HiPerConTracer – A Versatile Tool for IP Connectivity Tracing in Multi-Path Setups

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***Abstract*—Nowadays, we see a steadily increasing number of Internet devices with connections to multiple networks. For example, every smartphone provides mobile broadband and Wi-Fi connectivity. Multi-path transport protocols, like MPTCP, CMT-SCTP or Multipath-QUIC, allow for utilising all connected networks simultaneously. However, while there is a lot of research on the Transport Layer aspects of multi-path transport, there is not much work on the Network Layer perspective, yet.**

In this paper, we introduce our Open Source tool HiPerConTracer (High-Performance Connectivity Tracer) for efficient, parallelised, long-term measurements of the path connectivity characteristics among multi-homed Internet systems. HiPerConTracer is now running as a permanent feature in the NorNet Core infrastructure, which is used for research on multi-homed systems, and in particular for research on multi-path transport. Based on the HiPerConTracer data collected in NorNet Core so far, we finally present some interesting results from the analysis of the inter-continental site connectivity between China and Norway in January 2020.[1]

I. Introduction

Multi-path transport, e.g. with Concurrent Multipath Transfer for SCTP (CMT-SCTP) [1]–[3], Multi-Path TCP (MPTCP) [4], [5] or Multipath-QUIC [6], is becoming increasingly important. Today, many network devices are multi-homed. For instance, almost every smartphone provides mobile broadband and Wi-Fi connectivity. By utilising all connections to Internet Service Providers (ISP) *simultaneously*, redundancy and increased throughput is possible. But even when only running IPv4 and IPv6 over the same ISP, the connections with both protocols may use non-congruent routes in the Internet, allowing for load balancing and throughput improvements [7].

While there are various articles on all aspects of the multi-path transport protocols, e.g. congestion control [8]–[10], path management [11], buffer management [12], [13], shared bottleneck detection [14], handling of latency-sensitive traffic [15] and media streaming [16], [17], little work has been done to examine the properties of the underlying networks. In many cases, our Open Source tool NetPerfMeter[2] [18], [19] [1, Section 6.3] has been used to conduct *Transport Layer* performance measurements. However, another important question is: what can a multi-path transport protocol instance expect from the underlying *Network Layer* paths in today's Internet? Previous work like [20] has used the NorNet Core [21], [22] infrastructure for some initial analyses. NorNet Core is a larger-scale Internet testbed, providing researchers access to multi-homed Internet servers. These systems are connected to multiple ISP connections with different types of connections (e.g. business-grade fibre or consumer-grade ADSL) and with support for IPv6 where possible. [20] conducted measurements with the standard `ping` and `traceroute` command-line tools to obtain information about Internet routing. However, performance issues with large-scale runs of these command-line tools made long-term observations and results storage difficult.

In this paper, we introduce our Open Source tool HiPerConTracer[3] (High-Performance Connectivity Tracer), which has been developed to overcome the limitations of the setup in [20]. It allows for high-frequency, long-term measurements of Ping and Traceroute among different site and ISP combinations, with the possibility to compress and archive the results in SQL and NoSQL databases. After an introduction to HiPerConTracer, we will present some interesting proof-of-concept results from ongoing long-term measurements in the NorNet Core infrastructure.

II. High-Performance Connectivity Tracing

A. Previous Work and Limitations

Well-known tools for testing network connectivity are `ping` and `traceroute` [23]: `ping` uses the Internet Control Message Protocol (ICMP), i.e. ICMPv4 [24] for IPv4 and ICMPv6 [25] for IPv6, to send ICMP "Echo Request" messages to a destination. The destination's operating system responds with a copy of the request as ICMP "Echo Response". Writing a time stamp into the request allows for computing the packet Round-Trip Time (RTT) between sending the request and receiving the response. `traceroute` sends a sequence of messages to a destination with increasing IPv4 Time-to-Live or IPv6 Hop Limit field. This field is decremented by each router. When it reaches 0, the packet is not routed further but answered with an ICMP "Time Exceeded" error message from the router. By checking the responses, the sender can obtain a trace of all routers passed to reach a destination.

