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Milestone M6.10 (M56)
Evaluation of Planned Network Technology Experiments and Potential for Use by the GÉANT Community

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Abstract
This document reports on the technologies evaluated by GN4-3 WP6 T1 to assess their applicability in R&E use cases in the GÉANT and NREN community.

Table of Contents

Executive Summary 1

1 Introduction 2

2 Network Latency and Jitter Monitoring Supporting Low-Latency Applications 3

3 White Box for Research and Education (WB) 5

4 Router for Academia, Research and Education (RARE) 6

5 Data Plane Programming (DPP) 8

6 Optical Time and Frequency Network (OTFN) 10

7 Quantum Key Distribution and Exchange (QKD) 11

8 Conclusions 13

References 15

Glossary 17

Table of Figures

Figure 2.1: TimeMap screenshot showing periodic latency spikes 3

Figure 4.1: R&E use case anatomy according to the position of the router/node in the network 6

Figure 5.1: View of INT monitoring dashboard developed by DPP subtask 9

Executive Summary

As part of the GN4-3 project, the Network Technology Evolution task (Task 1) of the Network Technologies and Services Development work package (WP6) has assessed several technologies from the perspective of their importance and applicability in the NREN environment and use cases of interest to the GÉANT R&E community. The specific areas that were selected for exploration by the project include tools to support Low Latency network transmission and real-time applications (e.g. LoLa), the use of White Box technology for R&E (WB), the open-source Router for Academia, Research and Education (RARE) platform, Data Plane Programming (DPP, including the use of P4), Optical Time and Frequency Networks (OTFN) and Quantum Key Distribution and Exchange (QKD).

Some of the tools and solutions developed in the LoLa support, WB, RARE and OTFN work areas are sufficiently mature to be implemented in production. Support for LoLa is provided in the form of a network latency and jitter monitoring solution, while DPP was evaluated through the in-band network telemetry (INT) use case, with a focus on prototyping the measurement architecture and gaining deeper knowledge and understanding of practical deployment challenges as well as measurement results. Quantum technologies are at a very early development stage in the network communication domain with very few vendors making such products commercially available. However, QKD is seen as a potential first use case as quantum communication devices are just beginning to appear on the market.

This document summarises the results of WP6 T1's work and provides recommendations on how these various technologies could be used or implemented in an NREN context.

1 Introduction

This document reports on the technologies evaluated by GN4-3 WP6 T1 to assess their applicability for R&E use cases in the GÉANT and NREN community.

Each of the areas investigated is addressed in a separate document section, as follows: 2 Network Latency and Jitter Monitoring Supporting Low-Latency Applications; 3 White Box for Research and Education; 4 Router for Academia, Research and Education (RARE); 5 Data Plane Programming (DPP); 6 Optical Time and Frequency Network; and 7 Quantum Key Distribution and Exchange

Finally, some conclusions for implementing these technologies in an NREN context are given in Section 8.

2 Network Latency and Jitter Monitoring Supporting Low-Latency Applications

The work on supporting Low Latency network transmission and real-time applications is focused on developing a monitoring solution for networks over which real-time applications are run. An example of such an application is the LoLa audio-visual streaming system (lola.conts.it) used by performing arts communities. By monitoring latency and jitter, network operators can identify optimal low-latency, low-jitter paths through their network and detect changes in latency and jitter over time.

For this purpose, the WP6 T1 team has created TimeMap (timemap.geant.org[1]), an open-source tool that measures and visualises latency and jitter on the GÉANT backbone. TimeMap is based on the TWAMP protocol and is implemented as a segment-by-segment solution, run between adjacent routers in the network. The use of TWAMP measurements between router devices requires no additional monitoring hardware to be deployed. Although this particular implementation is vendor specific, TWAMP is an open standard supported by many platforms, and thus the approach implemented can be applied to other networks. TWAMP is also supported by perfSONAR (perfsonar.net).

