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Multi-path routing

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Abstract

For years the size and routing complexity of the internet increased. For every source/destination pairing there are several possible paths traffic can take. But only one is used and the remaining are only there as possible backups if the main link is interrupted for any reason.
The goal of this project is to analyze the performance of multiple paths from several stub-ASes to different destinations and make assumptions whether multi path routing would be a viable option to increase bandwidth and fault tolerance.

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Chapter 1

Introduction

For years the size and routing complexity of the internet increased. For every source-destination pairing there are several possible paths traffic can take. But only one is used and the remaining are only there as possible backups if the main link is interrupted for any reason.
The goal of this project is to analyze the performance of multiple paths from several stub-ASes[1] to different destinations and make assumptions whether multi path routing would be a viable option to increase bandwidth and fault tolerance.

1.1 Motivation

There are several positive aspects to multi-path routing. Due to using more than one link going to a destination the possibility of all links failing at the same time is siginificantly lower than the chance of it occuring for a single-path connection. But not only does this lead to increased fault tolerance but also to less possibility for congestion and increased bandwidth. Additionally it is possible to even increase security of TCP connections, see [16].

1.2 The Task

The goal of this project was an evaluation. Using probes in ASes all over the world we ran traceroutes to different websites to see possible different paths leading to these destinations. For this to happen we needed to create scripts that would help us generate a work flow to run experiments efficiently. The evaluation then concentrated on the performance differences between the different source ASes when they connect to a number of different destinations.

1.3 Related Work

This project is not the first in this regard and will certainly not be the last. There have been papers on this subject for a long time (relativ to the age of the internet), see [11]. But most of them are more recent and up to date (see [13]). There are even some very interesting applications that are evaluated, i.e. using game theory and multi-path routing to combat incidents which can include terrorist attacks, see [15].

1.4 Overview

In chapter 2 we give insight in the background of the tools used, the ASes that were used and the destination we probed. Following that in chapter 3 we show the programs that were created or modified to get our work flow. In chapter 4 we present the results we gathered which we then discuss in chapter 5. We finish it in chapter 6 with our conclusion of the project and a short outlook in further possible research problems.

[1] autonomous systems - short form used from now on

Chapter 2

Background

2.1 RIPE Atlas

The main platform used for gathering experiment data was RIPE Atlas. This is a internet data collection system run by RIPE NCC [10]. RIPE is the Regional Internet Registry (RIR) for Europe, Central Asia, Russia and West Asia.
RIPE Atlas [7] is essentially a database of small hardware devices called probes placed in ASes all over the world. Basic data is available to the public, for instance internet connectivity via traffic maps and streaming data visualizations. Members that host their own probe(s) are able to earn "credits" which they can use in turn to make specific measurements. Most interesting for us was the possibility to run traceroutes from probes in different ASes to specific destinations. Using the API that they provide it is easy to write scripts which run for an extended period of time and repeat the same measurements.

2.2 CAIDA data server

The CAIDA [4] data server [3] provides monthly updated relationship data between ASes. There are two sub folders in this server, serial-1 and serial-2. The former is created by using the method described in [17], whereas in the latter the result from serial-1 is used and combined with the relationships inferred from [14]. For this project the data set */serial-2/20180901.as-rel2.txt.bz2* was the basis on which we worked on. This file was generated on *20 September 2018*. The resulting .txt file has the layout seen at 2.1.

Listing 2.1: layout of the as relationship data set

```
<provider-as>|<customer-as>|-1
<peer-as>|<peer-as>|0|<source>
```

2.3 Source ASes

The source ASes that we make the traceroutes from are very important. They need enough probes to get multiple paths towards a destination. How exactly the ASes were chosen is described in chapter 3.1.4. The ASes used in this project can be seen in table 2.1. The location and the amount of IP addresses each AS is composed of was determined through an IP lookup website [6].

2.4 Experiment destinations

For our experiments to be as broadly applicable as possible the websites we want to reach should be commonly visited ones. Alexa [2] was our source of choice to get a list to choose from. Out of the top 50 sites[1] we picked a selection. As explained in section 2.5 we chose ten

[1] as of October 2018

AS	location	number of IP addresses
378	IUCC - Israel InterUniversity Computation Center	1,164,800
20880	Tele Columbus (Germany)	132,096
24398	Auckland University of Technology (New Zealand)	65,792
24560	Bharti Airtel Ltd., Telemedia Services (India)	2,514,432
35807	SkyNet Ltd (Russia)	278,016
43996	Booking.com BV (Netherlands)	6,656

Table 2.1: all ASes that were used for experiments

destinations at the start but increased this number to twenty for the last two 24 hour runs. Our selection was chosen randomly. See table 2.2 for all of them. The upper half were used for the first 24 hour experiment. The whole of them are the destinations for the last two experiments. The IP addresses were determined using the `dig` command. The URLs of the sites used were saved in a file called *ALEXA_OCT_2018.txt* where every line is one website address. The IPs were saved in a separate files called *ALEXA_OCT_2018_IP.txt*. To link the IP to the URL they have to be on the same line in both files.

websites	IP used
google.ru	216.58.210.3
linkedin.com	108.174.10.10
wikipedia.org	91.198.174.192
twitch.tv	151.101.66.167
youtube.com	216.58.210.14
google.com.hk	216.58.214.99
pages.tmall.com	80.231.126.253
jd.com	120.52.148.118
baidu.com	123.125.115.110
taobao.com	140.205.220.96
netflix.com	54.77.108.2
microsoft.com	191.239.213.197
t.co	199.16.156.11
yandex.ru	5.255.255.55
facebook.com	157.240.20.35
360.cn	36.110.213.49
amazon.com	176.32.98.166
csdn.net	47.95.164.112
aliexpress.com	198.11.132.250
twitter.com	104.244.42.1

Table 2.2: the websites that were used for the traceroutes

2.5 Experimentation timeline

The first two long experiment runs were for ASes 24398 and 43996. Eager to start and not thinking of the final analysis they were started with randomized websites. Every measurement block (see 3.1.4) used a newly pulled website from the top 50 Alexa websites (see 2.4). This was quickly realized and corrected for the next two experiments (AS 20880 and 35807) and always the same ten destination were used. Shortly after we decided to increase the amount of destinations to twenty. This would give us the most data while still being inside the limits set by RIPE Atlas. After the first 24 hour run with all four AS and twenty destinations it was decided to add more sources to get even more data. Two more ASes were added (378 and 24560). All the experiments up to now were repeated for these new ones. To get more comparison possibilities the 24 hour runs with twenty targets were repeated for all ASes. To have all the AS on the same level for all experiments we repeated the one with ten destinations for AS 24398 and AS 43996 to not rely on measurements made with random websites as destinations. In total we have one batch with ten destinations for every AS and two batches with twenty destinations for every AS. The exact date on which we ran the experiments are shown in table 2.3.

Run	378	20880	24398	24560	35807	43996
10	28.11.2018	31.10.2018	03.01.2019	08.12.2018	31.10.2018	03.01.2018
20-1	05.12.2018	07.12.2018	30.11.2018	27.11.2018	09.12.2018	01.12.2018
20-2	18.12.2018	19.12.2018	20.12.2018	21.12.2018	22.12.2018	23.12.2018

Table 2.3: dates for all experiments

Chapter 3

Implementation / Design

3.1 Scripts

There were 6 scripts written or modified for this project:

1. pref.sh
2. as_sort.py
3. probes.py
4. ripe_helpers.py
5. pull_experiment_data.py
6. make_analysis.py

Each of those has a part to play in the pipeline used for running experiments and will be further explained in the following subsections. The scripts pref.sh, probes.py, ripe_helpers.py and pull_experiment_data.py were originally written by Maria Apostolaki [1]. During this project they were then for the most parts modified to suit our needs.

3.1.1 pref.sh

Here we have a little program that pulls the `RIS Raw Data` [9] from a server [8]. The data we used was from September 2018[1]. Using `bgpdump` it creates one text-file with all IP prefix ranges mapped to the corresponding AS. We called this file *pref01.txt*.

3.1.2 as_sort.py

This rather short script was mainly used at the beginning. It takes the */serial-2/20180901.as-rel2.txt.bz2* file and goes through it searching for stub-ASes. It uses the layout that is given by listing 2.1 and puts all provider-ASes in one set and all customer-ASes in the other, then subtracts the provider-AS set from the other. The remaining are the ASes that don't provide and only receive, the stub-ASes.

3.1.3 probes.py

After receiving the list of ASes that should be searched for, it uses the RIPE Atlas API and pulls all probe-IDs for each corresponding AS. Specifically it also checks if there are five or more probes in an AS. If this is not the case it gets skipped. This decision was made to ensure that there are enough paths to compare.

[1] `2018.09` directory on the server

3.1.4 ripe_helpers.py

Employing the RIPE Atlas API we schedule experiments here. This script includes functions for traceroutes and for pings. We are only interested in the former. To use this feature of RIPE Atlas an API key is needed, which has to be generated by a user with an account.
The program goes through all six ASes, making measurements for 24 hours for each. Because the amount of simultaneous experiments is limited to 100 we have to schedule everything accordingly. Every traceroute has to run for ten minutes. We added a buffer of five minutes in the case something is not working as intended. In those fifteen minutes we want to run what we call a **measurement block** for every destination. The idea is that the traceroutes to a website from all probes should be simultaneous for the sake of comparison. To circumvent parallelism in this script we give every experiment in a measurement block the same start time [2]. For every AS the script generates a .txt file into which it puts the four-tuple

- measurement ID
- probe ID
- destination URL
- destination IP

for every traceroute done. The file is named *as_number_XYZ.txt*, where XYZ is the AS-number itself.

preliminary experiments For all the stub-ASes we found with probes.py we ran preparatory measurements to see how many different next hops they had. Ideally every probe would have a unique path leading to the destination. In reality this is usually not the case. All ASes that we found have at least two probes that share their first next hop. In the end we picked six ASes that were multi-homed. The reasons not more were picked were mostly the time constraints for this semester project and the amount of RIPE Atlas credits a single 24 hour experiment consumes. All of those ASes have five or more probes in them. For our 24 hour experiments we reduced the number of used probes in all of them to five or even less. This has two reasons. First, and most important, probes with duplicate first next hops were not needed as they send packets over the same path. Probes were only eliminated after carefully checking their next hops for all destinations. A probe was only removed from use in experiments if it had the same next hops for all destinations as a different probe. Secondly because we wanted to make measurements on twenty destinations and 100 experiments was the limit set by RIPE Atlas, in an ideal case we wouldn't have more than five probes to traceroute from. Of course the amount of twenty websites wasn't set in stone and could be lowered, but after all the duplicate elimination nearly all ASes were left with 5 or less probes. So it was a trade-off we accepted. See table 3.1 for an overview of all probes and the ones that were used in the end.

AS	all probe IDs - as of 13th Oct 2018
378	16933, **17832**, **17846**, 17847, 17855, 17856, **17875**, 17879, **17893**, **17895**
20880	**933**, **2443**, **11990**, **17540**, 29385, **30781**
24398	**11843**, **11947**, **12036**, **12171**, **12793**
24560	**23419**, **25164**, 25398, 32886, **33546**
35807	**3026**, **10221**, 11374, **20607**, 2515, **26658**, **28562**
43996	**6087**, **6088**, **6141**, **6144**, **6149**

Table 3.1: all probes per AS with those used for experiments fat

3.1.5 pull_experiment_data.py

This is the second half of the process of running experiments. After the 24 hour period is passed for an AS we run this script to pull the traceroute data from the RIPE Atlas web server and save it in our own format. We use the

[2] One minute added to the time when starting the for-loop which cycles through the probes

```
is_success, results = AtlasResultsRequest(**{"msm_id":msm_id}).create()
```

command to get the data as a JSON file. Because only a minimal part is needed for our analysis we are parsing it with the `read_traceroutes(msm_id)` function.

assumption To not be overwhelmed with different variations of the same path we take the assumption that the first next hop after the source AS in the traceroute path is unique for this route. Without it this project would get immensely more complicated. Nevertheless we tested this assumption for every source AS in numerous random paths and it was the case for all of them.

problem cases From the API we get the traceroute path with the IPs of the different hops. Because we want to know when the packets leavs our source AS we need to map the IP to the corresponding AS. This was done by using the *pref01.txt* file which contains all AS with their corresponding IP ranges. Using a *R-tree* finding the correct AS is done easily. Nonetheless there were several problem cases we had to handle during this process.

- If there is no experiment data on the server we don't receive anything when pulling with the API. The cause for this is that we tried to run traceroutes from probes that are offline or not reachable, but aren't marked as such when getting the probe data from RIPE Atlas. This led to the generation of a measurement ID but no resolvable traceroute, even though the four-tuple was written in the *as_number_XYZ.txt* file. If this is the case we return two dummy values[3] for the RTT and the delay. After returning from the function these will be checked and the file write skipped if those values are present.
- For our analysis the last hop of the traceroute is the only important part. It gives us the time it took the UDP packet to reach the final destination and the answer to arrive at the probe. But not all hosts will respond. For several reasons a firewall can block traceroute packets from entering and thus hindering us from getting the data we want. If the last hop is not resolved the measurement is unfortunately not useful for us and has to be dropped. Again the same dummy values as for the faulty measurements are filled in for the RTT and the delay and are checked after leaving the function.
- The traceroute AS-path doesn't always start with the source AS. Thus we decided that the first AS next hop will be the AS that follows the source AS in the path. In some cases the source AS does not appear at all. These also had to be discarded because we can not say where our source is situated.
- Following the last problem we discovered something during the last stage of this project. There is a possibilty for so-called **bogon IPs** [12] to appear in the path of a traceroute. Most of these are `martians` which are IPs used inside a network (i.e. loopback 127.0.0.1) but there also `unallocated` IPs which aren't yet assigned to an RIR by IANA [5]. This means for all these addresses we are not able to map them to an AS. What made this insidious is that when trying to map them to an AS the R-tree didn't throw an exception but just returned the entry on the bottom of the *perf01.txt* file: 0.0.0.0/0 14007. This led to this bug not being detected until nearly the end. Our solution for this was re-pulling all the data from the RIPE Atlas server and skipping all non-mappable IPs. Thus the paths we received don't contain any bogon IPs. For example if the path beforehand was `[378]-[172-17-200-105]-[16509]` it would turn into `[378]-[16509]`

After passing through the parser, the data is split in three different files: *experiment_data_xxx-xxx-xxx-xxx.txt*, *all_hops_XYZ.txt* and *next_hop_XYZ.txt*.

experiment_data Contains the five-tuple

- AS of the first hop after the source
- RTT of the first packet to the destination

[3] A value that is so big that traceroute would time out before reaching it

– epoch starting time stamp of the experiment [seconds]

– mean of all three RTT to the destination

– ID of the probe that was used

for every measurement that was available to be pulled and not rejected because of a missing first or last hop. The file is generated for every destination. The xxx-xxx-xxx-xxx is a placeholder for the IP address.

all_hops Here we save all the traceroute AS-paths. After every data pull via the API it is updated. XYZ again stands for the AS-number.

next_hops This file is generated at the end of the pull process for an AS. For each destination we take down all different next hops we found leading to it.

3.1.6 make_analysis.py

All analysis steps are executed in this program. For every AS we go through all of its *experiment_data* files (ten and twenty destinations). Some of the different evaluations are using only data from one destination, some all data of an AS.

best next hop change over time We define the best next hop as the one with the lowest RTT. For one AS we go through each destination and take the best one for every measurement block (the fifteen minutes when all probes are sending a traceroute at the same time). Then we check if the best next hop changes over time. For every change we increase a counter. At the end the program prints a number for each destination showing how many times the best next hop has changed.

best next hop for all destinations Extending from the last analysis we make a small statistic where we show how much a certain next hop and probe was the quickest path to a destination. This is across all destinations for an AS. For each next hop and probe a percentage is printed which shows the amount this path was the fastest over the whole experiment.

RTT change per source and destination For each destination we take all RTT of a probe in an AS and take the standard deviation[4]. This gives us a value for each probe for each destination. After sorting them from lowest to highest they are plotted as a cumulative distribution function (CDF). See Figure 4.7 for an example.

stableness of probes This evaluation consists of two steps. First we check if the probe ever changes its next hop. Secondly we make a CDF for every probe seperately using the standard deviations we got for every destination. In the end we write in the title if the next hop changed or not.

number of different next hops per source and destination Using all the data from an AS we make a dictionary where every destination has a list with counters showing how many different next hops it had for every measurement block. We just want to see if it changes over time so we go through each list and check that.