[20] uses the command-line tools `ping` and `traceroute` for a connectivity analysis in the Internet. However, this has the following limitations:

- Running many measurements leads to many invocations of the tools.
- The tools are intended for shell usage. Their results (in plain text form) need to be parsed and processed.
- There is no built-in possibility to simply parallelise independent runs (particularly over different ISPs).

[1]Parts of this work have been funded by the Research Council of Norway (Forskingsrådet), prosjektnummer 208798/F50.

[2]NetPerfMeter: https://www.uni-due.de/~be0001/netperfmeter/.

[3]HiPerConTracer: https://www.uni-due.de/~be0001/hipercontracer/.

- `traceroute` tests IPv4 Time-to-Live/IPv6 Hop Limit settings sequentially, which is very slow.
- Devices limit the number of ICMP responses/error messages per time interval, for security reasons. Too frequent measurements lead to missing responses.
- Load balancing in the Internet is not considered.

The load balancing issue is explained in detail by [26] for their software PARIS TRACEROUTE: load balancing is usually made by hashing the first 4 bytes of the Transport Layer protocol header. For TCP, UDP and SCTP, these bytes contain the port numbers, which can be set appropriately to have the same hashing for all packets of a Traceroute run. They should then take the same route on load balancers. For ICMP, there are no port numbers to adjust. But it has the ICMP message checksum (16 bits, Internet-16 checksum algorithm [27]) within the first 4 bytes. So, by crafting the payload appropriately, the checksum can be kept the same for all packets of a run.

B. HIPERCONTRACER

To overcome the limitations from [20], we developed our Open Source tool HIPERCONTRACER (High-Performance Connectivity Tracer). It has the following features:

- It is written in C++, using the BOOST libraries for platform independence (currently: Linux and FreeBSD).
- The measurement part is implemented as a shared library, i.e. it can be linked into other tools as well.
- Support for multiple source and destination addresses (e.g. one for each connected ISP, and IPv4/IPv6).
- A separate thread per source address is started, allowing to utilise multiple CPU cores.
- Ping runs are made in parallel for each source and destination address.
- Traceroute runs are made in parallel for each source address. But targets are measured sequentially, to avoid routers reaching their ICMP error message limitation.
- The inter-measurement time is slightly randomised by 25%, to avoid synchronised measurements from multiple source systems.
- Traceroute uses ICMP Echo Requests instead of sending UDP messages like the original `traceroute` command, since many firewalls block all UDP traffic.

Similar to PARIS TRACEROUTE, HIPERCONTRACER adjusts the first 4 bytes of the ICMP header to prevent multiple packets of a run being load balanced over different paths. However, in our approach – which we denote as "Oslo Traceroute" – we make further improvements:

- The last measurement's number of hops H_d^s is stored for each destination address d from source address s.
- For the first measurement, H_d^s is set to an initial Time-to-Live/Hop Limit setting Γ (e.g. Γ=5).
- ICMP Echo Requests from s to d are sent with Time-to-Live/Hop Limit from 1 to H_d^s as burst of packets.
- If not reaching the destination after Traceroute timeout Θ (e.g. Θ=2000 ms), send the next up to Time-to-Live/Hop Limit increment Ψ values (e.g. Ψ=5) as burst of packets.
- The previous step is repeated until the destination d has responded or the maximum Time-to-Live/Hop Limit Ω (e.g. Ω=35) has been reached.

By using parallelisation, the Traceroute runs are fast. That is, if H_d^s is known for destination d, the whole Traceroute run from each source address s for Θ=2000 ms just takes 2 s. If the destination is reached via disjoint paths, each router would have to answer only a single packet with ICMP "Time Exceeded" error message. So, there will be no overloading. Since the HIPERCONTRACER packets are small (44 B for IPv4, 64 B for IPv6), congestion is also highly unlikely.