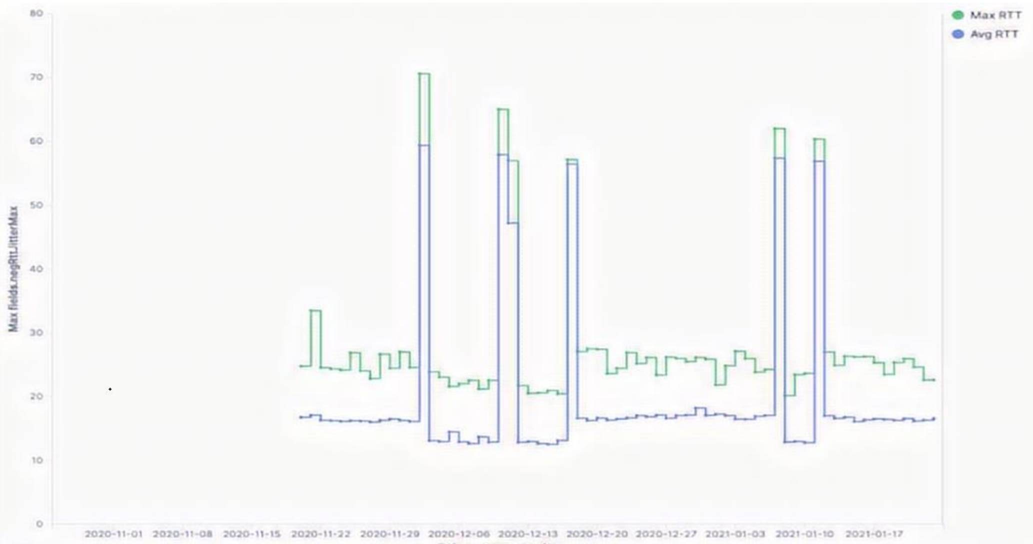

Figure 2.1: TimeMap screenshot showing periodic latency spikes

Figure 2.1 demonstrates the benefits of the TimeMap tool. The historic latency measurements on one backbone segment show some regular and long-lasting changes in Round-Trip Time (RTT); these are likely due to a re-routing happening on the circuit itself, which causes short periods of latency disruption. This might not be crucial for regular data transport and will likely go unnoticed by fault-

[1] TimeMap is accessible via eduGAIN authentication

focused monitoring tools but can significantly impact real-time applications and their performance. Noticing such behaviour on TimeMap can help network operators to focus their troubleshooting efforts in the right direction.

Such monitoring is likely to be of value to a wide range of NRENs given that most of them have users and communities who make use of real-time applications such as LoLa. The tool is also being adopted by the GÉANT Operations team, who plan to make it accessible to all NRENs. Although, as stated above, the current solution is vendor specific (using the TWAMP implementation on the GÉANT backbone routers) and the NRENs may have different backbone equipment and vendors, the principles that TimeMap is built upon can be ported to other platforms, and the WP6 T1 team is available to provide advice and guidance in this area.

3 White Box for Research and Education (WB)

A white box (WB) is a networking device based on commodity components that can run different network operating systems. First deployed widely in data centres, white boxes offer a rich set of features at a very low price and are now available for research and education (R&E) use cases. The advantage of white boxes is that it is possible to select which features from their network operating system (NOS) will be provided, and thus create a tailor-made solution dedicated to a specific use case. Most of the NOSs evaluated as part of this work were very easy to use as they resembled those provided by well-known traditional vendors.

White box technology allows NRENs to become more independent from router vendors and has the potential to change the way they manage their network deployments. Although vendors might react to such competition by adjusting their pricing and feature sets to regain an advantage on the market, the experience gained by an NREN in setting up a tailor-made solution can help them better understand their specific use case requirements, as well as their network's performance possibilities and characteristics.

WP6 T1's work was focused on real NREN use cases from the perspective of their implementation in production networks, while also considering Total Cost of Ownership (TCO) as well as performance characteristics and limits.

The following use cases have been investigated:

- NREN backbone: P/LSR router
- CPE/CE (customer premises equipment)
- Global Internet eXchange (GIX)
- Data centre/Cloud fabric

Two use cases – CPE and GIX – have been implemented in RENATER in production and described in white papers [CPE], [GIX], while the data centre/cloud fabric solution is in the pre-production phase. A TCO analysis has been performed for a CPE use case [TCO] and a template for TCO calculation is provided [TCOxls]. Network performance considerations and validations are summarised in [WBperf], providing a model for white box testing and performance verification that considers hardware and software platforms of a given white box device first separately and then jointly, using as a reference the RFC benchmarks [RFC2544], [RFC2889], [RFC3918].