[4] using numpy.std()

standard deviation and mean for every next hop to a destination To be able to compare the different next hops (and thus different paths to a destination) we need a metric to do that. For every destination we take all RTTs of a next hop and take the standard deviation and the mean[5] of those values. Again we put this into a dictionary leading to the keys being all the destination websites. Every one of those has its own dictionary with the next hops as entries. Each next hop then has a list with the standard deviation, the mean and the amount of times this next hop was used for this destination. See listing 3.1 for a visualization.

Listing 3.1: Visualization of the next hop RTT dictionary

```
next_hop_rtt_dict
|       baidu.com
|       |       14007
|       |       |       1.858  (standard deviation [ms])
|       |       |       0.859  (mean [ms])
|       |       |       143 (amount of times this next hop was used here)
|       |       21320
|       |       4808
|       google.com.hk
|       jd.com
|       etc.
```

[5] using numpy.mean()

Chapter 4

Results

4.1 Analysis 1 - best next hop changes per source and destination

In table 4.1 we have a detailed view on the amount of different best next hop over each 24 hour period. Every time the best next hop changed the counter is increased.

4.2 Analysis 2 - probes and next hop distribution with the best RTT

For each AS we have a double plot here. On the top the distribution for all probes and on the bottom the same but for all next hops. See figures 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6

4.3 Analysis 3 - standard deviation CDFs for every AS

The plots 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12 are CDFs for all standard deviations of a AS. The standard deviations were made for all RTTs from one probe going to one destination. The plots include the standard deviations from all three experiment runs.

4.4 Analysis 4 - stability and standard deviation CDFs for every probe

For every probe we checked if its next hop changes for any destination. The plots 4.13, 4.14, 4.15, 4.16, 4.17 and 4.18 show for each probe a CDF containing all standard deviations (one per destination). There is one plot per experimentation run.

4.5 Analysis 5 - number of next hops per source and destination

The tables 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 give answer to the question whether the number of concurrent next hops towards a destination changed over time. Included in the each cell is the number of websites for which the answer is valid and which ones it includes.

4.6 Analysis 6 - different next hops comparison for every source and destination

In tables 4.8, 4.9, 4.10, 4.11, 4.12 and 4.13 we have for every AS all destinations that were used in all experiments with detailed information to each next hop. This includes the AS number, the standard deviation and mean of all RTTs and the amount this next hop was used.

	378			20880			24398			24650			35807			43996		
	10	20-1	20-2	10	20-1	20-2	10	20-1	20-2	10	20-1	20-2	10	20-1	20-2	10	20-1	20-2
google.ru	41	26	5	1	1	1	7	11	9	14	29	1	38	8	35	11	36	14
linkedin.com	47	41	5	1	1	1	9	15	9	2	1	10	3	4	3	1	7	1
wikipedia.org	37	39	13	1	1	1	7	10	9	1	1	1	11	2	8	17	20	13
twitch.tv	31	9	3	1	5	1	7	11	11	1	5	1	1	2	3	8	50	14
youtube.com	40	37	18	3	1	1	13	17	21	28	21	9	40	1	39	10	44	12
google.com.hk	34	31	20	7	3	5	9	23	19	26	2	27	42	1	17	10	44	13
pages.tmall.com	15	13	6	1	7	5	3	9	17	14	1	9	7	1	1	49	42	51
jd.com	41	30	33	9	36	9	9	14	15	5	3	7	16	2	2	48	39	48
baidu.com	13	13	6	3	5	3	3	11	17	13	3	9	1	2	3	49	28	42
taobao.com	41	2	3	1	5	5	3	22	13	6	17	10	9	3	3	43	41	42
netflix.com		41	33		3	9		23	11		3	3		3	8		29	52
microsoft.com		9	11		1	2		1	1		0	0		0	0		0	0
t.co		37	31		33	10		27	13		1	1		9	16		1	0
yandex.ru		44	29		33	11		31	13		5	7		21	33		47	32
facebook.com		7	3		2	4		1	1		1	1		0	0		0	0
360.cn		33	20		1	3		24	25		13	17		11	18		59	58
amazon.com		20	17		3	3		31	27		13	5		23	31		59	57
csdn.net		16	16		7	1		31	31		10	15		9	12		64	56
aliexpress.com		25	21		54	46		28	20		1	1		9	9		65	60
twitter.com		15	15		40	13		27	31		1	1		5	19		13	52

Table 4.1: Amount of best next hop changes per AS/experiment run (10 dest, first 20 dest or second 20 dest) and destination

AS 378	10	20-1	20-2
Yes	3/10 google.com.hk, pages.tmall.com, taobao.com	11/20 twitch.tv, yandex.ru, amazon.com, taobao.com, microsoft.com, t.co, facebook.com, youtube.com, netflix.com, aliexpress.com, linkedin.com	13/20 yandex.ru, baidu.com, amazon.com, taobao.com, microsoft.com, twitter.com, t.co, facebook.com, youtube.com, jd.com, netflix.com, aliexpress.com, csdn.net
No	7/10 twitch.tv, wikipedia.org, youtube.com, google.ru, baidu.com, jd.com, linkedin.com	9/20 google.com.hk, 360.cn, wikipedia.org, baidu.com, pages.tmall.com, google.ru, twitter.com, jd.com, csdn.net	7/20 google.com.hk, 360.cn, twitch.tv, wikipedia.org, pages.tmall.com, google.ru, linkedin.com

Table 4.2: For AS 378 did the number of different next hops for a destination change over time?

AS 20880	10	20-1	20-2
Yes	6/10 google.com.hk, youtube.com, pages.tmall.com, baidu.com, jd.com, linkedin.com	15/20 google.com.hk, 360.cn, twitch.tv, yandex.ru, baidu.com, pages.tmall.com, amazon.com, taobao.com, twitter.com, t.co, youtube.com, jd.com, netflix.com, aliexpress.com, csdn.net	16/20 google.com.hk, 360.cn, twitch.tv, yandex.ru, baidu.com, pages.tmall.com, amazon.com, taobao.com, twitter.com, t.co, youtube.com, jd.com, netflix.com, aliexpress.com, csdn.net, linkedin.com
No	4/10 twitch.tv, wikipedia.org, taobao.com, google.ru	5/20 wikipedia.org, google.ru, microsoft.com, facebook.com, linkedin.com	4/20 wikipedia.org, google.ru, microsoft.com, facebook.com

Table 4.3: For AS 20880 did the number of different next hops for a destination change over time?

AS 24398	10	20-1	20-2
Yes	4/10 google.com.hk, twitch.tv, wikipedia.org, pages.tmall.com	4/20 baidu.com, pages.tmall.com, taobao.com, youtube.com	7/20 google.com.hk, pages.tmall.com, amazon.com, taobao.com, google.ru, microsoft.com, jd.com
No	6/10 youtube.com, taobao.com, google.ru, baidu.com, jd.com, linkedin.com	16/20 google.com.hk, 360.cn, twitch.tv, yandex.ru, wikipedia.org, amazon.com, google.ru, microsoft.com, twitter.com, t.co, facebook.com, jd.com, netflix.com, aliexpress.com, csdn.net, linkedin.com	13/20 360.cn, twitch.tv, yandex.ru, wikipedia.org, baidu.com, twitter.com, t.co, facebook.com, youtube.com, netflix.com, aliexpress.com, csdn.net, linkedin.com

Table 4.4: For AS 24398 did the number of different next hops for a destination change over time?

AS 24560	10	20-1	20-2
Yes	9/10 google.com.hk, twitch.tv, wikipedia.org, youtube.com, pages.tmall.com, taobao.com, baidu.com, jd.com, linkedin.com	12/20 360.cn, twitch.tv, yandex.ru, baidu.com, pages.tmall.com, amazon.com, taobao.com, microsoft.com, jd.com, netflix.com, csdn.net, linkedin.com	16/19 google.com.hk, 360.cn, twitch.tv, yandex.ru, wikipedia.org, baidu.com, pages.tmall.com, amazon.com, taobao.com, google.ru, youtube.com, t.co, jd.com, netflix.com, csdn.net, linkedin.com
No	1/10 google.ru	8/20 google.com.hk, wikipedia.org, google.ru, twitter.com, t.co, facebook.com, youtube.com, aliexpress.com	3/19 twitter.com, facebook.com, aliexpress.com

Table 4.5: For AS 24560 did the number of different next hops for a destination change over time?

AS 35807	10	20-1	20-2
Yes	4/10 google.com.hk, wikipedia.org, youtube.com, jd.com	3/19 microsoft.com, jd.com, linkedin.com	3/18 yandex.ru, jd.com, netflix.com
No	6/10 twitch.tv, pages.tmall.com, taobao.com, google.ru, baidu.com, linkedin.com	16/19 google.com.hk, 360.cn, twitch.tv, yandex.ru, wikipedia.org, baidu.com, pages.tmall.com, aliexpress.com, taobao.com, google.ru, twitter.com, t.co, amazon.com, netflix.com, youtube.com, csdn.net	15/18 google.com.hk, 360.cn, twitch.tv, wikipedia.org, baidu.com, pages.tmall.com, aliexpress.com, taobao.com, google.ru, youtube.com, twitter.com, t.co, amazon.com, csdn.net, linkedin.com

Table 4.6: For AS 35807 did the number of different next hops for a destination change over time?

AS 43996	10	20-1	20-2
Yes	1/10 taobao.com	2/18 amazon.com, csdn.net	5/18 baidu.com, twitter.com, t.co, amazon.com, csdn.net
No	9/10 google.com.hk, twitch.tv, wikipedia.org, youtube.com, pages.tmall.com, google.ru, baidu.com, jd.com, linkedin.com	16/18 google.com.hk, 360.cn, twitch.tv, yandex.ru, wikipedia.org, baidu.com, pages.tmall.com, aliexpress.com, taobao.com, google.ru, youtube.com, twitter.com, t.co, jd.com, netflix.com, linkedin.com	13/18 google.com.hk, 360.cn, twitch.tv, yandex.ru, wikipedia.org, pages.tmall.com, aliexpress.com, taobao.com, google.ru, youtube.com, jd.com, netflix.com, linkedin.com

Table 4.7: For AS 43996 did the number of different next hops for a destination change over time?

AS 378	10				20-1				20-2			
	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4
google.ru	AS 15169 std: 0.244 mean: 0.831 how much: 174	AS 21320 std: 5.119 mean: 68.741 how much: 264			AS 15169 std: 0.245 mean: 0.874 how much: 170	AS 21320 std: 10.865 mean: 64.933 how much: 85			AS 15169 std: 0.254 mean: 0.876 how much: 172	AS 21320 std: 2.238 mean: 63.669 how much: 86		
linkedin.com	AS 14413 std: 5.311 mean: 1.248 how much: 173	AS 21320 std: 29.401 mean: 163.632 how much: 265			AS 14413 std: 0.259 mean: 0.882 how much: 169	AS 21320 std: 7.716 mean: 157.162 how much: 85			AS 14413 std: 0.259 mean: 0.884 how much: 172	AS 21320 std: 2.779 mean: 154.811 how much: 86		
wikipedia.org	AS 21320 std: 4.253 mean: 64.940 how much: 266	AS 14907 std: 0.281 mean: 0.854 how much: 172			AS 21320 std: 0.728 mean: 63.291 how much: 87	AS 14907 std: 0.246 mean: 0.900 how much: 170			AS 21320 std: 50.478 mean: 71.134 how much: 87	AS 14907 std: 0.311 mean: 0.956 how much: 168		
twitch.tv	AS 21320 std: 2.648 mean: 59.098 how much: 269	AS 54113 std: 0.212 mean: 0.856 how much: 161			AS 21320 std: 0.511 mean: 63.034 how much: 86	AS 54113 std: 0.271 mean: 0.942 how much: 159			AS 21320 std: 35.815 mean: 66.536 how much: 91	AS 54113 std: 0.286 mean: 0.983 how much: 160		
youtube.com	AS 15169 std: 2.850 mean: 1.075 how much: 160	AS 21320 std: 7.597 mean: 69.092 how much: 263			AS 15169 std: 0.270 mean: 0.956 how much: 155	AS 21320 std: 2.199 mean: 63.986 how much: 87			AS 15169 std: 3.406 mean: 1.264 how much: 156	AS 21320 std: 10.906 mean: 65.937 how much: 87		
google.com.hk	AS 15169 std: 0.197 mean: 0.850 how much: 165	AS 21320 std: 10.107 mean: 67.982 how much: 194			AS 15169 std: 1.069 mean: 1.025 how much: 152	AS 21320 std: 0.224 mean: 65.013 how much: 85			AS 15169 std: 0.236 mean: 1.005 how much: 154	AS 21320 std: 10.702 mean: 66.123 how much: 86		
pages.tmall.com	AS 6453 std: 0.225 mean: 0.841 how much: 169	AS 21320 std: 8.744 mean: 103.107 how much: 264			AS 6453 std: 0.244 mean: 0.914 how much: 144	AS 21320 std: 4.255 mean: 89.547 how much: 88			AS 6453 std: 0.229 mean: 0.958 how much: 150	AS 21320 std: 2.774 mean: 90.074 how much: 88		
jd.com	AS 133119 std: 0.207 mean: 0.792 how much: 171	AS 21320 std: 78.517 mean: 411.218 how much: 258			AS 133119 std: 0.263 mean: 0.836 how much: 147	AS 21320 std: 79.154 mean: 379.390 how much: 89			AS 133119 std: 0.285 mean: 0.850 how much: 138	AS 21320 std: 129.018 mean: 408.940 how much: 83		
baidu.com	AS 4808 std: 1.402 mean: 0.984 how much: 173	AS 21320 std: 71.580 mean: 365.059 how much: 185			AS 4808 std: 0.498 mean: 0.941 how much: 140	AS 21320 std: 74.540 mean: 345.733 how much: 92			AS 4808 std: 0.248 mean: 0.937 how much: 144	AS 21320 std: 91.559 mean: 344.034 how much: 94		
taobao.com	AS 37963 std: 0.194 mean: 0.815 how much: 171	AS 21320 std: 47.385 mean: 346.424 how much: 92			AS 37963 std: 0.229 mean: 0.847 how much: 130	AS 21320 std: 0.262 mean: 72.351 how much: 4			AS 37963 std: 0.230 mean: 0.883 how much: 143	AS 21320 std: 46.799 mean: 93.271 how much: 6		
netflix.com					AS 7713 std: 0.142 mean: 58.466 how much: 3	AS 20965 std: 37.206 mean: 77.028 how much: 86	AS 16509 std: 0.465 mean: 0.890 how much: 141		AS 7713 std: 0.177 mean: 58.467 how much: 4	AS 20965 std: 1.099 mean: 72.687 how much: 86	AS 16509 std: 0.270 mean: 0.884 how much: 148	
microsoft.com					AS 7713 std: 0.263 mean: 58.763 how much: 3	AS 8075 std: 0.322 mean: 0.885 how much: 151	AS 21320 std: 0.300 mean: 75.554 how much: 2		AS 7713 std: 0.203 mean: 58.431 how much: 4	AS 8075 std: 0.364 mean: 0.928 how much: 161		
t.co					AS 7713 std: 0.301 mean: 58.502 how much: 2	AS 21320 std: 15.653 mean: 162.290 how much: 87	AS 13414 std: 3.840 mean: 1.221 how much: 159		AS 21320 std: 59.566 mean: 168.320 how much: 90	AS 13414 std: 5.679 mean: 1.519 how much: 161		
yandex.ru					AS 13238 std: 0.278 mean: 0.911 how much: 162	AS 21320 std: 5.825 mean: 87.851 how much: 90			AS 13238 std: 0.834 mean: 0.956 how much: 165	AS 21320 std: 7.235 mean: 91.499 how much: 90		
facebook.com					AS 32934 std: 0.247 mean: 0.931 how much: 169	AS 21320 std: 0.566 mean: 74.412 how much: 2			AS 32934 std: 0.656 mean: 0.961 how much: 169	AS 21320 std: 8.095 mean: 66.729 how much: 2		
360.cn					AS 21320 std: 45.721 mean: 270.758 how much: 88	AS 23724 std: 0.242 mean: 0.923 how much: 165			AS 21320 std: 65.939 mean: 286.902 how much: 88	AS 23724 std: 0.276 mean: 0.916 how much: 167		
amazon.com					AS 21320 std: 17.882 mean: 151.961 how much: 88	AS 16509 std: 0.288 mean: 0.872 how much: 165			AS 21320 std: 20.024 mean: 150.937 how much: 91	AS 16509 std: 0.268 mean: 0.875 how much: 169		
csdn.net					AS 37963 std: 0.260 mean: 0.870 how much: 167	AS 21320 std: 70.513 mean: 249.422 how much: 92			AS 37963 std: 0.576 mean: 0.915 how much: 169	AS 21320 std: 90.595 mean: 249.863 how much: 96		
aliexpress.com					AS 21320 std: 59.573 mean: 193.068 how much: 16	AS 45102 std: 1.346 mean: 1.001 how much: 169			AS 21320 std: 51.696 mean: 187.513 how much: 12	AS 45102 std: 0.238 mean: 0.909 how much: 170		
twitter.com					AS 21320 std: 54.922 mean: 69.237 how much: 87	AS 13414 std: 0.218 mean: 0.848 how much: 168			AS 21320 std: 0.068 mean: 63.081 how much: 85	AS 13414 std: 0.255 mean: 0.877 how much: 172		