C. Output and Database Import

HIPERCONTRACER produces output in text files, which are on-the-fly compressed with the efficient BZip2 algorithm [28]. In regular intervals (configurable, e.g. every 15 min), HIPERCONTRACER starts a new file, i.e. a crash or power loss will only destroy the currently used one. As a background task, e.g. scheduled by `cron`, the importer script can import the output files' results into a database. Currently, the importer supports the SQL database PostgreSQL and the NoSQL database MongoDB. However, the Python-based importer script could be extended easily with other database backends as well.

III. THE MEASUREMENT SETUP

In the following, we introduce our measurement setup.

A. The NORNET CORE *Infrastructure*

NORNET CORE [21], [22] is the wired-network part of the NORNET[4] infrastructure. It consists of 23 active sites being located in eight different countries. The testbed connects to 17 different ISPs supporting both, IPv4 (total of 41 interfaces) and IPv6 (total of 23 interfaces). Table I provides an overview of the sites and ISP connections. A particularly unique feature of NORNET CORE is that the ISPs not only consist of research networks (like Uninett in Norway or CERNET in China), but there are also consumer-grade connections, like e.g. PowerTech and Telenor Asymmetric Digital Subscriber Lines (ADSL). This allows for experiments where systems experience a "normal" user's quality of service.

B. The HIPERCONTRACER *Service*

On each active site of the NORNET CORE infrastructure, HIPERCONTRACER is deployed as a service on the router connecting to all ISPs of the site. From each site and ISP, HIPERCONTRACER performs a Ping measurement to each other site and ISP every second. Traceroute is run as well; since the destinations are tested sequentially to avoid overload, there is approximately one Traceroute run for each destination around every 10-15 min. As parameters for HIPERCONTRACER (see Subsection II-B), we use:

- Initial Time-to-Live/Hop Limit setting Γ=5,
- Time-to-Live/Hop Limit increment Ψ=5,
- Maximum Time-to-Live/Hop Limit Ω=35,
- Traceroute timeout Θ=2000 ms.

The resulting BZip2-compressed output files are stored on the routers. 5-10 GiB of disk space on a router like for the Simula site (see Table I; it has 4 ISPs, 3 of them also support IPv6, i.e. 7 source addresses in total) are sufficient for several weeks of measurements. We set up a central MongoDB database server to import the results into. Due to the local storage, the uptime of the MongoDB database becomes uncritical. The HIPERCONTRACER service in NORNET CORE is set up as a permanent feature of the infrastructure, i.e. we

[4] NORNET: https://www.nntb.no.