The work on white box evaluation for the R&E community has thus explored methodology and approaches in testing and validation and has demonstrated real production use cases that are implemented in European NREN environments.

4 Router for Academia, Research and Education (RARE)

The Router for Academia, Research and Education (RARE) is an open-source routing platform that combines an open-source network operating system [FreerTr] with a P4 or DPDK data plane (plus virtual data plane bmv2). It is a performant, flexible routing platform that can easily and quickly be adapted and used for a variety of research and production use cases, on low-cost hardware such as the 32x100G Edgecore Wedge. Being fully configurable, RARE allows rapid development and automated testing of new protocols and features, either to be used by researchers for testing their own protocols or in a real production network. RARE supports a virtual target (bmv2 software switch), a hardware P4 Programmable Ethernet ASIC (Intel® Tofino™ - WEDGE-BF100-32X), and DPDK hardware.

A RARE node can be used as a core, aggregation or edge device as shown in Figure 4.1.

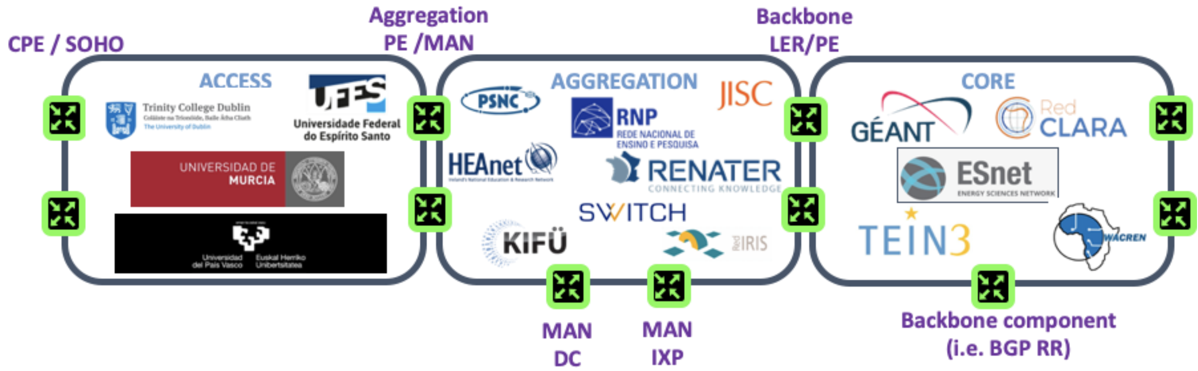

Figure 4.1: R&E use case anatomy according to the position of the router/node in the network

RARE can also be used as/for:

- Route Reflector on a virtual or bare metal server
- Source routing for R&E networks
- IP network telemetry
- Bit Index Explicit Replication (BIER) Multicast forwarding using encapsulation for MPLS and Ethernet
- Multidomain networking architectures, as used by GNA-G and Caltech University.

Additionally, RARE can be used for:

- Global research projects, for evaluation of networking and/or protocol features, usually including large volume and bursty traffic generators and/or sensors and in combination with a production network. An example of such use has been by the PolKa project (Source routing in P4 networks using Polynomials) [PolKA]; PolKA demonstrated the concept by using the GÉANT P4 lab and was awarded the best research scholar program award by Google in the network category [Google Academy];

- Regional, campus network and education/school connections – seen more often today in NRENs as part of the digital transformation strategy led by governments, where RARE can provide a specific feature set tailored to each use case. In such a setup, RARE can be used as:
  - High speed (10/100Gbps) border router on bare metal and P4 hardware
  - Small routers for schools: CPE on platforms similar to Dell VEP hardware

In order to demonstrate the functionalities of RARE and thus its value for researchers and the community, the GÉANT P4 lab (GP4Lab) was created, with four P4 switches running the RARE/FreerTr software connected at GÉANT backbone network PoPs. The lab is also made available for researchers to test their P4-based programs and protocols, such as the PolKA project, and its use can be scheduled using [NMaaS], which is also used for monitoring and management of the GP4Lab platform.