Table 4.8: mean and standard deviation for all RTTs of all next hops in AS 378 (standard deviation and mean in milliseconds)

AS 20880	10				20-1				20-2			
	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4
google.ru	AS 15169 std: 14.030 mean: 33.632 how much: 286				AS 15169 std: 31.060 mean: 36.549 how much: 214				AS 15169 std: 33.376 mean: 38.360 how much: 213			
linkedin.com	AS 14413 std: 1.356 mean: 109.419 how much: 2	AS 3356 std: 9.441 mean: 109.253 how much: 289			AS 3356 std: 138.167 mean: 124.476 how much: 217				AS 3356 std: 42.970 mean: 116.135 how much: 224			
wikipedia.org	AS 3209 std: 15.541 mean: 33.327 how much: 286				AS 3209 std: 116.839 mean: 41.927 how much: 223				AS 3209 std: 26.302 mean: 37.162 how much: 217			
twitch.tv	AS 3356 std: 18.043 mean: 28.464 how much: 293				AS 3356 std: 20.024 mean: 29.912 how much: 174	AS 3209 std: 13.419 mean: 27.730 how much: 35			AS 3356 std: 23.404 mean: 34.574 how much: 176	AS 3209 std: 37.442 mean: 35.920 how much: 43		
youtube.com	AS 15169 std: 17.462 mean: 34.440 how much: 290				AS 15169 std: 157.901 mean: 44.319 how much: 222				AS 15169 std: 17.717 mean: 35.995 how much: 221			
google.com.hk	AS 15169 std: 16.028 mean: 35.080 how much: 231	AS 3356 std: 58.551 mean: 70.900 how much: 4			AS 15169 std: 21.895 mean: 31.568 how much: 215	AS 3209 std: 17.759 mean: 42.500 how much: 2			AS 15169 std: 17.149 mean: 29.607 how much: 225	AS 3356 std: 1.983 mean: 33.189 how much: 3	AS 6939 std: 25.356 mean: 47.579 how much: 3	
pages.tmall.com	AS 3356 std: 19.576 mean: 52.324 how much: 235				AS 3356 std: 23.116 mean: 54.963 how much: 224	AS 6939 std: 1.416 mean: 40.230 how much: 2			AS 3356 std: 17.960 mean: 53.103 how much: 226	AS 6939 std: 1.955 mean: 38.646 how much: 2		
jd.com	AS 3356 std: 227.959 mean: 253.424 how much: 2	AS 25291 std: 92.133 mean: 409.574 how much: 98	AS 3209 std: 50.258 mean: 344.562 how much: 127	AS 6939 std: 51.406 mean: 468.334 how much: 12	AS 3356 std: 135.797 mean: 226.341 how much: 7	AS 25291 std: 113.464 mean: 377.549 how much: 41	AS 3209 std: 123.548 mean: 338.631 how much: 171	AS 6939 std: 3.214 mean: 375.460 how much: 8	AS 6939 std: 164.545 mean: 459.595 how much: 8	AS 25291 std: 121.205 mean: 377.338 how much: 46	AS 3209 std: 86.928 mean: 341.649 how much: 174	AS 3356 std: 136.537 mean: 274.777 how much: 6
baidu.com	AS 3356 std: 97.295 mean: 372.671 how much: 236	AS 6939 std: 4.411 mean: 345.548 how much: 2			AS 3356 std: 121.953 mean: 406.400 how much: 225	AS 6939 std: 75.197 mean: 502.907 how much: 2			AS 3356 std: 85.689 mean: 410.173 how much: 223	AS 6939 std: 32.099 mean: 409.864 how much: 2		
taobao.com	AS 3356 std: 97.576 mean: 294.860 how much: 173				AS 3356 std: 40.918 mean: 281.101 how much: 135				AS 3356 std: 67.396 mean: 286.042 how much: 136			
netflix.com					AS 16509 std: 21.424 mean: 47.021 how much: 50				AS 3356 std: 0.003 mean: 24.973 how much: 2	AS 16509 std: 27.554 mean: 47.910 how much: 53		
microsoft.com					AS 25291 std: 8.254 mean: 23.968 how much: 3	AS 8075 std: 31.300 mean: 71.303 how much: 2			AS 30132 std: 7.598 mean: 18.324 how much: 2	AS 8075 std: 7.032 mean: 24.009 how much: 3		
t.co					AS 3356 std: 78.394 mean: 127.503 how much: 172	AS 25291 std: 1.995 mean: 31.793 how much: 5	AS 3209 std: 118.451 mean: 156.420 how much: 47		AS 3356 std: 30.422 mean: 117.120 how much: 175	AS 25291 std: 1.175 mean: 30.998 how much: 4	AS 3209 std: 134.427 mean: 174.608 how much: 45	
yandex.ru					AS 3356 std: 18.794 mean: 34.374 how much: 168	AS 25291 std: 33.682 mean: 54.566 how much: 53			AS 3356 std: 8.401 mean: 31.741 how much: 176	AS 25291 std: 55.136 mean: 55.596 how much: 49		
facebook.com					AS 25291 std: 0.544 mean: 12.233 how much: 2	AS 3209 std: 509.222 mean: 317.582 how much: 4			AS 25291 std: 2.119 mean: 31.599 how much: 3	AS 3209 std: 4.895 mean: 21.006 how much: 5		
360.cn					AS 3356 std: 85.598 mean: 227.916 how much: 212				AS 3356 std: 89.210 mean: 245.306 how much: 218	AS 25291 std: 42.245 mean: 72.062 how much: 2		
amazon.com					AS 3356 std: 37.594 mean: 126.081 how much: 220				AS 10886 std: 0.350 mean: 11.995 how much: 4	AS 174 std: 0.297 mean: 28.268 how much: 2	AS 3356 std: 23.635 mean: 127.033 how much: 221	
csdn.net					AS 10886 std: 1.945 mean: 12.113 how much: 5	AS 3356 std: 145.110 mean: 376.930 how much: 211	AS 25291 std: 9.927 mean: 21.090 how much: 2		AS 10886 std: 2.241 mean: 12.266 how much: 3	AS 3356 std: 98.727 mean: 365.227 how much: 210		
aliexpress.com					AS 10886 std: 1.422 mean: 12.379 how much: 5	AS 3356 std: 17.228 mean: 163.634 how much: 112	AS 25291 std: 39.525 mean: 179.482 how much: 53		AS 10886 std: 0.962 mean: 11.821 how much: 6	AS 3356 std: 8.167 mean: 158.727 how much: 109	AS 25291 std: 48.634 mean: 187.213 how much: 41	
twitter.com					AS 3356 std: 91.895 mean: 34.503 how much: 172	AS 3209 std: 67.543 mean: 45.353 how much: 53			AS 3356 std: 6.534 mean: 21.734 how much: 175	AS 3209 std: 47.078 mean: 46.958 how much: 43		

Table 4.9: mean and standard deviation for all RTTs of all next hops in AS 20880 (standard deviation and mean in milliseconds)

AS 24398	10				20-1				20-2			
	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4
google.ru	AS 15169 std: 0.251 mean: 0.876 how much: 314	AS 38022 std: 26.924 mean: 203.416 how much: 210			AS 15169 std: 0.174 mean: 0.871 how much: 261	AS 38022 std: 7.624 mean: 202.139 how much: 176			AS 15169 std: 0.168 mean: 0.867 how much: 256	AS 38022 std: 7.598 mean: 201.713 how much: 174		
linkedin.com	AS 14413 std: 0.195 mean: 0.887 how much: 311	AS 38022 std: 10.104 mean: 161.897 how much: 210			AS 14413 std: 0.177 mean: 0.894 how much: 254	AS 38022 std: 2.070 mean: 152.481 how much: 176			AS 14413 std: 0.180 mean: 0.880 how much: 252	AS 38022 std: 2.386 mean: 154.329 how much: 174		
wikipedia.org	AS 14907 std: 0.202 mean: 0.900 how much: 304	AS 38022 std: 57.347 mean: 277.787 how much: 210			AS 14907 std: 0.184 mean: 0.891 how much: 245	AS 38022 std: 78.788 mean: 289.183 how much: 176			AS 14907 std: 0.215 mean: 0.881 how much: 240	AS 38022 std: 98.081 mean: 285.798 how much: 174		
twitch.tv	AS 54113 std: 0.246 mean: 0.898 how much: 301	AS 38022 std: 0.420 mean: 1.903 how much: 210			AS 54113 std: 0.265 mean: 0.914 how much: 219	AS 38022 std: 0.351 mean: 1.884 how much: 176			AS 54113 std: 0.188 mean: 0.892 how much: 233	AS 38022 std: 0.370 mean: 1.890 how much: 174		
youtube.com	AS 15169 std: 0.215 mean: 0.898 how much: 303	AS 38022 std: 23.274 mean: 203.267 how much: 210			AS 15169 std: 0.168 mean: 0.901 how much: 231	AS 38022 std: 44.871 mean: 205.050 how much: 176			AS 15169 std: 0.224 mean: 0.900 how much: 223	AS 38022 std: 76.682 mean: 211.282 how much: 174		
google.com.hk	AS 15169 std: 0.189 mean: 0.825 how much: 303	AS 38022 std: 37.929 mean: 204.083 how much: 210			AS 15169 std: 0.189 mean: 0.851 how much: 214	AS 38022 std: 71.660 mean: 235.552 how much: 176			AS 15169 std: 0.321 mean: 0.864 how much: 232	AS 38022 std: 7.927 mean: 200.007 how much: 172		
pages.tmall.com	AS 6453 std: 0.151 mean: 0.874 how much: 305	AS 38022 std: 49.422 mean: 277.765 how much: 210			AS 6453 std: 0.183 mean: 0.901 how much: 221	AS 38022 std: 59.458 mean: 286.987 how much: 176			AS 6453 std: 0.183 mean: 0.881 how much: 206	AS 38022 std: 48.990 mean: 272.791 how much: 174		
jd.com	AS 133119 std: 0.190 mean: 0.830 how much: 310	AS 38022 std: 28.254 mean: 278.701 how much: 210			AS 133119 std: 0.174 mean: 0.857 how much: 221	AS 38022 std: 82.069 mean: 307.289 how much: 176			AS 133119 std: 0.300 mean: 0.854 how much: 223	AS 38022 std: 20.969 mean: 268.956 how much: 174		
baidu.com	AS 4808 std: 0.157 mean: 0.862 how much: 308	AS 38022 std: 12.430 mean: 256.226 how much: 210			AS 4808 std: 0.166 mean: 0.897 how much: 224	AS 38022 std: 35.671 mean: 272.601 how much: 176			AS 4808 std: 0.158 mean: 0.876 how much: 229	AS 38022 std: 37.326 mean: 259.448 how much: 174		
taobao.com	AS 37963 std: 0.155 mean: 0.858 how much: 311	AS 38022 std: 21.416 mean: 182.410 how much: 210			AS 37963 std: 0.174 mean: 0.903 how much: 226	AS 38022 std: 73.615 mean: 263.725 how much: 176			AS 37963 std: 0.313 mean: 0.910 how much: 214	AS 38022 std: 68.829 mean: 191.054 how much: 174		
netflix.com					AS 16509 std: 0.563 mean: 0.889 how much: 223	AS 38022 std: 39.550 mean: 277.150 how much: 176			AS 16509 std: 0.187 mean: 0.842 how much: 225	AS 38022 std: 18.996 mean: 273.489 how much: 174		
microsoft.com					AS 8075 std: 0.323 mean: 0.870 how much: 226				AS 8075 std: 0.165 mean: 0.821 how much: 229			
t.co					AS 4826 std: 54.551 mean: 223.767 how much: 176	AS 13414 std: 0.204 mean: 0.868 how much: 232			AS 4826 std: 71.998 mean: 227.393 how much: 174	AS 13414 std: 0.187 mean: 0.844 how much: 226		
yandex.ru					AS 13238 std: 0.227 mean: 0.910 how much: 238	AS 38022 std: 102.064 mean: 314.609 how much: 176			AS 13238 std: 0.193 mean: 0.884 how much: 239	AS 38022 std: 93.688 mean: 314.018 how much: 174		
facebook.com					AS 32934 std: 0.180 mean: 0.848 how much: 231				AS 32934 std: 0.182 mean: 0.832 how much: 238			
360.cn					AS 38022 std: 66.395 mean: 281.120 how much: 174	AS 23724 std: 0.180 mean: 0.853 how much: 243			AS 38022 std: 41.937 mean: 188.575 how much: 174	AS 23724 std: 0.267 mean: 0.861 how much: 244		
amazon.com					AS 16509 std: 0.273 mean: 0.905 how much: 244	AS 38022 std: 28.094 mean: 188.169 how much: 176			AS 16509 std: 0.214 mean: 0.910 how much: 239	AS 38022 std: 1.862 mean: 184.558 how much: 174		
csdn.net					AS 37963 std: 0.162 mean: 0.886 how much: 242	AS 38022 std: 57.208 mean: 267.316 how much: 176			AS 37963 std: 0.178 mean: 0.877 how much: 243	AS 38022 std: 48.438 mean: 199.130 how much: 174		
aliexpress.com					AS 45102 std: 0.176 mean: 0.890 how much: 252	AS 38022 std: 27.729 mean: 137.624 how much: 176			AS 45102 std: 0.174 mean: 0.888 how much: 246	AS 38022 std: 27.167 mean: 141.928 how much: 174		
twitter.com					AS 4826 std: 0.918 mean: 25.923 how much: 176	AS 13414 std: 0.260 mean: 0.897 how much: 255			AS 4826 std: 0.842 mean: 26.128 how much: 174	AS 13414 std: 0.284 mean: 0.886 how much: 247		

Table 4.10: mean and standard deviation for all RTTs of all next hops in AS 24398 (standard deviation and mean in milliseconds)