TABLE I
THE NORNET CORE SITES IN 2017

No.	Site	Location (City, Province, Country)	ISP 1	ISP 2	ISP 3	ISP 4
1	Simula Research Laboratory	Fornebu, Viken, Norway	Uninett[F]	Kvantel[B]	Telenor[2,A]	PowerTech[A]
2	Universitetet i Oslo	Oslo, Oslo, Norway	Uninett[F]	PowerTech[A]	Broadnet[1,A]	–
3	NTNU Gjøvik	Gjøvik, Innlandet, Norway	Uninett[F]	PowerTech[A]	–	–
4	Universitetet i Tromsø	Tromsø, Troms og Finnmark, Norway	Uninett[2,F]	Telenor[1,A]	PowerTech[A]	–
5	Universitetet i Stavanger	Stavanger, Rogaland, Norway	Uninett[2,F]	Altibox[A]	PowerTech[A]	–
6	Universitetet i Bergen	Bergen, Vestland, Norway	Uninett[F]	BKK[B]	–	–
7	Universitetet i Agder	Kristiansand, Agder, Norway	Uninett[F]	PowerTech[A]	–	–
8	Universitetet på Svalbard	Longyearbyen, Svalbard, Norway	Uninett[2,F]	Telenor[1,C]	–	–
9	NTNU Trondheim	Trondheim, Trøndelag, Norway	Uninett[F]	PowerTech[A]	–	–
10	Høgskolen i Narvik	Narvik, Nordland, Norway	Uninett[2,F]	PowerTech[A]	Broadnet[1,A]	–
11	Oslo Metropolitan University	Oslo, Oslo, Norway	Uninett[F]	–	–	–
12	Karlstads Universitet	Karlstad, Värmland, Sweden	SUNET[2,F]	–	–	–
13	Hochschule Hamburg	Hamburg, Hamburg, Germany	DFN[2,F]	–	–	–
14	Universität Duisburg-Essen	Essen, Nordrhein-Westfalen, Germany	DFN[F]	–	–	–
15	Lab. Informatique Grenoble	Grenoble, Auvergne-Rhône-Alpes, France	RENATER[F]	–	–	–
16	Hainan University	Haikou, Hainan, China	CERNET[F]	CnUnicom[1,C]	–	–
17	The University of Kansas	Lawrence, Kansas, U.S.A.	KanREN[F]	–	–	–
18	New York University	New York, New York, U.S.A.	Lightower[2,F]	–	–	–
19	Korea University	Seoul, Sudogwon, South Korea	KREONET[2,F]	–	–	–
20	Universität Kaiserslautern	Kaiserslautern, Rheinland-Pfalz, Germany	DFN[F]	–	–	–
21	Universität Darmstadt	Darmstadt, Hessen, Germany	DFN[2,F]	–	–	–
22	Haikou College of Economics	Guilinyang, Hainan, China	CnTelecom[1,B]	CERNET[2,F]	–	–
23	National ICT Australia	Sydney, New South Wales, Australia	AARNet[2,F]	–	–	–

[1] Only IPv4; IPv6 is not available from ISP. [2] Only IPv4; IPv6 available from ISP but not deployed in site's network.
[F] Research network fibre. [B] Business-grade fibre. [C] Consumer-grade fibre. [A] Consumer-grade ADSL.

are continuously collecting data now. In the future, we plan to also make this data available to researchers.

C. Results Analysis Setup

For analysis and plotting of the proof-of-concept results in Section IV and Section V, we used GNU R [29], with DATA.TABLE for data handling and GGPLOT2 for plotting. Furthermore, we used simple geo-location with RGEOLOCATION and the free GEOLITE2 databases[5]. Since geo-location for router addresses is not very accurate in these databases, we also used the HLOC tool [30] to obtain more accurate information. HLOC performs measurements using the RIPE ATLAS infrastructure to measure the RTT to a router from different known vantage points. This is used for approximating a destination's location. For simplicity in our proof-of-concept evaluation, we only took the most-likely location approximation from HLOC. Highly accurate geo-location [31] is out-of-scope for this paper. For Autonomous System (AS) [32] information, we used the list provided by CIDR REPORT[6] and the AS number lookup from the free GEOLITE2 database.

IV. HIPERCONTRACER PING RESULTS

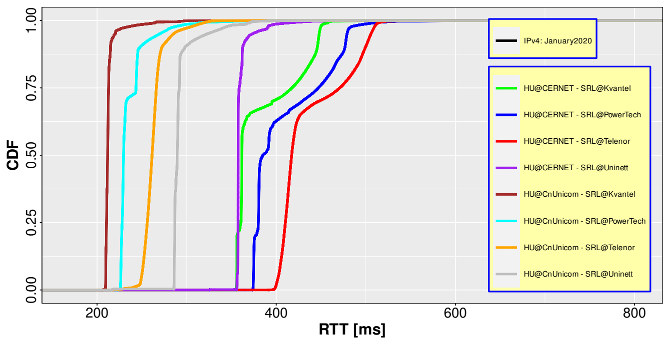
For our proof-of-concept analysis, we extracted the results from our HIPERCONTRACER results database in NORNET CORE from January 1 to 31, 2020 (00:00 to 24:00 UTC) (see Subsection III-B). For analysing the performance of multi-path transport, it is particularly interesting to look at sites with multiple dissimilar ISPs. Of particular interest are of course multi-homed inter-continental connections, as explained in [11], [33]. Figure 1 therefore presents the cumulative distribution function (CDF) of the RTTs for HIPERCONTRACER Ping from Hainan University (HU) in Haikou (Hainan province), China to the Simula Research Laboratory (SRL) site in Fornebu (Viken province), Norway (see also Table I). We split up between IPv4 (Subfigure 1(a)) and IPv6 (Subfigure 1(b)) for better visibility.