RARE can considerably reduce the cost of a routing solution, e.g., for NRENs looking for a lower cost in terms of price per bandwidth per port. The combined RARE/FreeRtr open-source platform provides a networking "Swiss Army Knife" solution based on the P4 language. New targeted devices such as FPGA and Intel Tofino chipsets alongside technology such as DPDK or RDMA have the potential to unlock the door to exciting new use cases. The control plane FreerTr [FreerTr DOC] and the data plane RARE [RARE DOC] are well documented, while the RARE blog [RARE BLOG] helps users to make a start on their deployment, providing descriptions of implementations for concrete use cases.

5 Data Plane Programming (DPP)

The goal of the Data Plane Programming (DPP) sub-task is to assess the potential benefits and capabilities that may be enabled by the disaggregation of traditional components of the network in the routing elements. Some recent chipsets are capable of accepting high-level programming in the handling of bit flows, using dedicated languages such as P4. White box hardware supporting such languages is increasingly available, giving the benefits described in the previous section. Such hardware can also permit real-time processing of bits in packets beyond what is possible on more traditional network equipment. It can also facilitate more complex decision-making and analysis within the network. The DPP team has focused its effort on two initial use cases through a dedicated testbed running over production NREN network environments [2]:

1. Detection of distributed denial of service (DDoS) attacks.
2. Detailed packet monitoring by in-band network telemetry (INT).

The security use case allowed the analysis of the boundaries of the capabilities of data plane network programming, which need to be considered when engineering any general DPP use case. The main constraints identified were available memory, number of cycles for each packet, complexity of the algorithm and data structures. The results of a specific hardware platform (Tofino) are reported in an article written by the DPP sub-task within WP6 T1 [DPP_DDoS]. Currently, with the hardware and algorithms used, the performance was found not to be adequate for production use at line rates over 1Gbps, so this effort was parked and the focus switched to the second use case.

The second use case, In-band Network Telemetry (INT) [INT_WIKI], offers the potential to extend traditional monitoring capabilities by increasing their level of granularity, for example focusing on a specific set of characteristics in a packet or frame, for each switch traversed and capable of providing INT information. INT is like a magnifying glass that allows network engineers to identify events that were previously unknown to them, as shown in Figure A3, and can be used in synergy with local statistics according to user requirements, for example to send INT data when a specific trigger event occurs or to send data at a specific interval.

Figure 5.1 shows an example of data provided by INT on five minutes of UDP traffic between PSNC and CESNET.