AS 24560	10				20-1				20-2			
	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4
google.ru	AS 9498 std: 16.788 mean: 245.223 how much: 88	AS 15169 std: 5.900 mean: 255.169 how much: 88			AS 9498 std: 75.795 mean: 261.594 how much: 230	AS 15169 std: 68.764 mean: 270.149 how much: 136			AS 9498 std: 73.868 mean: 257.157 how much: 172	AS 15169 std: 28.808 mean: 262.324 how much: 84		
linkedin.com	AS 9498 std: 30.710 mean: 242.331 how much: 144	AS 7713 std: 10.105 mean: 274.576 how much: 25			AS 9498 std: 57.359 mean: 261.747 how much: 364				AS 9498 std: 53.287 mean: 257.526 how much: 206	AS 7713 std: 24.219 mean: 239.115 how much: 48		
wikipedia.org	AS 9498 std: 9.804 mean: 159.362 how much: 169	AS 13030 std: 0.758 mean: 168.391 how much: 7			AS 9498 std: 23.636 mean: 163.527 how much: 366				AS 9498 std: 10.509 mean: 162.150 how much: 249	AS 13030 std: 7.033 mean: 168.530 how much: 7		
twitch.tv	AS 9498 std: 10.980 mean: 151.758 how much: 156	AS 1200 std: 1.996 mean: 158.995 how much: 20			AS 9498 std: 40.856 mean: 144.644 how much: 310	AS 1200 std: 3.198 mean: 163.462 how much: 56			AS 9498 std: 37.917 mean: 149.810 how much: 233	AS 1200 std: 1.694 mean: 156.667 how much: 23		
youtube.com	AS 9498 std: 13.049 mean: 245.417 how much: 76	AS 15169 std: 8.240 mean: 257.735 how much: 100			AS 9498 std: 13.557 mean: 253.545 how much: 250	AS 15169 std: 13.768 mean: 261.370 how much: 116			AS 9498 std: 68.345 mean: 262.001 how much: 169	AS 15169 std: 19.568 mean: 260.560 how much: 87		
google.com.hk	AS 9498 std: 26.646 mean: 246.172 how much: 55	AS 15169 std: 7.963 mean: 251.446 how much: 120			AS 9498 std: 73.219 mean: 260.169 how much: 266	AS 15169 std: 27.841 mean: 264.323 how much: 100			AS 9498 std: 78.426 mean: 263.545 how much: 161	AS 15169 std: 117.445 mean: 273.814 how much: 93		
pages.tmall.com	AS 9498 std: 8.962 mean: 161.568 how much: 116	AS 6453 std: 2.954 mean: 172.891 how much: 60			AS 9498 std: 14.716 mean: 170.669 how much: 323	AS 6453 std: 7.317 mean: 179.804 how much: 42			AS 9498 std: 28.042 mean: 174.245 how much: 200	AS 6453 std: 9.948 mean: 168.654 how much: 56		
jd.com	AS 9498 std: 26.033 mean: 328.325 how much: 130	AS 6762 std: 16.653 mean: 348.939 how much: 46			AS 9498 std: 91.093 mean: 359.621 how much: 320	AS 6762 std: 47.676 mean: 360.634 how much: 46			AS 9498 std: 95.419 mean: 318.067 how much: 208	AS 6762 std: 13.652 mean: 344.725 how much: 45		
baidu.com	AS 9498 std: 24.510 mean: 278.249 how much: 98	AS 4637 std: 17.124 mean: 324.212 how much: 77			AS 9498 std: 32.740 mean: 331.779 how much: 307	AS 4637 std: 9.150 mean: 334.104 how much: 59			AS 9498 std: 39.392 mean: 321.423 how much: 181	AS 4637 std: 20.607 mean: 316.706 how much: 71		
taobao.com	AS 9498 std: 58.084 mean: 462.772 how much: 116	AS 174 std: 70.348 mean: 399.587 how much: 56			AS 9498 std: 87.827 mean: 448.783 how much: 277	AS 174 std: 78.700 mean: 445.866 how much: 80			AS 9498 std: 112.118 mean: 386.109 how much: 197	AS 174 std: 57.941 mean: 371.524 how much: 52		
netflix.com					AS 9498 std: 51.553 mean: 175.094 how much: 257	AS 16509 std: 7.593 mean: 180.413 how much: 43			AS 9498 std: 36.297 mean: 174.976 how much: 208	AS 16509 std: 8.266 mean: 170.386 how much: 11		
microsoft.com												
t.co					AS 9498 std: 28.722 mean: 282.152 how much: 333				AS 9498 std: 74.288 mean: 289.971 how much: 253			
yandex.ru					AS 9498 std: 68.705 mean: 199.130 how much: 262	AS 13238 std: 134.737 mean: 217.115 how much: 70			AS 9498 std: 126.740 mean: 201.490 how much: 192	AS 13238 std: 5.447 mean: 193.147 how much: 62		
facebook.com					AS 9498 std: 18.635 mean: 180.569 how much: 6							
360.cn					AS 9498 std: 203.887 mean: 492.248 how much: 263	AS 174 std: 165.072 mean: 470.892 how much: 62			AS 9498 std: 187.916 mean: 461.983 how much: 189	AS 174 std: 174.630 mean: 478.547 how much: 52		
amazon.com					AS 9498 std: 43.736 mean: 257.538 how much: 293	AS 3257 std: 5.414 mean: 243.275 how much: 40			AS 9498 std: 19.759 mean: 258.168 how much: 213	AS 3257 std: 3.839 mean: 285.668 how much: 40		
csdn.net					AS 9498 std: 174.782 mean: 504.671 how much: 247	AS 174 std: 155.652 mean: 507.379 how much: 66			AS 9498 std: 164.456 mean: 436.392 how much: 187	AS 174 std: 149.715 mean: 462.480 how much: 52		
aliexpress.com					AS 9498 std: 56.681 mean: 279.871 how much: 320				AS 9498 std: 30.219 mean: 272.345 how much: 203			
twitter.com					AS 9498 std: 95.281 mean: 190.427 how much: 333				AS 9498 std: 84.911 mean: 190.462 how much: 254			

Table 4.11: mean and standard deviation for all RTTs of all next hops in AS 24560 (standard deviation and mean in milliseconds)

AS 35807	10				20-1				20-2			
	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4
google.ru	AS 15169 std: 2.061 mean: 36.583 how much: 164	AS 48076 std: 4.126 mean: 37.356 how much: 246			AS 15169 std: 1.125 mean: 36.318 how much: 87	AS 48076 std: 19.639 mean: 42.302 how much: 174			AS 15169 std: 1.684 mean: 36.298 how much: 86	AS 48076 std: 2.009 mean: 36.924 how much: 172		
linkedin.com	AS 48076 std: 51.100 mean: 120.234 how much: 82	AS 9002 std: 47.271 mean: 114.392 how much: 328			AS 48076 std: 50.301 mean: 125.033 how much: 87	AS 9002 std: 48.802 mean: 120.747 how much: 174			AS 48076 std: 21.047 mean: 110.547 how much: 86	AS 9002 std: 8.423 mean: 115.993 how much: 172		
wikipedia.org	AS 20764 std: 2.458 mean: 37.596 how much: 328	AS 48076 std: 4.468 mean: 38.100 how much: 82			AS 48076 std: 20.413 mean: 41.434 how much: 87	AS 9002 std: 0.598 mean: 33.897 how much: 174			AS 48076 std: 1.381 mean: 33.869 how much: 86	AS 9002 std: 36.528 mean: 37.717 how much: 86		
twitch.tv	AS 48076 std: 4.968 mean: 34.058 how much: 82	AS 9002 std: 1.578 mean: 33.729 how much: 328			AS 48076 std: 46.617 mean: 46.169 how much: 87	AS 9002 std: 0.557 mean: 33.219 how much: 174			AS 48076 std: 1.747 mean: 33.843 how much: 86	AS 9002 std: 25.600 mean: 35.138 how much: 172		
youtube.com	AS 15169 std: 11.928 mean: 37.511 how much: 164	AS 48076 std: 3.167 mean: 36.981 how much: 246			AS 15169 std: 0.933 mean: 35.978 how much: 87	AS 48076 std: 21.319 mean: 42.470 how much: 174			AS 15169 std: 10.942 mean: 37.399 how much: 86	AS 48076 std: 2.056 mean: 36.701 how much: 171		
google.com.hk	AS 15169 std: 10.557 mean: 36.870 how much: 144	AS 48076 std: 4.428 mean: 37.435 how much: 226			AS 15169 std: 0.229 mean: 36.632 how much: 87	AS 48076 std: 13.281 mean: 40.957 how much: 174			AS 15169 std: 0.320 mean: 34.645 how much: 86	AS 48076 std: 2.293 mean: 34.764 how much: 172		
pages.tmall.com	AS 48076 std: 4.092 mean: 64.633 how much: 62	AS 9002 std: 9.342 mean: 65.233 how much: 248			AS 48076 std: 24.006 mean: 70.452 how much: 87	AS 9002 std: 3.372 mean: 61.472 how much: 174			AS 48076 std: 5.477 mean: 62.998 how much: 86	AS 9002 std: 10.983 mean: 62.677 how much: 171		
jd.com	AS 20764 std: 26.163 mean: 355.726 how much: 144	AS 9002 std: 44.100 mean: 368.095 how much: 43			AS 48076 std: 61.608 mean: 411.562 how much: 70	AS 9002 std: 50.186 mean: 384.816 how much: 174			AS 48076 std: 47.267 mean: 370.144 how much: 62	AS 9002 std: 36.913 mean: 380.891 how much: 86		
baidu.com	AS 48076 std: 60.076 mean: 423.268 how much: 62	AS 9002 std: 60.706 mean: 406.425 how much: 248			AS 48076 std: 34.284 mean: 439.741 how much: 87	AS 9002 std: 29.685 mean: 428.043 how much: 174			AS 48076 std: 35.772 mean: 417.727 how much: 86	AS 9002 std: 45.965 mean: 413.387 how much: 172		
taobao.com	AS 48076 std: 35.241 mean: 248.439 how much: 62	AS 9002 std: 41.177 mean: 249.532 how much: 248			AS 48076 std: 41.017 mean: 262.252 how much: 87	AS 9002 std: 58.326 mean: 258.060 how much: 174			AS 48076 std: 49.411 mean: 269.243 how much: 86	AS 9002 std: 62.327 mean: 264.798 how much: 171		
netflix.com					AS 48076 std: 51.428 mean: 65.337 how much: 87	AS 9002 std: 25.877 mean: 53.551 how much: 174			AS 48076 std: 3.212 mean: 51.550 how much: 85	AS 9002 std: 2.435 mean: 51.674 how much: 86		
microsoft.com												
t.co					AS 48076 std: 88.766 mean: 154.733 how much: 87	AS 9002 std: 7.339 mean: 133.652 how much: 174			AS 48076 std: 11.528 mean: 133.136 how much: 86	AS 9002 std: 4.941 mean: 134.559 how much: 86		
yandex.ru					AS 13238 std: 134.028 mean: 25.349 how much: 87	AS 48076 std: 31.246 mean: 16.777 how much: 173			AS 13238 std: 13.961 mean: 13.954 how much: 85	AS 48076 std: 2.112 mean: 11.948 how much: 172		
facebook.com												
360.cn					AS 48076 std: 99.101 mean: 231.884 how much: 87	AS 9002 std: 31.204 mean: 199.263 how much: 174			AS 48076 std: 70.761 mean: 240.126 how much: 86	AS 9002 std: 54.217 mean: 227.461 how much: 172		
amazon.com					AS 48076 std: 22.682 mean: 137.032 how much: 87	AS 9002 std: 3.228 mean: 127.354 how much: 174			AS 48076 std: 12.353 mean: 127.536 how much: 86	AS 9002 std: 6.558 mean: 127.599 how much: 172		
csdn.net					AS 48076 std: 77.983 mean: 233.600 how much: 87	AS 9002 std: 24.184 mean: 204.055 how much: 174			AS 48076 std: 35.383 mean: 233.457 how much: 86	AS 9002 std: 65.810 mean: 234.846 how much: 172		
aliexpress.com					AS 48076 std: 26.509 mean: 197.503 how much: 87	AS 9002 std: 8.521 mean: 185.367 how much: 174			AS 48076 std: 10.437 mean: 185.061 how much: 86	AS 9002 std: 7.004 mean: 181.763 how much: 172		
twitter.com					AS 48076 std: 68.478 mean: 46.626 how much: 87	AS 9002 std: 2.431 mean: 31.999 how much: 174			AS 48076 std: 2.601 mean: 33.168 how much: 86	AS 9002 std: 3.468 mean: 32.184 how much: 85	AS 29216 std: 0.071 mean: 1.109 how much: 2	

Table 4.12: mean and standard deviation for all RTTs of all next hops in AS 35807 (standard deviation and mean in milliseconds)

AS 43996	10				20-1				20-2			
	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4	next hop 1	next hop 2	next hop 3	next hop 4
google.ru	AS 7713 std: 35.388 mean: 51.195 how much: 210	AS 1200 std: 0.151 mean: 7.027 how much: 105			AS 7713 std: 36.921 mean: 50.293 how much: 175	AS 4637 std: 0.481 mean: 248.038 how much: 88	AS 1200 std: 0.187 mean: 7.095 how much: 88		AS 7713 std: 36.425 mean: 50.159 how much: 176	AS 1200 std: 0.173 mean: 7.042 how much: 88		
linkedin.com	AS 3356 std: 37.011 mean: 53.714 how much: 314				AS 3356 std: 37.914 mean: 54.656 how much: 264	AS 4637 std: 6.081 mean: 227.093 how much: 88			AS 3356 std: 37.203 mean: 53.918 how much: 264			
wikipedia.org	AS 12956 std: 1.375 mean: 79.892 how much: 105	AS 1200 std: 5.261 mean: 5.726 how much: 210			AS 12956 std: 2.400 mean: 80.133 how much: 88	AS 4637 std: 32.350 mean: 169.593 how much: 88	AS 1200 std: 5.570 mean: 6.455 how much: 176		AS 12956 std: 1.000 mean: 79.648 how much: 88	AS 1200 std: 5.261 mean: 6.216 how much: 176		
twitch.tv	AS 6461 std: 0.592 mean: 1.260 how much: 105	AS 3356 std: 0.161 mean: 1.972 how much: 105	AS 7922 std: 0.303 mean: 0.781 how much: 105		AS 6461 std: 0.102 mean: 1.188 how much: 88	AS 3356 std: 0.077 mean: 1.960 how much: 88	AS 7922 std: 0.066 mean: 0.984 how much: 88	AS 4637 std: 0.228 mean: 0.972 how much: 88	AS 6461 std: 0.065 mean: 1.197 how much: 88	AS 3356 std: 0.076 mean: 1.968 how much: 88	AS 7922 std: 0.064 mean: 0.980 how much: 88	
youtube.com	AS 7713 std: 35.910 mean: 50.533 how much: 210	AS 1200 std: 0.129 mean: 7.108 how much: 105			AS 7713 std: 35.572 mean: 50.879 how much: 176	AS 4637 std: 91.921 mean: 258.090 how much: 88	AS 1200 std: 0.111 mean: 7.150 how much: 88		AS 7713 std: 35.266 mean: 51.209 how much: 176	AS 1200 std: 0.129 mean: 7.150 how much: 88		
google.com.hk	AS 7713 std: 35.742 mean: 47.376 how much: 210	AS 1200 std: 0.131 mean: 4.390 how much: 105			AS 7713 std: 36.565 mean: 43.612 how much: 174	AS 4637 std: 10.535 mean: 243.130 how much: 88	AS 1200 std: 1.429 mean: 10.227 how much: 88		AS 7713 std: 34.856 mean: 48.176 how much: 176	AS 1200 std: 0.138 mean: 4.353 how much: 88		
pages.tmall.com	AS 12956 std: 0.618 mean: 96.602 how much: 105	AS 3356 std: 0.425 mean: 24.370 how much: 105	AS 6762 std: 0.864 mean: 32.834 how much: 105		AS 12956 std: 4.221 mean: 97.146 how much: 88	AS 3356 std: 1.856 mean: 35.776 how much: 88	AS 4637 std: 48.353 mean: 245.187 how much: 88	AS 6762 std: 3.018 mean: 34.863 how much: 88	AS 12956 std: 0.315 mean: 96.524 how much: 88	AS 3356 std: 0.290 mean: 24.323 how much: 88	AS 6762 std: 1.627 mean: 31.798 how much: 88	
jd.com	AS 12956 std: 18.114 mean: 238.678 how much: 105	AS 1299 std: 326.176 mean: 414.030 how much: 105	AS 6762 std: 257.471 mean: 356.944 how much: 105		AS 12956 std: 53.501 mean: 263.964 how much: 88	AS 1299 std: 37.357 mean: 322.386 how much: 88	AS 4637 std: 126.562 mean: 153.949 how much: 88	AS 6762 std: 12.116 mean: 300.595 how much: 88	AS 12956 std: 30.705 mean: 256.702 how much: 88	AS 1299 std: 6.517 mean: 329.708 how much: 88	AS 6762 std: 6.260 mean: 296.995 how much: 88	
baidu.com	AS 12956 std: 12.023 mean: 250.985 how much: 105	AS 1299 std: 2.229 mean: 298.280 how much: 5	AS 6762 std: 20.811 mean: 304.672 how much: 105	AS 3356 std: 33.713 mean: 401.195 how much: 100	AS 12956 std: 11.622 mean: 244.878 how much: 88	AS 3356 std: 32.591 mean: 376.874 how much: 88	AS 4637 std: 42.373 mean: 127.652 how much: 88	AS 6762 std: 9.968 mean: 298.176 how much: 88	AS 12956 std: 20.991 mean: 254.557 how much: 87	AS 1299 std: 47.080 mean: 346.082 how much: 2	AS 6762 std: 6.255 mean: 297.634 how much: 88	AS 3356 std: 35.790 mean: 374.999 how much: 86
taobao.com	AS 12956 std: 17.643 mean: 282.405 how much: 104	AS 3356 std: 3.752 mean: 290.423 how much: 105	AS 6762 std: 12.284 mean: 306.396 how much: 105		AS 12956 std: 14.081 mean: 278.669 how much: 88	AS 3356 std: 33.796 mean: 309.552 how much: 88	AS 4637 std: 75.929 mean: 213.792 how much: 88	AS 6762 std: 29.992 mean: 320.631 how much: 88	AS 12956 std: 4.553 mean: 278.769 how much: 88	AS 3356 std: 4.266 mean: 293.341 how much: 88	AS 6762 std: 6.803 mean: 305.681 how much: 88	
netflix.com					AS 12956 std: 1.925 mean: 94.111 how much: 88	AS 4637 std: 35.608 mean: 187.890 how much: 88	AS 7713 std: 0.230 mean: 11.484 how much: 88	AS 1200 std: 5.875 mean: 17.835 how much: 88	AS 12956 std: 22.013 mean: 98.245 how much: 88	AS 7713 std: 0.193 mean: 11.448 how much: 88	AS 1200 std: 0.765 mean: 19.339 how much: 88	
microsoft.com												
t.co					AS 7713 std: 51.015 mean: 227.397 how much: 88							
yandex.ru					AS 7713 std: 50.058 mean: 81.447 how much: 176	AS 4637 std: 99.613 mean: 291.515 how much: 88	AS 1200 std: 3.827 mean: 32.049 how much: 88		AS 7713 std: 40.528 mean: 77.462 how much: 176	AS 1200 std: 4.876 mean: 32.548 how much: 88		
facebook.com												
360.cn					AS 12956 std: 45.380 mean: 267.886 how much: 88	AS 3356 std: 90.214 mean: 341.351 how much: 88	AS 4637 std: 27.719 mean: 213.028 how much: 88	AS 6762 std: 98.166 mean: 433.443 how much: 88	AS 12956 std: 54.625 mean: 272.816 how much: 88	AS 3356 std: 116.450 mean: 323.359 how much: 88	AS 6762 std: 38.953 mean: 337.801 how much: 88	
amazon.com					AS 7713 std: 0.101 mean: 0.721 how much: 86	AS 3356 std: 10.796 mean: 107.071 how much: 88	AS 4637 std: 59.671 mean: 244.144 how much: 88	AS 6762 std: 0.696 mean: 96.597 how much: 88	AS 7713 std: 0.107 mean: 0.765 how much: 87	AS 3356 std: 1.397 mean: 107.813 how much: 88	AS 6762 std: 0.686 mean: 97.285 how much: 88	
csdn.net					AS 12956 std: 73.230 mean: 270.733 how much: 88	AS 3356 std: 179.289 mean: 425.051 how much: 87	AS 4637 std: 322.675 mean: 261.525 how much: 88	AS 6762 std: 132.963 mean: 442.907 how much: 87	AS 12956 std: 103.203 mean: 307.023 how much: 85	AS 3356 std: 34.723 mean: 394.134 how much: 85	AS 6762 std: 55.092 mean: 355.878 how much: 86	
aliexpress.com					AS 12956 std: 1.090 mean: 71.698 how much: 88	AS 3356 std: 9.345 mean: 146.511 how much: 88	AS 4637 std: 9.537 mean: 176.624 how much: 88	AS 6762 std: 6.728 mean: 140.937 how much: 88	AS 12956 std: 20.850 mean: 74.934 how much: 88	AS 3356 std: 7.632 mean: 147.032 how much: 88	AS 6762 std: 5.915 mean: 136.492 how much: 88	
twitter.com					AS 7713 std: 3.063 mean: 2.514 how much: 176	AS 1200 std: 1.501 mean: 14.116 how much: 88			AS 7713 std: 3.316 mean: 3.960 how much: 87	AS 1200 std: 1.463 mean: 13.793 how much: 88		