It is clearly observable that there is a significant difference between the RTTs of different ISP combinations for IPv4 in Subfigure 1(a): the usual RTT from China Unicom (CnUnicom) at HU (consumer-grade fibre) to Kvantel at SRL (business-grade fibre) is just slightly above 200 ms (dark red curve), while it reaches more than 500 ms for combinations of CERNET (Chinese research network ISP) to Telenor and PowerTech at SRL (red and blue curves; consumer-grade ADSL) as well as up to 450 ms for Kvantel at SRL (green curve; business-grade fibre). Also note the dent around 400 ms. This is caused by significant changes, which we explain below. Note, that CERNET to Uninett at SRL (purple curve; Norwegian research network ISP) does not show this dent. It also has RTTs of around 400 ms. That is, in this scenario, the performance from a research network to another research network is more stable than from a research network to a commercial network. We explain this in more details in Section V.

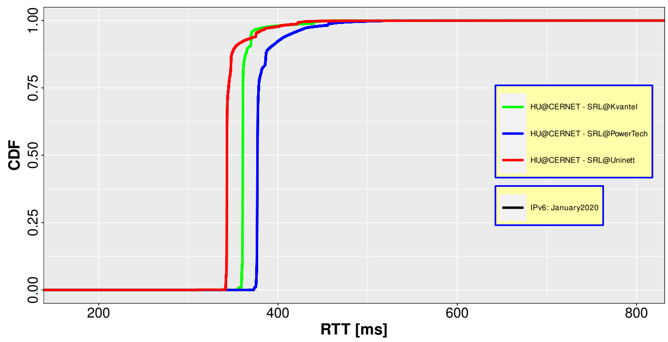
Interesting in this scenario is also a look at IPv6 in Subfigure 1(b): since China Unicom does not support IPv6, there is only CERNET at HU. Also, Telenor at SRL does not have IPv6 support. Compared to IPv4, the RTTs are lower: ca. 350 ms for CERNET to Uninett (red curve; research network to research network), slightly more for CERNET to Kvantel (green curve; business-grade fibre), and around 400 ms for PowerTech (blue curve; consumer-grade ADSL).

While the CDF presents the RTT distribution over the whole month of January 2020, it is also very interesting to look at

[5] GEOLITE2: https://dev.maxmind.com/geoip/geoip2/geolite2/.
[6] CIDR REPORT AS list: https://www.cidr-report.org/as2.0/autnums.html.