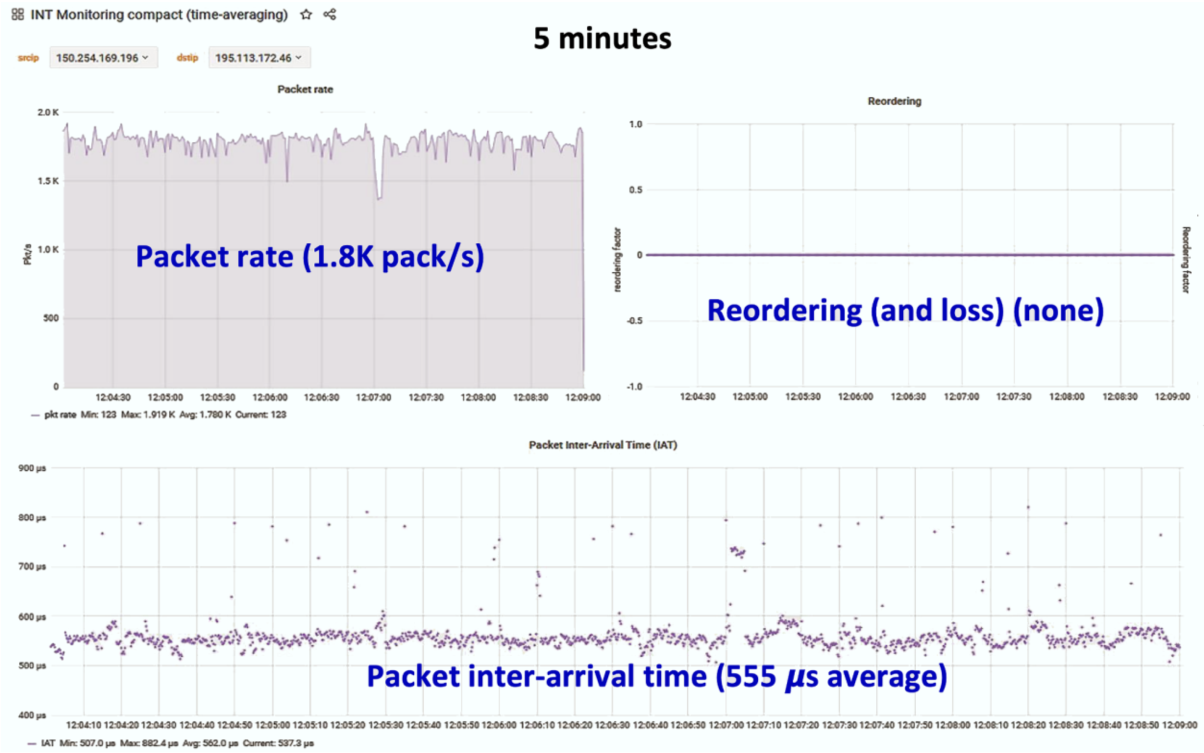

Figure 5.1: View of INT monitoring dashboard developed by DPP subtask

As a part of this work, the DPP team has set up a testbed that spans three production NREN networks (CESNET, PSNC and FBK/GARR). The INT P4 code used for testing has been made publicly available for various platforms (FPGA, Tofino, Virtual node BMv2) and is being extended to DPDK [INT_CODE] [INT_VIS].

The code can be used as a standalone tool that can be implemented on demand, in multiple platforms, in a research as well as in a production environment. INT operational considerations and implementation specifics are presented in a white paper [DPP_INT] and infoshare [INT_Infoshare]. The INT functionality can be used to debug high-speed network behaviour and issues as well as contribute to greater understanding of network baselining and behaviour. Overall, as DPP enables fine-tuning in the gathering of data and information from and about the network; it can help researchers and network operators gain a better understanding of their networks and network services, with a focus on targeted use cases that are of particular interest to them.

6 Optical Time and Frequency Network (OTFN)

The success of the first, early deployments of time and frequency (T&F) services over optical links has triggered additional interest for T&F signals distribution over the existing NREN infrastructures, primarily from European National Metrology Institutes (NMIs) as well as from organisations from the GÉANT and NREN communities. Together with the interest for transmission of T&F services, some NRENs with sufficient optical infrastructure are looking for ways to use their fibre infrastructure more efficiently and to include additional non-IP services and new applications, including T&F and quantum services.

The diversity of existing techniques (optical carrier, radio frequency modulation, White Rabbit, etc.), setup choices (dark fibre, dark channel, unidirectional, bidirectional) and wavelength (S-Band, C-Band, L-Band) that might have brought agility and adaptability to more traditional services, has on the contrary resulted in the lack of a unique and easily implementable single compatible solution for all NRENs. Due to the variety of existing scenarios, use cases, user demands and constraints, different organisations are choosing solutions that differ in technique, setup or wavelength bands, thus impacting both the need as well as the possibility for interconnectivity and collaboration.

Given that there is no one-size-fits-all OTFN solution, the focus of the OTFN WP6 T1 team has been on helping to increase understanding of existing use cases, solutions and best practices, in order to provide sufficient information for organisations or individuals – researchers and/or network engineers – who are just starting their journey towards deploying their own OTFN services. Knowledge and experience have been shared through dissemination activities which include an infoshare [OTFN Infoshare] and a white paper [OTFN], as well as regular meetings with community members interested in optical T&F techniques, methodologies and solutions.

Even though the transmission of T&F services over optical infrastructure is relatively new and still under development, some solutions have been implemented in production networks long enough for their operators to have gained good operational experience of them. On the one hand, this means that there is a known and proven model of how such services can be introduced in a network, with good examples such as those from the NRENs in the WP6 T1 OTFN team. On the other hand, the diversity of the existing solutions requires a thorough analysis of the use cases and user groups for a given NREN in order to ensure that the design of their future OTFN network is steady and sustainable.