Table 4.13: mean and standard deviation for all RTTs of all next hops in AS 43996 (standard deviation and mean in milliseconds)

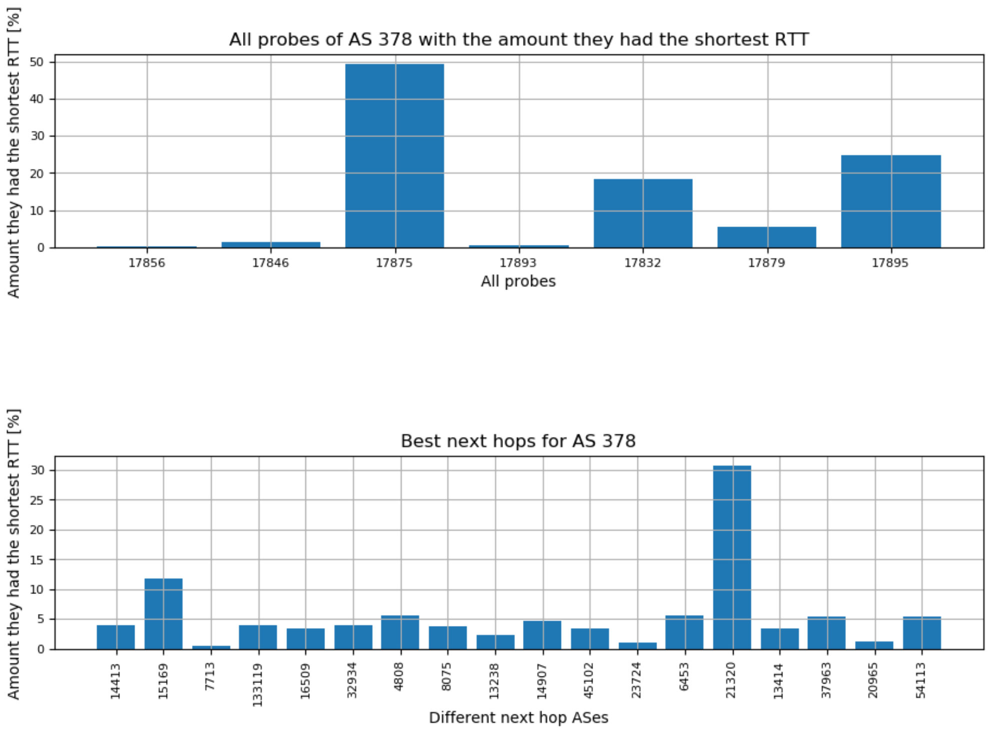

Figure 4.1: distribution of the probes and next hops that had the shortest RTT for AS 378

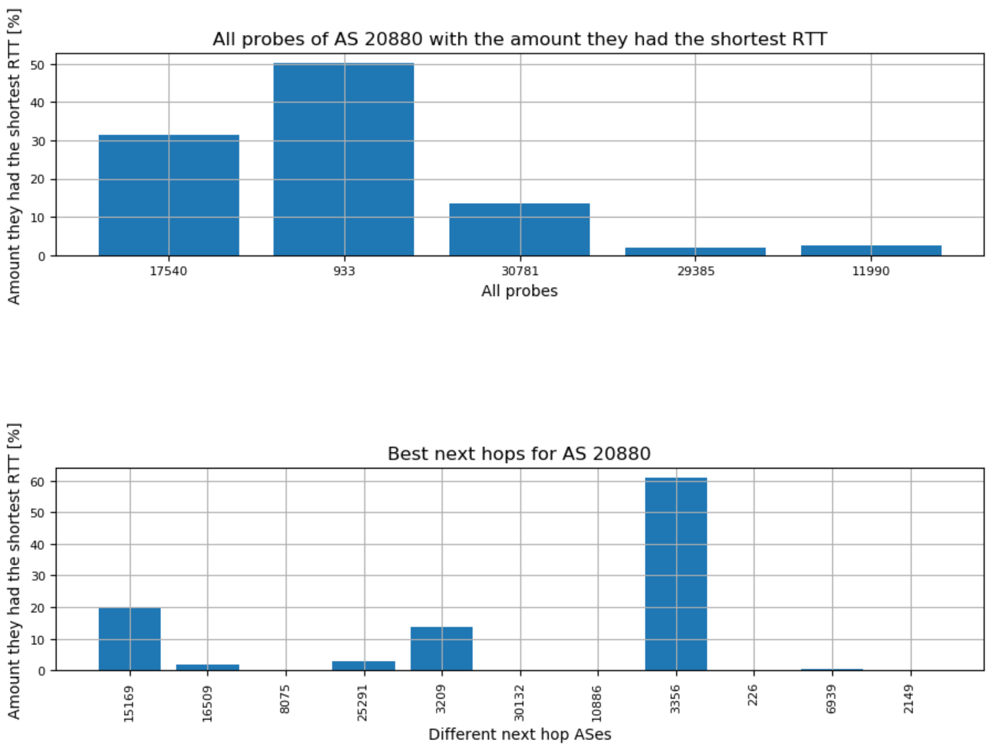

Figure 4.2: distribution of the probes and next hops that had the shortest RTT for AS 20880

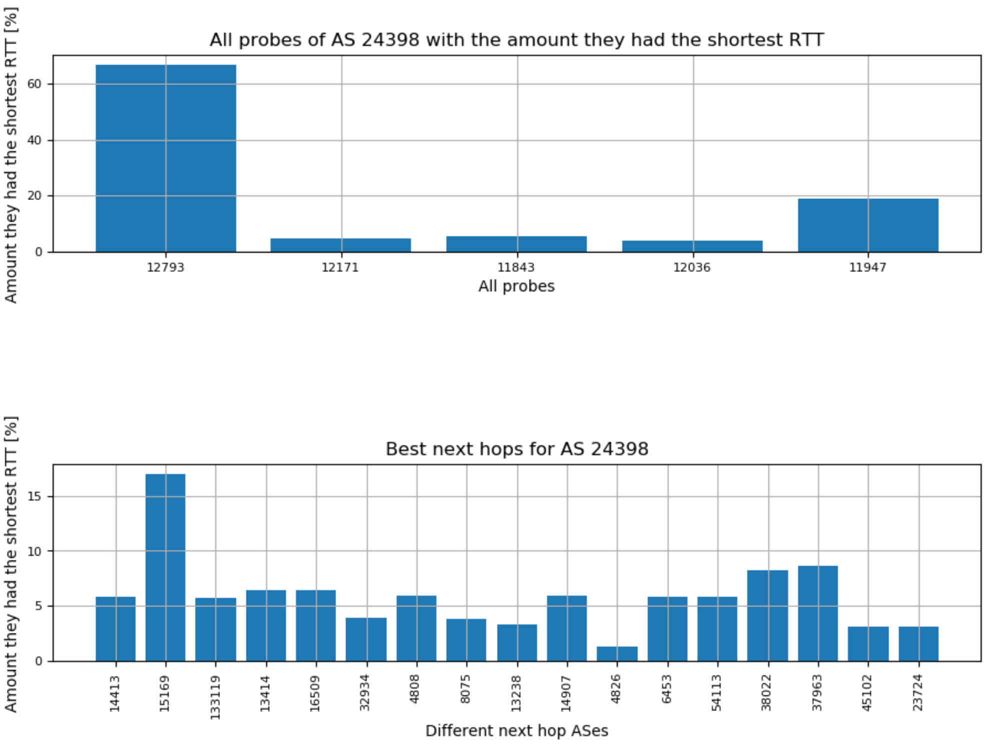

Figure 4.3: distribution of the probes and next hops that had the shortest RTT for AS 24398

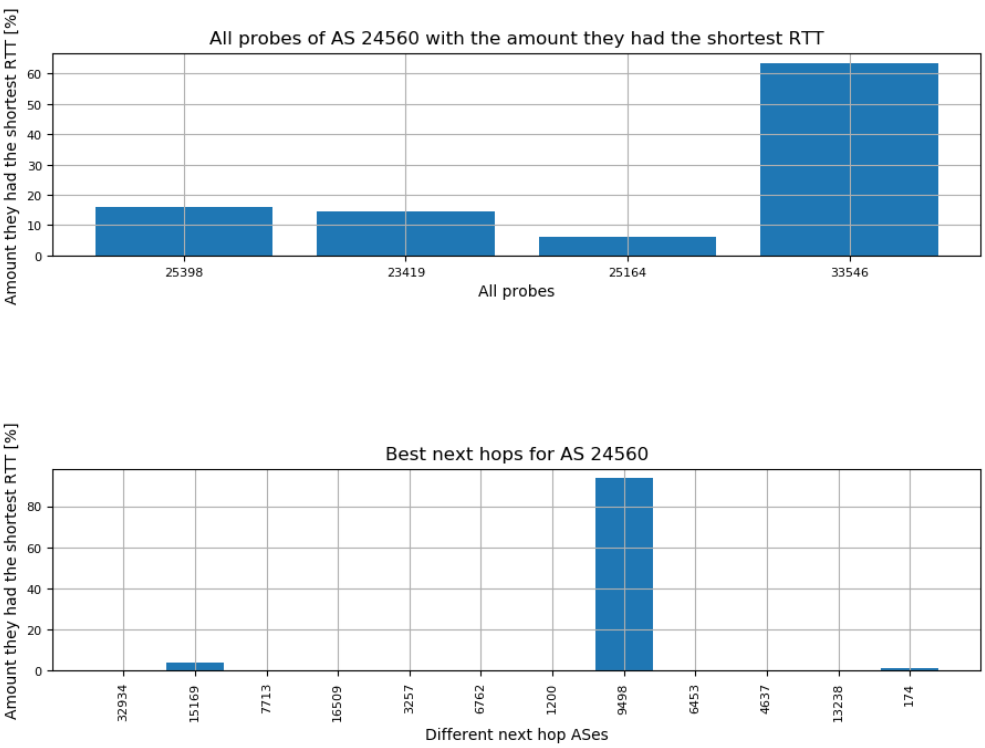

Figure 4.4: distribution of the probes and next hops that had the shortest RTT for AS 24560

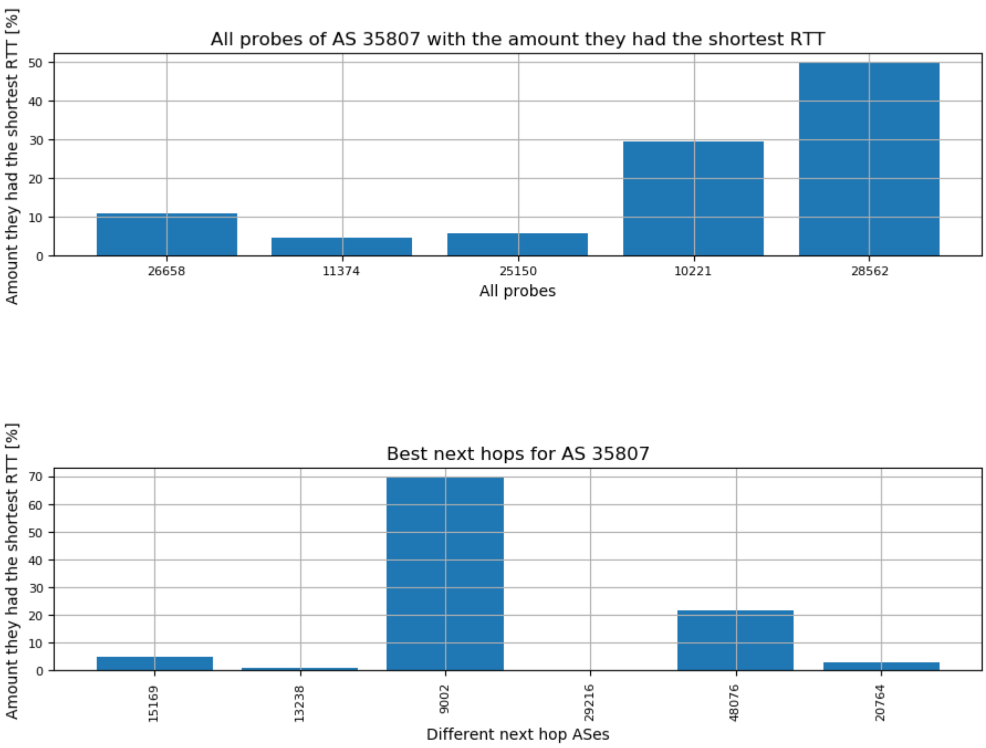

Figure 4.5: distribution of the probes and next hops that had the shortest RTT for AS 35807