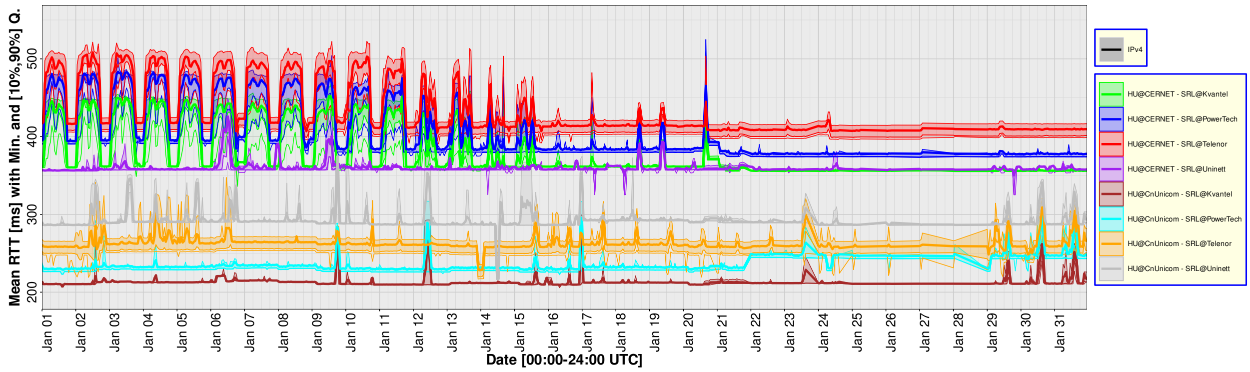


(a) IPv4

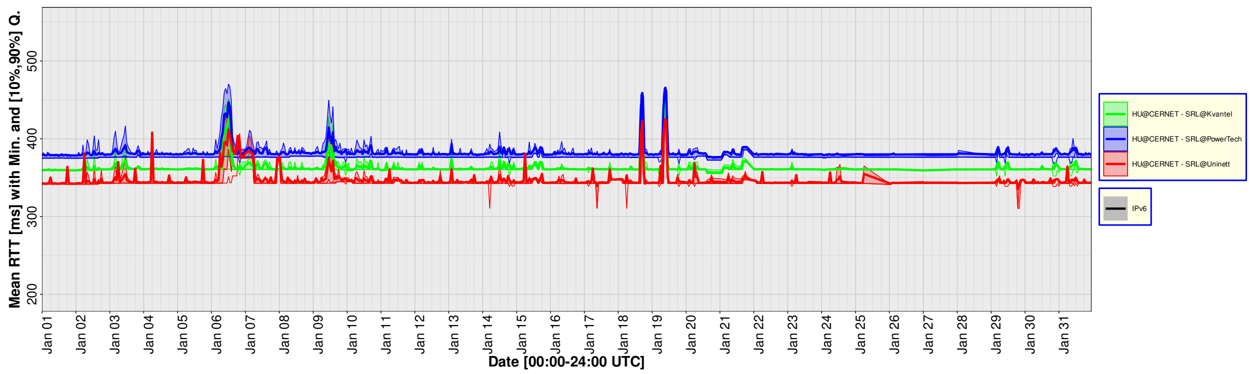


(b) IPv6

Fig. 1. CDF of the RTTs from Simula Research Laboratory (Fornebu, Viken, Norway) to Hainan University (Haikou, Hainan, China)



(a) IPv4



(b) IPv6

Fig. 2. Time Series of the RTTs from Simula Research Laboratory (Fornebu, Viken, Norway) to Hainan University (Haikou, Hainan, China)

the corresponding time series in Figure 2: The plots show the average, 10% and 90% quantiles (darker area), as well as the difference between the minimum RTT and 10% quantile (lighter area) in 1-hour intervals. Again, we split up between IPv4 (Subfigure 2(a)) and IPv6 (Subfigure 2(b)) for improved visibility. Note, that January 2020 contains two public holidays: Western New Year (January 1), and the Chinese New Year/Spring Festival Golden Week holiday period (January 24 to February 2, 2020).

First, is can be seen that there is a daily variation, particularly for the CERNET at HU to Kvantel, PowerTech and Telenor at SRL relations. Note, that time is given in Coordinated Universal Time (UTC), while China Standard Time (CST) is UTC+0800. That is, the RTTs increase between morning and late evening in CST. It is clearly possible to see the usual working times in China, i.e. the results are mainly affected by the underlying Chinese networks (we examine this in more detail in Section V). From around January 12, the RTTs reduce, with significant further reduction from January 22: people at Hainan University start going on Chinese New Year/Spring Festival holiday. This explains the dents seen in Subfigure 1(a). From January 25 (Chinese New Year of the Rat), there is very small variation in the results for *all* ISP combinations. At that time, the university is mostly closed.