7 Quantum Key Distribution and Exchange (QKD)

The objective of the QKD subtask is to assess the potential implementation of quantum cryptography within GÉANT and NREN infrastructures. Quantum technologies are still developing and even though several vendors are working on solutions to be implemented in production networks, very few have commercial products ready. Interest in quantum technologies is growing In the GÉANT community, from the researchers to the NREN operational teams that are considering providing quantum technologies and services – especially quantum key distribution and exchange in their networks.

Given that quantum technologies – as well as awareness of and readiness for them in NRENs – are not sufficiently mature yet, the QKD WP6 T1 team has focused on gathering and building the community around these topics, sharing knowledge and expertise and encouraging discussion around use cases and design considerations. A survey conducted in 2020 highlighted which NRENs are either already involved in early quantum projects or include quantum technologies in their short-term plans; as a result, the initial team has been extended with new members from some of these NRENs.

As a starting point, a white paper was published [QKDWP] describing the principles of current quantum technologies, including services, use cases, projects, initiatives and challenges, and the status of such work in a number of NRENs. It also covered technology testing opportunities, initiatives and strategies for the GÉANT and NREN communities. In addition, two infoshares were held, the first [QTinfo] on the principles, challenges and applications of quantum technologies, and the second [QKDInfo] on the practical implementations, challenges and R&E use cases of quantum key distribution and the outlook for its standardisation.

Considering the limited availability of production-ready QKD equipment, the WP6 T1 team is exploring quantum simulators to verify how their use might help NRENs in better understanding the technology, use case solutions and design requirements for future implementation of quantum technology solutions in their networks. Two simulators are being tested:

- QuISP (Quantum Internet Simulation Package) – A C++ based open-source quantum network simulation package optimised for repeater/router software development that allows simulation of large-scale networks [QUI2020], [QUIGIT], [MAT2019].
- QKDNETSIM (Quantum Key Distribution Network Simulation Module for NS-3) – a QKD simulator intended to provide additional understanding of QKD technology with respect to existing network solutions [MEH2017], [QKD2020].

More information about other simulators available today is included in the white paper [QKDWP].

In addition, several NRENs have already established close relationships with QKD development companies and teams. Apart from closely monitoring the progress of quantum solutions development, NRENs have helped with equipment testing. A plan for a proof of concept of quantum key exchange between two quite distant GÉANT PoPs is being drawn up in collaboration with Toshiba and the Open

QKD project. The team is continually focused on developing possible QKD designs and solutions for the GÉANT environment and community.

The WP6 T1 QKD team welcomes further collaboration and discussions with other NRENs to share knowledge and better understand how they are approaching the deployment of quantum services in their network, and to share best (current) practices and thus help NRENs to better prepare to provide quantum services in their environments.

8 Conclusions

GN4-3 WP6 T1 has been evaluating a range of technologies to assess their applicability and readiness for deployment in R&E use cases across the GÉANT and NREN network infrastructure. The observed technologies are at different stages of maturity. Some are candidates for a production service, others are at a level where further testing and piloting is now appropriate, while others still are earlier stage technologies that would benefit most from coordinated information gathering and community building. The work done by the teams in WP6 T1 has supported all levels of activity, i.e., development of candidate production services, the testing and piloting of technologies in the R&E context and driving and facilitating knowledge exchange of early-stage technologies.

The TimeMap tool developed by the LoLa team that provides per-segment latency and jitter measurements of the GÉANT backbone network is at production-grade level and is being implemented by the GÉANT operations team, with ongoing discussions with NRENs about providing similar functionality in their networks. This tool is a good complement to standard monitoring tools that are more focused on fault than performance management, which makes it valuable for both network operators and users of real-time applications sensitive to networking delay and jitter. Based on the zero-footprint monitoring approach and providing the option of using widely accepted tools, the TimeMap tool is easy both to implement and use.

