admin. It is possible to pre-configure the Raspberry Pi at the central site and ship it pre-configured to the MA site. However that requires funding the central site Raspberry Pi acquisitions, may raise issues of on-going commitment, and may not be acceptable for the Cyber security folks at the MA site. We are looking at simplifying the install process, possibly by creating an ISO Image.

Building upon the expected advantages of deploying PingER functionality onto inexpensive hardware, such as a Raspberry Pi, we will also explore development of PingER software to be run on Android-based smartphones and tablets as a Java APK. This offers several potential advantages, including expected simplification of installation/setup and cost. To accelerate the process, we plan to leverage the existing codebase of active open-source IoT projects running on Android, including Rainforest Connection (RFCx). This is expected to lower the barrier-to-entry for potential PingER MA clients, as Android phones are readily available worldwideeither inexpensively, or free of cost. Android-based PingER MAs will likely obtain network connectivity from local WiFi networks, contrary to the hardwired ethernet connections expected from a Raspberry Pi PingER MA. The addition of WiFi interfaces to the PingER network may introduce additional latencies/disruptions that will also be studied.

VII. Conclusion

The RTT distributions for the bare metal server (pinger.SLAC) are significantly different to those for the Raspberry Pi. However, most of the difference is due to the Raspberry Pi responding more slowly and this response time difference is small (< 0.5 ms). For PingER, the minimum RTT from SLAC is about 2 ms, and the median from SLAC to all other sites is about 190 ms. Thus the impact of the difference in the RTTs is considered insignificant. Further about 1/3 of the difference can be corrected for by measuring the loopback interface.

The power draw is $< 3W$ and appears to be sustainable with an off the shelf solar cell and battery. We still need to verify the long term reliability and robustness of this solution.

In summary the Raspberry Pi appears to be an excellent candidate to deploy as a PingER MA. The measurements have shown the differences in measured RTTs compared with the current SLAC bare-metal conventional Intel rack-mounted based 2U server are insignificant for the PingER MA application.

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