Corresponding to the CDF in Subfigure 1(b), the time series for IPv6 in Subfigure 2(b) show much less variation than for IPv4. However, the start of the holiday period around January 22 is still visible. In result, it is clearly observable that the IPv6 performance between HU and SRL is more stable than the IPv4 performance. This may be caused by reduced middlebox activity (e.g. bandwidth limitations, deep packet inspection in the Great Firewall of China, less congestion due to the low number of IPv6 users in China, etc.).

Of course, the most significant impact on the RTT performance is caused by the routing. So, we are going to analyse the HIPERCONTRACER Traceroute results in the following.

V. HIPERCONTRACER TRACEROUTE RESULTS

Figure 3 visualises the routing for the scenario of Section IV. Links seen in the HIPERCONTRACER Traceroute results are distinguished by their AS number. Solid lines mark intra-AS links (within the same AS), while dashed lines mark inter-AS links (different AS, the colour of the source AS is used). Note, that some routers may not respond, i.e. there may be "missing" links (here: e.g. from Moscow and from Singapore), where a link cannot be determined and therefore not be plotted. Routers are shown as circles with the country flag of their geo-location (see Subsection III-C for details about the used geo-location). We only visualise successful Traceroute runs, i.e. the destination at SRL has always been reached.

As stated in Section IV, inter-continental setups – like HU in China to SRL in Norway – are interesting because of their dissimilar paths. In this scenario, packets can either be routed eastwards (from Europe to Asia) or westwards (from Europe via North America to Asia). That is, depending on the ISP combinations, the routes taken by packets can significantly deviate from the optimal beeline flight path (ca. 8,600 km). That is, the choice of direction already sets a lower bound for the RTT of a relation. Furthermore, there are many different combinations observed, e.g. using different trans-Atlantic and trans-Pacific submarine cables. The actual link combinations may change over time, leading to a change of the RTT. While research networks are usually interconnected well with other research networks, which leads to a more stable performance (CERNET to Uninett, see Section IV), there is much more variation when it comes to the combinations with commercial networks (CERNET to PowerTech, Telenor and Kvantel, see Section IV). We are currently analysing this in more detail in ongoing work.

Interesting to see is also that for the connection between China and Norway, many countries and administrative areas are involved. In addition to various countries in the European Economic Area (EEA; seen: Norway, Iceland, Switzerland, United Kingdom) and European Union (EU; seen: Sweden, Denmark, Germany, Netherlands, Austria, Ireland), most routes also include routers in the United States. But routers in Russia, Singapore, Japan, Indonesia, Vietnam and Hong Kong (special administrative region of China) have been observed as well. An interesting part of ongoing work is therefore to analyse more details about the countries and regions affecting the routing in the Internet.

In summary, particularly with respect to multi-path transport protocols like MPTCP, CMT-SCTP or Multipath-QUIC, there are obviously very dissimilar and changing path characteristics in multi-homed Internet setups. For better understanding of these characteristics, more detailed research is necessary. HIPERCONTRACER, and also the data already collected in the NORNET CORE infrastructure, can therefore provide very helpful insights for the ongoing and future research.