The exploratory work carried out to evaluate the applicability of white box technology for the GÉANT community has yielded several products, some of which are being implemented by NRENs in production environments. White box-based customer premises equipment (CPE) and an Internet exchange point (IXP) are implemented in production in RENATER. Data centre and P/LSR white box solution evaluations are in progress. White box devices are evaluated from the perspective of their performance characteristics, and a total cost of ownership (TCO) analysis is performed for the CPE use case. Overall, it can be concluded that production white box solutions could have a place in NREN networks with the advantages they bring in terms of low price and independence from network device vendors, with a possible disadvantage being that some care needs to be taken to ensure the right hardware and software configuration is chosen to be suitable for a specific use case.

Of particular interest is the approach to white box implementation used in RARE – the Router for Academia, Research and Education project – where an open-source control plane (FreerTr) and a P4/DPDK data plane have been integrated into a high-performance, flexible routing operating system (ROS). The RARE ROS provides a significant number of functionalities and is suitable for many use cases, as a core network device, a special-case device, or as a research platform for testing newly developed protocols. RARE has attracted considerable interest worldwide and is the subject of ongoing and increasing collaboration, particularly in the P4 community.

The usefulness of data plane programmability (DPP) has been explored in the cases of DDoS detection and in-band network telemetry (INT). While the assessment of DDoS detection highlighted challenges in performance for the algorithm and approach used at speeds over 1Gbps, the work on In-band Network Telemetry (INT) was more promising, with successful testing at higher rates being run across production NREN infrastructures. This new capability to monitor the network in fine detail brings additional questions about issues such as time synchronisation and dealing with the potentially very large volumes of gathered data, including their storage, analysis, interpretation, etc. Although the P4 code used in these tests is made available for use as open source, more work is needed in order to clarify all aspects necessary for production.

Time and Frequency services are already implemented in production in several NRENs. Current implementations differ in terms of technology, design approaches, required precision and the targeted user groups, which prevents the possibility of adopting a single uniform solution across Europe. Therefore, the WP6 T1 OTFN team has documented examples of specific solutions implemented in NRENs and supports and encourages discussions and the exploration of options towards reaching a more common consensus on European time and frequency distribution and exchange services.

Quantum technologies are attracting a high level of interest, even in their currently relatively early stages of development. Of several quantum technology use cases that are recognised as having the potential to be implemented in production, quantum key distribution and exchange (QKD/E) is the first quantum service to show developments towards that stage. Since this technology and the related production-grade solutions are still "under construction" and what little hardware is available is very expensive, the main emphasis of the WP6 T1 QKD team's work was to raise awareness in the community of the technology and its applicability, as well as of the interest in quantum services for our end users. This was achieved through sharing knowledge and simulations and exploring the possibilities for a proof of concept, as well as through focus-group discussions and infoshares.

The evaluated technologies presented in this document cover only part of the work done in the Network Technologies and Services Development work package. More information on the activities of WP6, including further details on the work summarised here, is available on the NETDEV wiki page [NETDEV].

References

[CPE] "White Box CPE" https://www.geant.org/Resources/Documents/GN4-3_White-Paper_CPE_Router.pdf

[DPP_DDoS] "In-Network Volumetric DDoS Victim Identification Using Programmable Commodity Switches", Damu Ding, Marco Savi, Federico Pederzolli, Mauro Campanella, Domenico Siracusa Accepted by IEEE Transactions on Network and Service Management Special issue on Latest Developments for Security Management of Networks and Service, April 2021 https://arxiv.org/abs/2104.06277

[DPP INT] "In-Band Network Telemetry Tests in NREN Networks" - https://www.geant.org/Resources/Documents/GN4-3_White-Paper_In-Band-Network-Telemetry.pdf

[FreerTr] http://www.freertr.net/

[FreerTr_DOC] FreerTr control plane documentation http://docs.freertr.net/

[GIX] "GIX Implementation Based on White Box" https://www.geant.org/Resources/Documents/GN4-3_White-Paper_White_Box_GIX.pdf

[Google_Academy] https://research.google/outreach/research-scholar-program/recipients/

[INT_CODE] https://github.com/GEANT-DataPlaneProgramming/In_band_telemetry_bvm2 **[INT_WIKI]** https://wiki.geant.org/display/NETDEV/INT