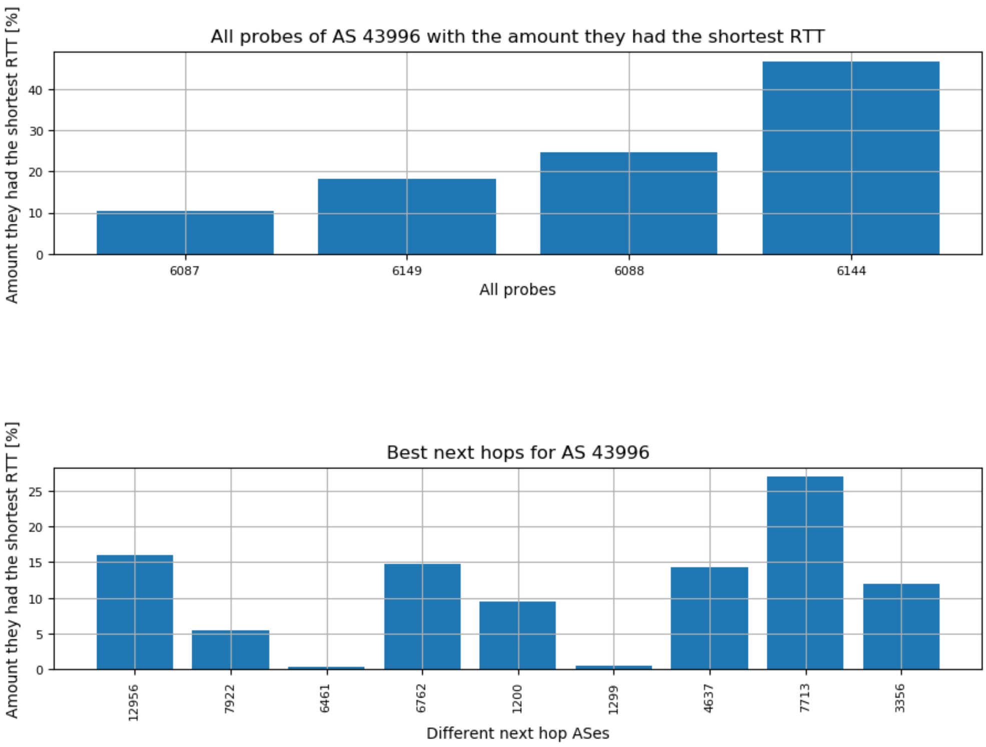

Figure 4.6: distribution of the probes and next hops that had the shortest RTT for AS 43996