VI. CONCLUSIONS AND FUTURE WORK

Multi-path transport, e.g. with MPTCP, CMT-SCTP or Multipath-QUIC, is becoming increasingly important. While there has already been a lot of work on the Transport Layer aspects, such as congestion control, path and buffer management, etc., there is little work on the Network Layer perspective, yet. In this paper, we introduced our Open Source tool HIPERCONTRACER, which performs high-performance continuous measurement runs of Ping and Traceroute between multi-homed systems. HIPERCONTRACER is now running as a permanent feature in the NORNET CORE infrastructure. As a proof-of-concept for HIPERCONTRACER, and to illustrate the characteristics of the underlying networks used for multi-path transport research in NORNET CORE, we examined the connectivity between multi-homed sites in China and Norway. Particularly, we illustrated the differences of connection characteristics between research network ISPs, as well as in mixed combinations with commercial ISPs. Furthermore, we showed differences between IPv4 and IPv6. In ongoing and future work, we are going to evaluate the performance and routing behaviour of multi-homed sites in more detail, using the long-term measurement data collected by the HIPERCONTRACER service in NORNET CORE. Of particular interest is also a combination with Transport Layer performance evaluation, e.g. by measurements with our Open Source tool NETPERFMETER [18], [19], [1, Section 6.3]. For a more detailed analysis of the HIPERCONTRACER Traceroute results, we are furthermore working on improving the accuracy of the geo-location [31]. Finally, we are working on further HIPERCONTRACER performance enhancements by utilising the Data Plane Development Kit (DPDK) for packet processing.

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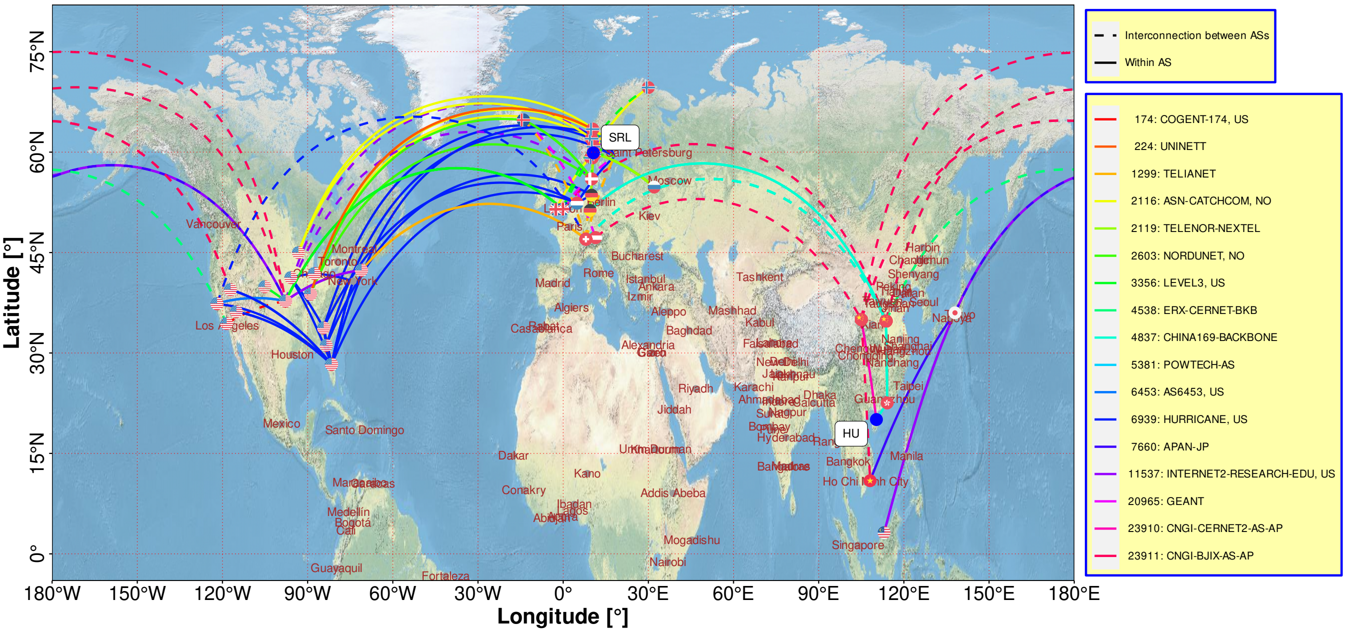

Fig. 3. Autonomous Systems (AS) from Simula Research Laboratory (Fornebu, Norway) to Hainan University (Haikou, Hainan, China)

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