[INT_VIS] https://github.com/GEANT-DataPlaneProgramming/In_band_telemetry_visualisation

[LoLa] https://lola.conts.it/

[MAT2019] Simulation of a Dynamic, RuleSet-based Quantum Network, https://arxiv.org/abs/1908.10758

[MEH2017] Implementation of quantum key distribution network simulation module in the network simulator NS-3, https://link.springer.com/article/10.1007/s11128-017-1702-z

[NETDEV] https://wiki.geant.org/display/NETDEV/

[NMaaS] https://nmaas.eu/

[OTFN] Distributing New Performant Time and Frequency Services over NREN Networks, https://www.geant.org/Resources/Documents/GN4-3_White-Paper_Time_and_Frequency.pdf

[OTFN_Infoshare] GÉANT Infoshare: European Time and Frequency Services - Principles, Challenges and Use Cases, https://events.geant.org/event/451/

[PolKA] PolKA: Polynomial Key-based Architecture for Source Routing in Network Fabrics, https://ieeexplore.ieee.org/document/9165501

[QKD2020] QKDNETSIM, Quantum Key Distribution Network Simulation Module for NS-3, https://www.qkdnetsim.info/

[QKDInfo] Quantum Key Distribution - Practical Implementation, Challenges, R&E Use Cases and Standardisation outlook – https://events.geant.org/event/453/; https://youtu.be/Bg1vZQ_arOY

[QKDWP] *Quantum Technologies Status Overview,* https://www.geant.org/Resources/Documents/GN4-3_White-Paper_Quantum-Technologies-Status-Overview.pdf

[QTinfo] Quantum Technologies - Principles, Challenges and Applications https://events.geant.org/event/453/, https://youtu.be/eZN41xyfUr4

[QUI2020] https://github.com/sfc-aqua/quisp

[QUIGIT] QuISP - Quantum Internet Simulation Package, https://aqua.sfc.wide.ad.jp/quisp_website/

[RARE_BLOG] RARE blog https://wiki.geant.org/pages/viewrecentblogposts.action?key=RARE

[RARE_DOC] RARE data plane documentation https://wiki.geant.org/display/RARE/Home

[RFC2544] *Benchmarking Methodology for Network Interconnect Devices*, S. Bradner, J. McQuaid, IETF RFC 2544, March 1999.

[RFC2889] *Benchmarking Methodology for LAN Switching Devices*, R. Mandeville and J.Perser, IETF RFC 2889, August 2000.

[RFC3918] *Methodology for IP Multicast Benchmarking*, D. Stopp, B. Hickman, IETF RFC 3918, October 2004.

[TCO] "White Box Total Cost of Ownership", https://www.geant.org/Resources/Documents/GN4-3_White-Paper_White-Box-TCO.pdf

[TCOxls] "TCO Calculator spreadsheet", https://www.geant.org/Resources/Documents/TCO-Calculator.xlsx?web=1

[TimeMap] https://timemap.geant.org/ (accessible via eduGAIN authentication)

[WBperf] "White Box Performance Testing and Evaluation", https://www.geant.org/Resources/Documents/GN4-3_White-Paper_White-Box-Testing-and-Evaluation.pdf

Glossary

BIER	Bit Index Explicit Replication
CPE	Customer premises equipment
DDoS	Distributed Denial of Service
DPDK	Data Plane Development Kit
DPP	Data Plane Programming
FPGA	Field-programmable gate array
INT	In-band Network Telemetry
IXP	Internet Exchange Point
LoLa	Low Latency audio visual streaming system
NMI	National Metrology Institute
NOS	Network operating system
NREN	National Research and Education Network
OFTN	Optical Time and Frequency Network
P/LSR	Provider/Label Switch Router
PoP	Point of Presence
QCI	Quantum Communication Infrastructure
QKD	Quantum Key Distribution
RARE	Router for Academia, Research and Education
RDMA	Remote Direct Memory Access
ROS	Routing operating system
RTT	Round-Trip Time
T&F	Time and Frequency
TCO	Total Cost of Ownership
TWAMP	Two-Way Active Measurement Protocol
UDP	User Datagram Protocol