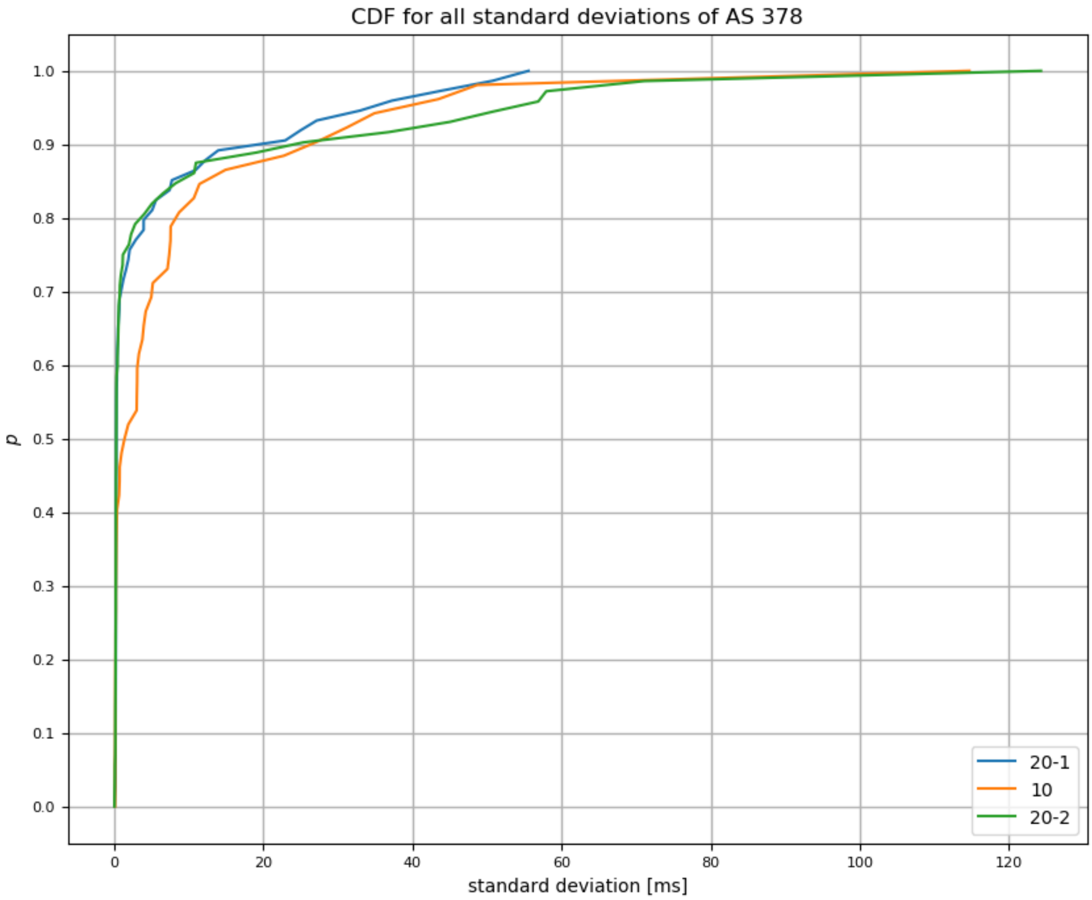

Figure 4.7: CDF graphs for all experimentation runs of AS 378

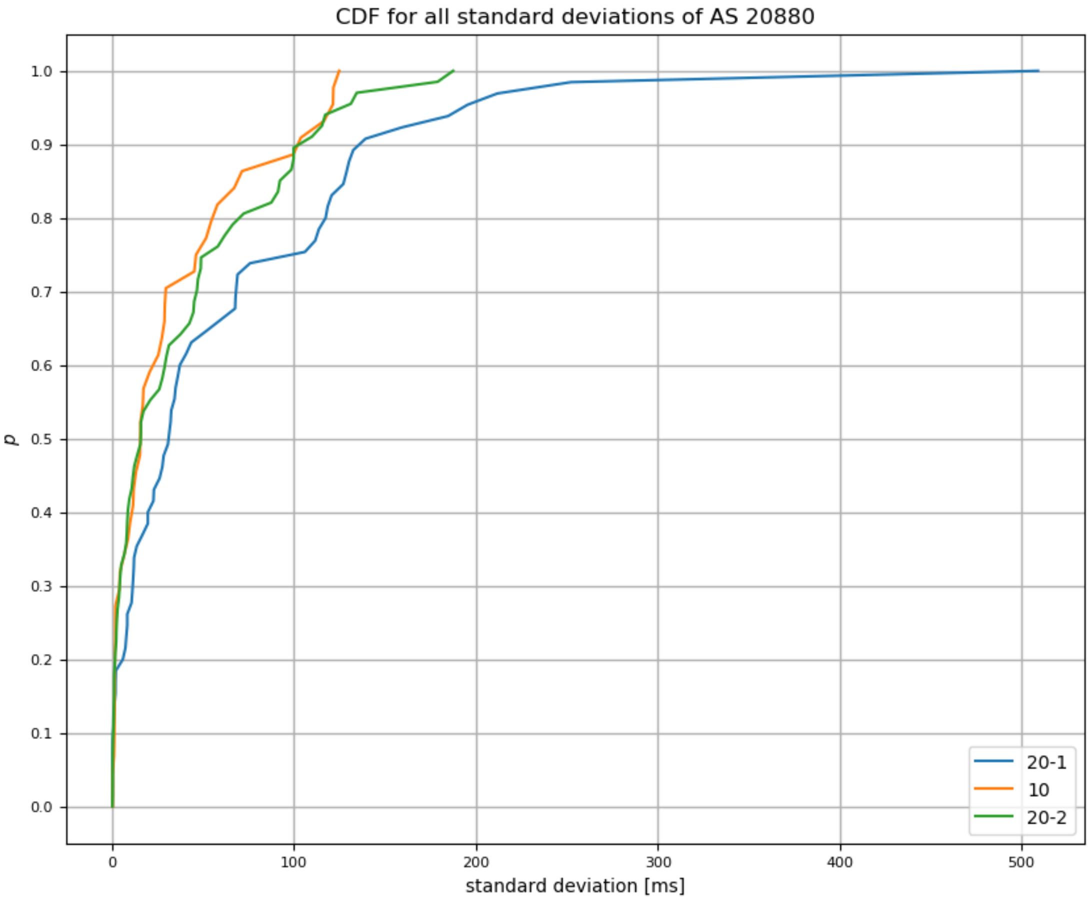

Figure 4.8: CDF graphs for all experimentation runs of AS 20880

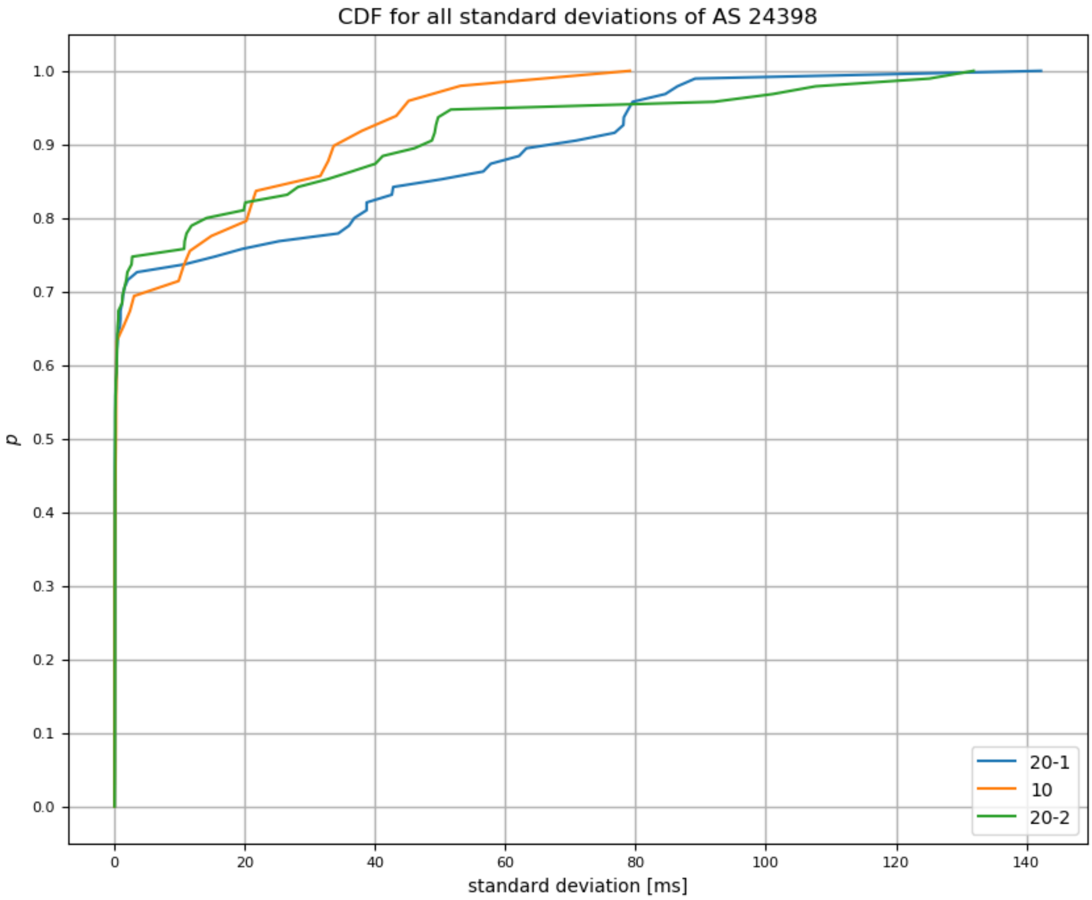

Figure 4.9: CDF graphs for all experimentation runs of AS 24398

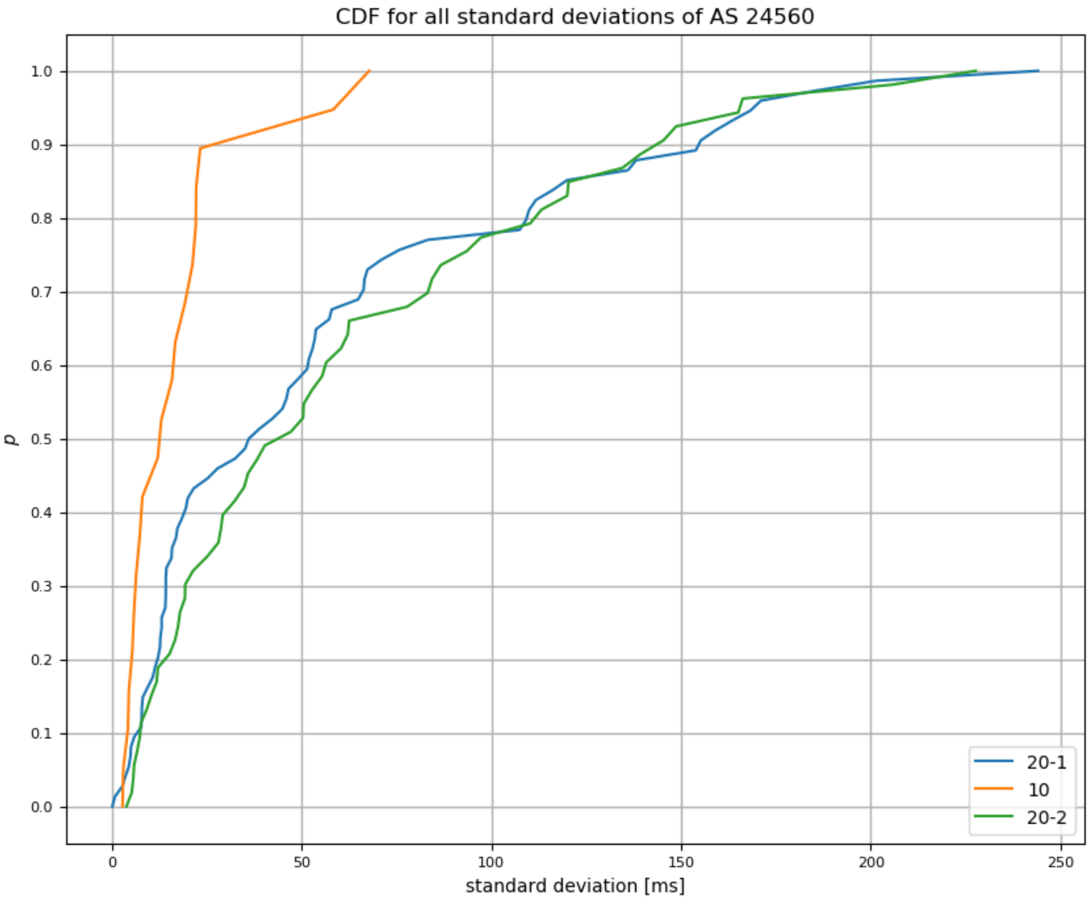

Figure 4.10: CDF graphs for all experimentation runs of AS 24560

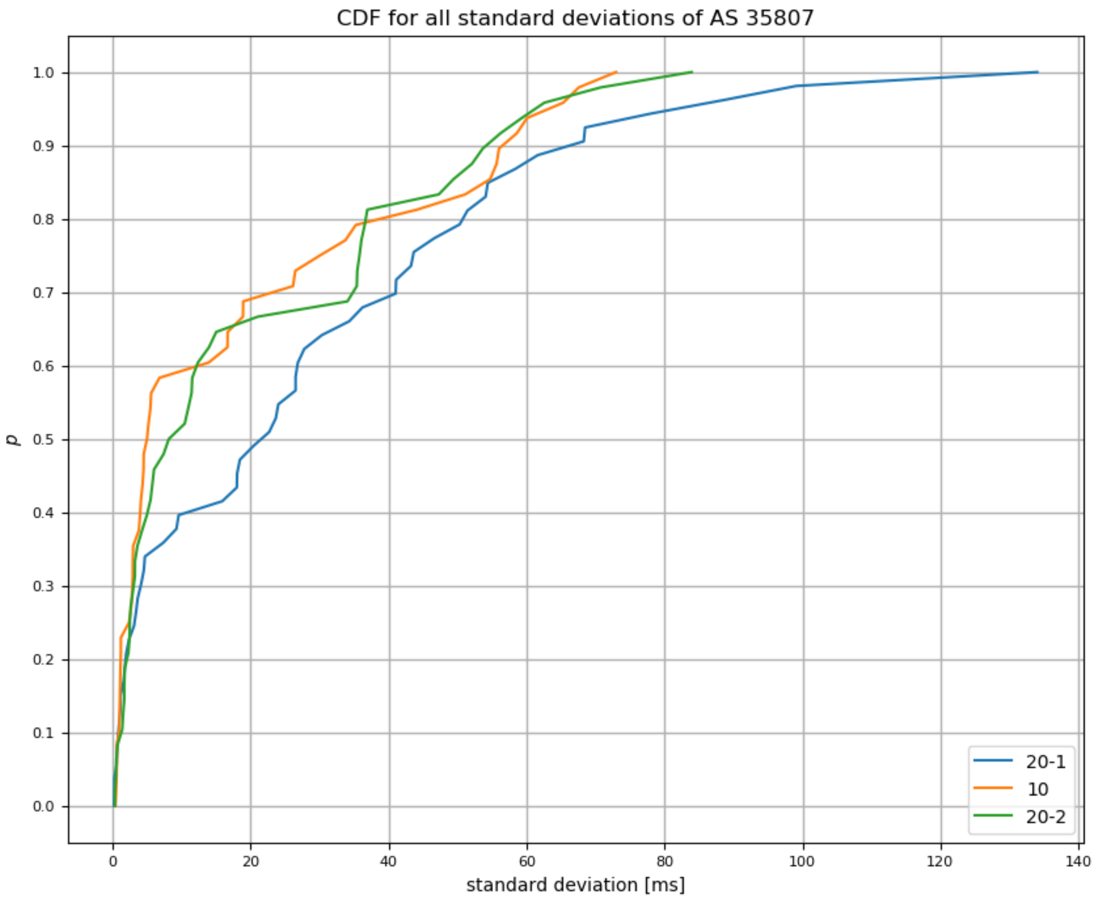

Figure 4.11: CDF graphs for all experimentation runs of AS 35807

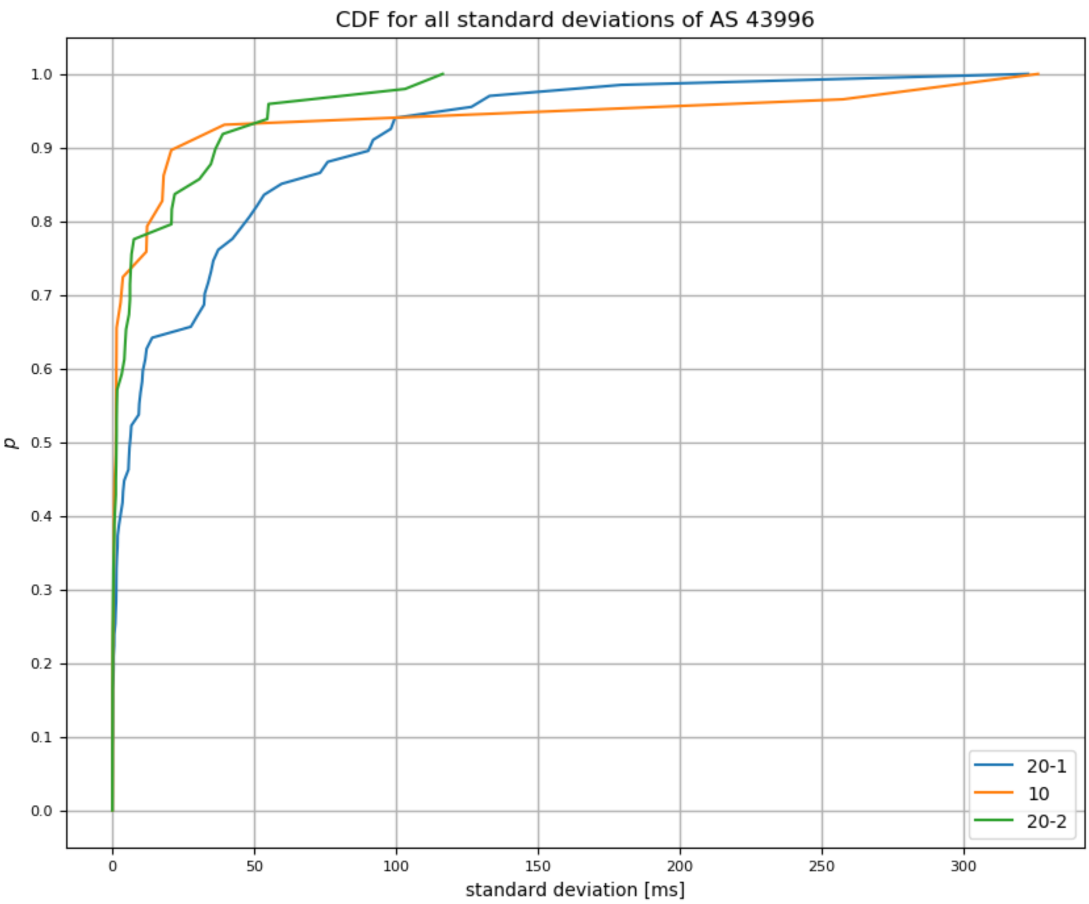

Figure 4.12: CDF graphs for all experimentation runs of AS 43996

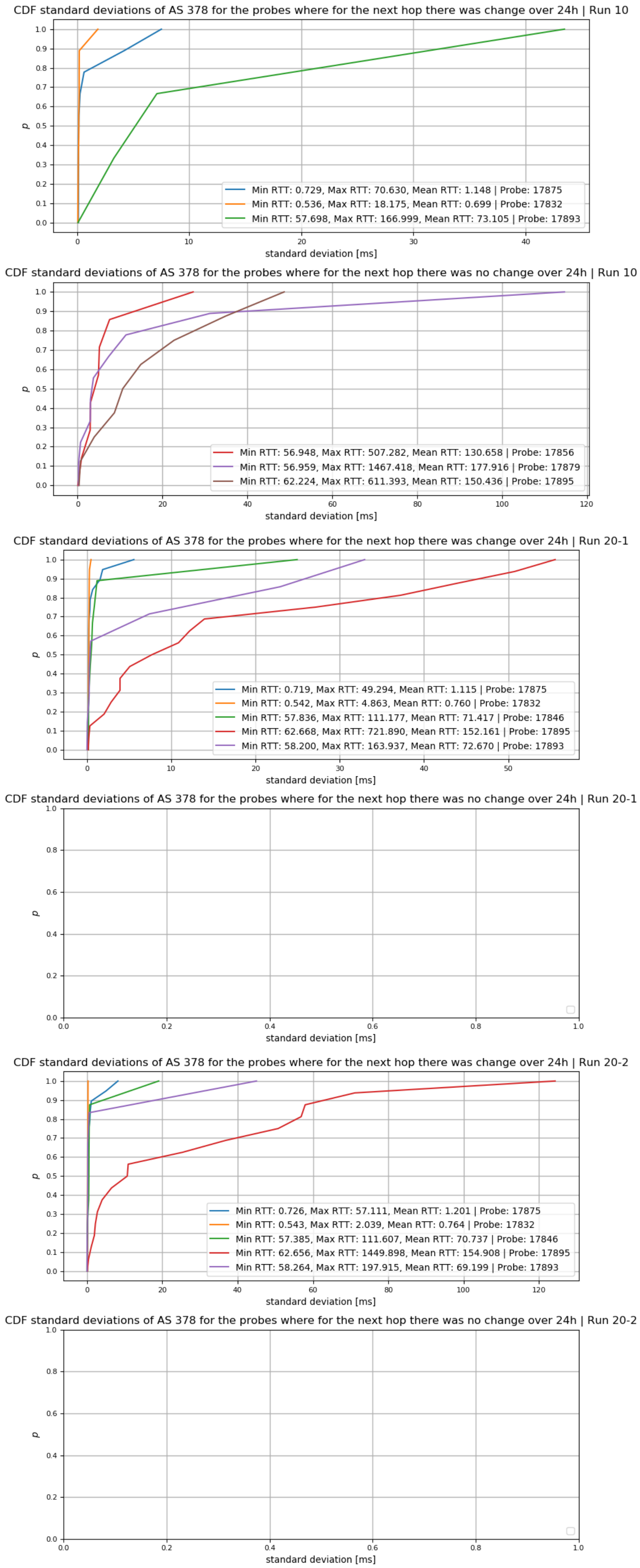

Figure 4.13: all probe CDFs for every experimentation run on AS 378

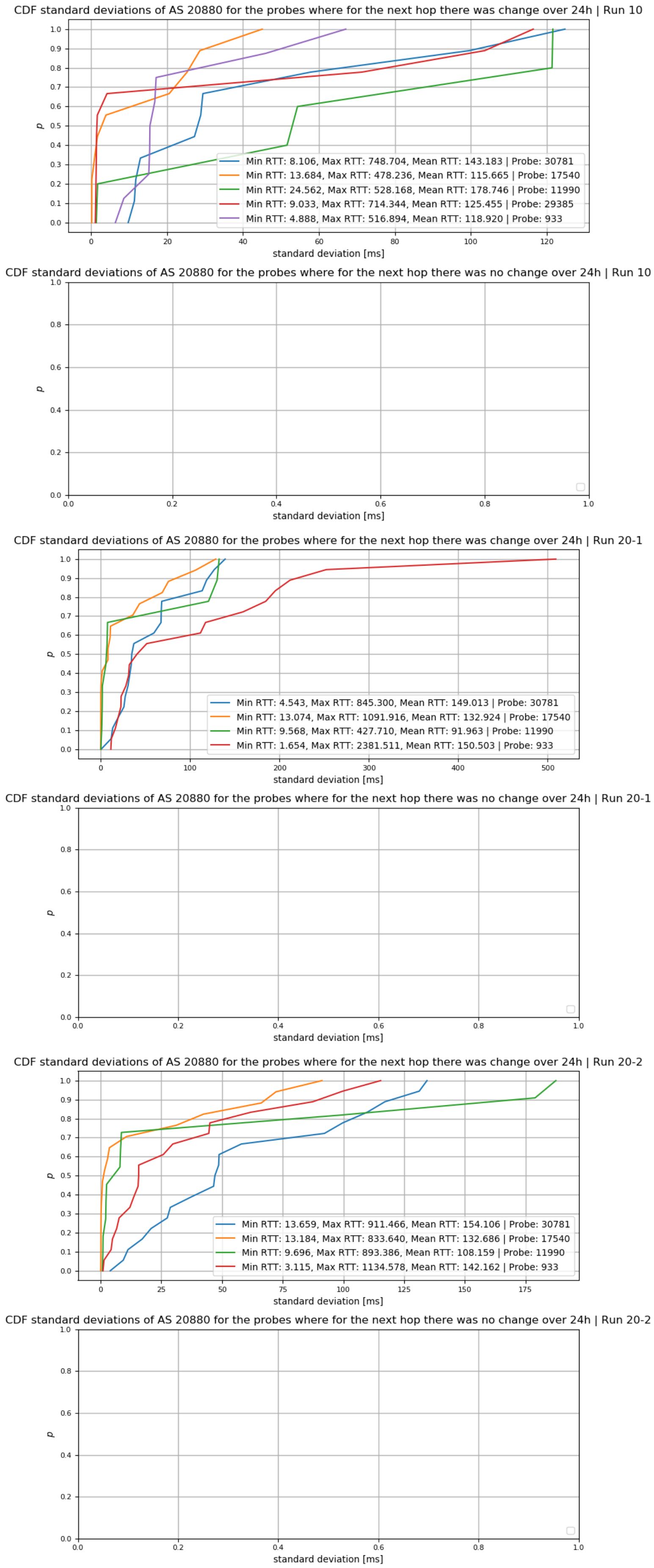

Figure 4.14: all probe CDFs for every experimentation run on AS 20880

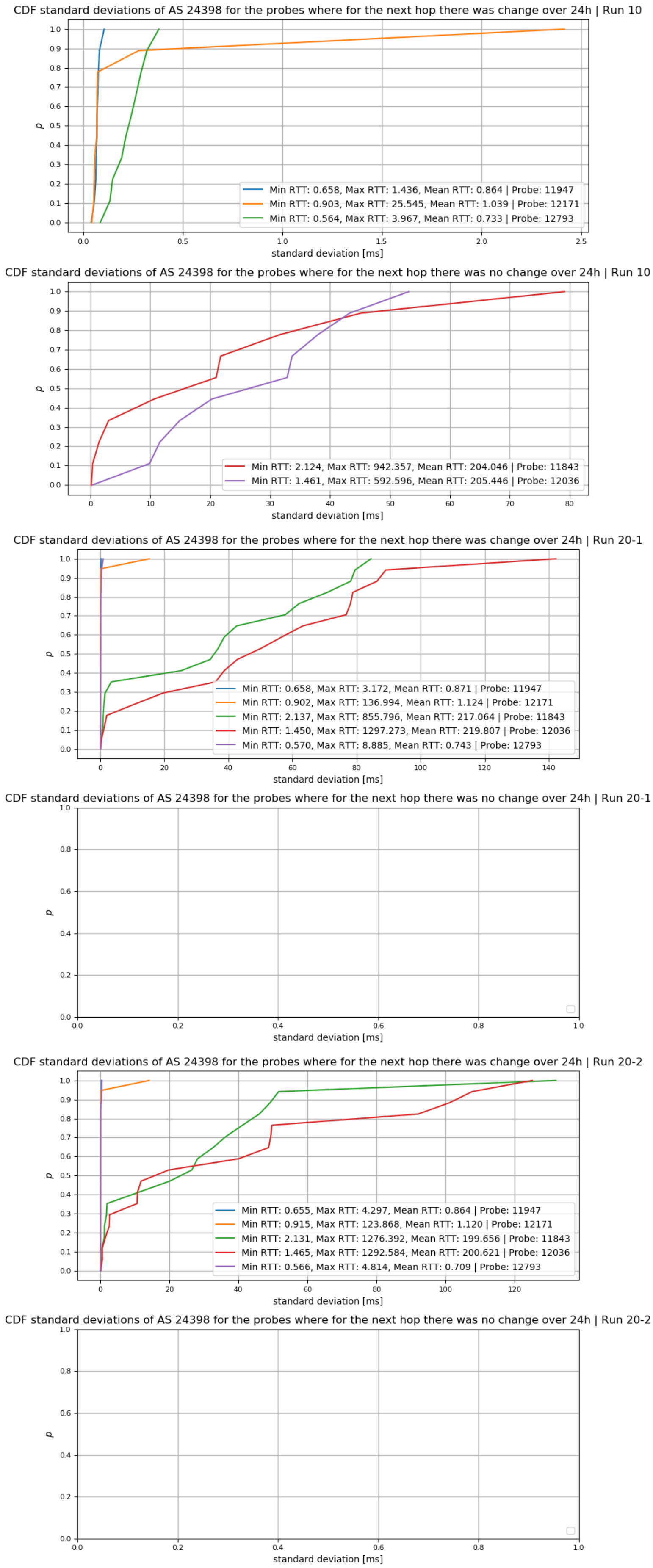

Figure 4.15: all probe CDFs for every experimentation run on AS 24398

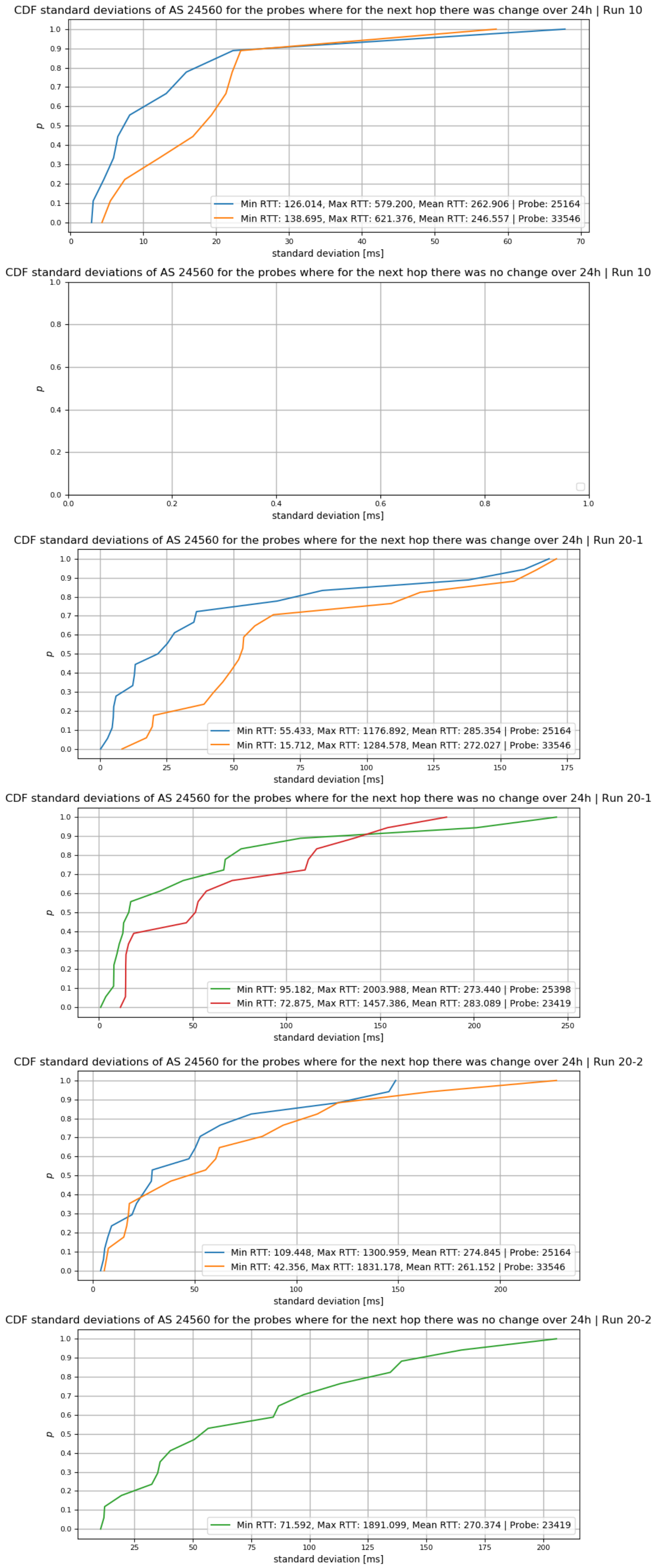

Figure 4.16: all probe CDFs for every experimentation run on AS 24560

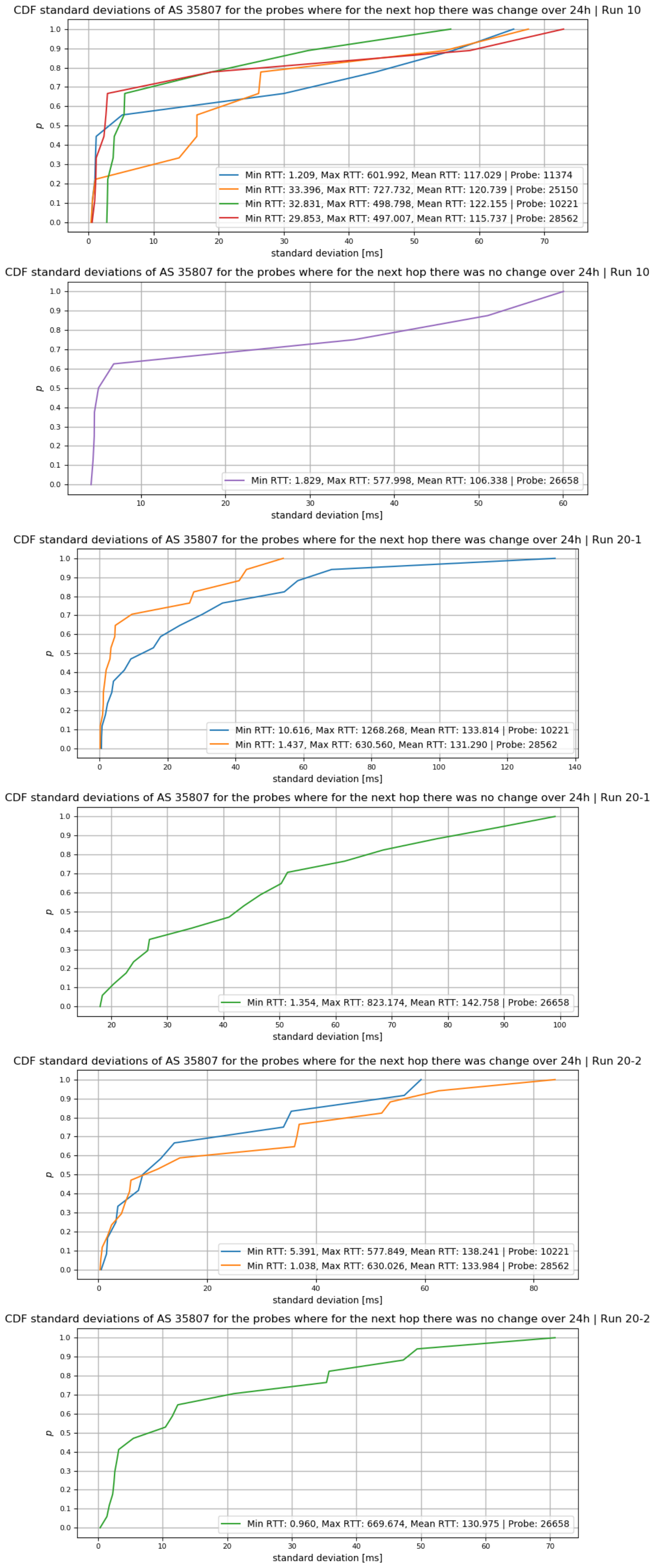

Figure 4.17: all probe CDFs for every experimentation run on AS 35807

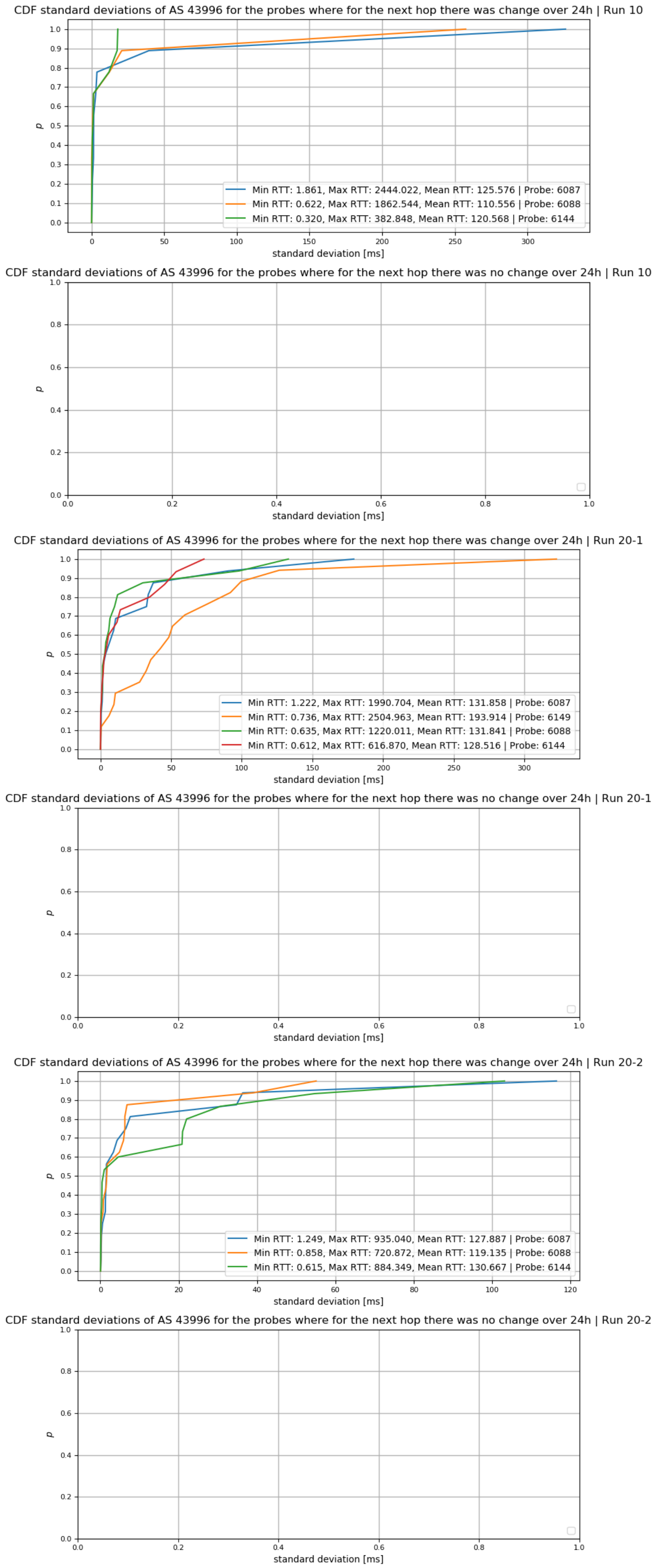

Figure 4.18: all probe CDFs for every experimentation run on AS 43996

Chapter 5

Discussion

5.1 Inter-AS differences

Looking at the CDF graphs for the whole AS (tables 4.7 - 4.12) we can see clear differences showing the possibilty for congestion is bigger in some of them. Especially AS 24560 (table 4.10) and AS 20880 (table 4.8) where around twenty percent of all communication had a standard deviation of more than 100 milliseconds. Interestingly AS 24560 is the biggest one we used for our project (see table 2.1). In figure 4.16 we can also see that every probe in this AS has high latency conncetions. At some points the last RTT of the traceroute took nearly one second to reach the probe again. Of course for example AS 43996 (figure 4.18) has also pretty high mean and maximum RTT values but the connections are more stable as can be seen by the lower standard deviations. Interesting is that ASes 20880, 24398, 35807 and 43996 have clearly lower standard deviations on the *20-1* experiment run (see figures 4.8, 4.9, 4.11 and 4.12). The cause for this is hard to determine especially as they were conducted on different days (see table 2.3).
Table 4.1 gives an interesting view at how some of the ASes have only one next hop that is viable (especially 20880 and 24560) and thus don't have a change in the next best hop. This can also be seen in tables 4.2 for AS 20880 and 4.4 for AS 24560. Each has one next hop that dominates the others (3356 for AS 20880 and 9498 for AS 24560).

5.2 Multi-path routing evaluation

The data needed here is mostly given in tables 4.8 - 4.13. For multi-path routing to be feasible the given paths need to be on the same level considering latency and stability of the connection. We have examples where this is undoubtedly the case (i.e. AS 43996) and where it is not (i.e. 24398). Let's take a look at the latter first.
AS 378 (table 4.8) and AS 24398 (table 4.8) fall in this category. Both have two different next hops for most of their destinations. These are used pretty evenly, one a bit more as several probes will be using it as its route. For most of them the problems begin with the standard deviation and thus the possible congestion on the way which differ noticeably. But what differentiates them the most is the mean time it takes the traceroute packet to loop back to the probe. For some of them it is three orders of magnitude higher than their counterpart, especially in AS 24398. As an example we can take the connection from AS 24398 to `baidu.com`. In all three experiment runs the traffic over next hop AS 4808 had a mean time around 0.87 ms where as the packets over AS 38022 needed more than 250 ms on average to reach the website and loop back. On AS 378 this is even worse with AS 4808 giving around 0.95 ms and AS 21320 giving 350 ms of delay. This is mostly a problem for eventual TCP connections. If you would connect to `baidu.com` from AS 378 the packets would be given an ordering which would be re-established when receiving them. If now some of these packets took 300 ms instead of 0.8 ms to reach the destination everything else would have to wait for them to get the whole data set again. For UDP this is not a problem, as packet ordering is not a concern here. See [18] for an analysis of UDP and TCP in multi-path routing.
Now let's take a look at examples where the paths are comparably. For AS 24560, 35807 and

43996 (table 4.11, 4.12 and 4.13 respectively) we have routes that are offering nearly the same delay and almost the same possibility for congestion. Interesting here is that AS 24560 and AS 35807 have connections which are not that fast but because all their paths take around the same time these would be viable again. AS 43996 on the other hand has for most of its connections pretty low delay and most importantly it has a lot of different next hops. Together with AS 24398 its shortest RTTs are the most evenly distributed over all next hops (see figure 4.3 for AS 24398 and figure 4.6 for AS 43996) showing its viability for multi-path routing. What is intriguing here, in experiment run 20-1 we have for nearly all destinations one additional next hop *AS 4637*. It does not appear before nor after. Unfortunately it is not possible to evaluate exactly why, but it is possible that this is due to a short lived routing change for this AS.
This leaves AS 20880 (table 4.9). At first glance we can already see that for almost all destinations there is only one path used. But even the sparingly additional routes are used only a handful of times during an experiment run. For the rare case that there are two (or more) paths that are equally used they are actually pretty similar. See `jd.com` as an example here. Next hops 25291 and 3209 are pretty close concerning standard deviation and mean time. But that doesn't make this AS a good candidate for multi-path routing. Why this AS was chosen even though it is not multi-homed for most of the destination will be explained in section 5.3.
How fickle the different ASes are can also be seen in tables 4.2 - 4.7. Especially for AS 20880 (table 4.3) which has a varying amount of next hops during the experiment runs. As we already saw this AS has a lot of next hops that pop up for a small timeslot and then don't appear again. In contrary we have AS 43996 (table 4.7) where we can see how consistent it was over all runs.

5.3 Difficulties and how to avoid them

We already explained some problem cases in section 3.1.5 and most importantly there is the part about bogon IPs. During the preliminary experiments we conducted (see section 3.1.4) we would see how many different next hops were leading from a source AS to every website. Because these IPs gave us an AS that didn't indicate a different path it tricked us into thinking that an AS would be viable for evaluation. This is especially the case for AS 20880. As discussed eliminating these IPs gives you the real next hop when looking at the AS-path. Unfortunately this was discovered too late into the project to gather new ASes for testing thus we had to work with the results we got.
Another problem that was discovered too late is that not all ASes are reliably able to reach certain destinations (see tables 4.11, 4.12 and 4.13 for examples). The most likely cause for this is the IP that was chosen for each website. As described in section 2.4 `dig` was used when determining the IP addresses. This was done in Zurich, Switzerland. The source ASes are situated all over the globe and when accessing a certain website, are quite possibly only able to access them via a given IP prefix. To circumvent this the preliminary experiments should have been run on these twenty destinations from the beginning and not on randomly chosen websites. This would also allow for them to run for a longer time and thus give the ability to see exactly which ASes are able to connect to them and which do not.
This leads into another problem that stems from this being a semester project. The time given here is limited. For every website/source pairing we have at maximum three different data sets (10, 20-1, 20-2). To get a clearer picture more experiment runs would be ideal.

Chapter 6

Conclusion & Outlook

6.1 Conclusion

We showed that multi-path routing from a performance standpoint is worth further investigation. There are most definitely ASes that meet the requirements for sending traffic over several paths. Most importantly we established an efficient work flow which allows the running of an experiment on the RIPE Atlas platform and its further analysis. This allows further research to be conducted in a much faster manner and for them to concentrate on more important tasks.

6.2 Outlook

Some future improvements were already discussed in section 5.3. If more time was available we would look for more ASes to run measurements from and as already mentioned also gather more data for every source/destination-pairing through more experiment runs.
Future research would need the evaluation of different routing algorithms. Some examples can be seen at [18]. Further experiments could take a look at the ideal network structure for multi-path routing (see [13]).

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Appendix A

Timetable of project

The following tables show the timetable that was proposed at the beginning (table A.1) and the sequence of events that ultimately lead to this report (table A.2).

Week number	Schedule
Week 1	Familiarize with the RIPE Atlas platform
Week 2 & 3	Find interesting stub networks (multi-homed & with ATLAS probes & static routing)
Week 4	Perform measurements from multiple stub networks for multiple days
Week 5	Analyze data with respect to path selection (static / dynamic)
Week 6 & 7	Analyze data with respect to performance in time per destination
Week 8	Predict performance or ranking or performance difference
Week 9 & 10	Predict optimal routing decisions
Week 11 & 12	Write report

Table A.1: proposed timetable at the start of the project

Week number	Schedule
Week 1	Evaluation of ASes and probes in them
Week 2	Modifying scripts and making first measurements on RIPE Atlas
Week 3	Writing scripts to pull experiment data via API and writing into files
Week 4	First plots to see different RTTs of connections, started first 24 hour experiments
Week 5	Evaluation to see if experiments up to now are actually correctly done
Week 6	Writing scripts for analysis (make_analysis.py)
Week 7	First CDF plots (not enough data points)
Week 8	CDFs are correct now, more 24 hour experiments
Week 9	New ASes found for experiments (378 & 24560), repeated experiments for them. Started new experiments (20 destinations)
Week 10	Continued new experiments (still 20-1), written half of the final analysis scripts
Week 11	Finished all analysis scripts, started making the results concise and humanly-readable
Week 12	Meeting with Prof. Vanbever. On his behest started second twenty destination experiment run (20-2)
Week 13 & 14	Writing of report. In process found the bogon IPs and correct the pull_experiment_data.py script.

Table A.2: Actual timetable

Appendix B

Originalproblem

Multi-path routing

Measure performance difference across alternative next hops

Over the years Internet is becoming flatter, in that network operators are continually trying to peer directly with more ASes in order to achieve better performance. This increase in alternative paths does not come with a change in the mon- itoring or routing infrastructure though. As such, our understanding of the dynamic characteristics of the alternative paths is limited. The purpose of this project is to investigate and analyse the performance difference among alternative next hops from stub ASes. In particular, we are intersected in understanding the temporal and spatial patterns of perfor- mance difference among alternative paths and across different destinations. Using this knowledge we can then model and predict the performance difference of alternative paths.

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