Dark Fibre Facilities for Research and Experimentation

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Abstract—**This paper introduces the Czech National Research and Educational Network called CESNET2 and especially experimental facility. The paper also addresses a necessity of full access to the physical layer in experimental networking. Furthermore it summarizes research and experimental achievements and resources available for experimentation and formulates suggestions for the future international cooperation.**

Keywords-photonic testbed; experimental facility; photonic networking; open design; lightpaths to dispersed users; Fiber-to-the-x (FTTx) networks; user's involvement in testbeds

I. Introduction

CESNET, association of legal entities, is a National Research and Educational Network (NREN) operator in the Czech Republic. Members of CESNET are all public universities and Academy of Science. The association operates NREN called CESNET2 and Experimental Facility (EF). CESNET win competition organised by Ministry of Education, Youth and received National Research Plan "Optical NREN and Its New Applications" ending in year 2010 [1]. In preparation and realization of this plan, new concepts have been developed, especially:

- CEF (Customer Empowered Fibre networks), [2-6, 15]
- NIL (Nothing In Line), [7 - 8]
- CBF (Cross Border Fibre), [9 - 11]
- Dark Fibre Experimental facility (open wide area field testbed), [12 - 13]
- Family of Open Photonic Devices for network research, design and operation, [2, 4, 16]
- LTTx (Lightpaths To The x), [14].

Concepts above proved to be very important in testing of new network features and services and are expected to be very helpful in a wide area experimental evaluation of other Future Internet ideas.

This paper summarizes achievements and resources available for experimentation on the physical layer and formulates suggestions for the future international extension.

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II. CESNET Experience in Experimental Networking

CESNET has a rather extensive experience in building and operating experimental facility (or former testbeds). It started back in 2001, as a dark fibre testbed with real dark fibre lines and some fibre reels. The testbed was connected to NetherLight, Amsterdam (the first international lambda exchange point of Global Lambda Integrated Facility (GLIF)) in the beginning of 2003 with the 2.5 Gb/s link and the Czech Republic became the official associate member of GLIF in 2004. Since then more both dark fibre lines and fibre reels have been added to the original testbed and this upgraded testbed has been used for pilot testing and deployment of new types of the optical equipment developed by CESNET (amplifiers, switches) and the commercial equipment (routers, Ethernet switches) [4], [5], [6]. For GLIF access services, the testbed had to be upgraded because more applications started to utilize its capabilities and the link to NetherLight was upgraded to 10 Gb/s in 2004 (1.9.2004) and the testbed had become more CESNET Experimental Facility than only a testbed. In December 2006, CESNET was connected to StarLight in Chicago with another 10 Gb/s link.

A. Experimental Facility Utilization

We believe that a testbed (and experimental facility later) based on dark fibres can provide very valuable services for different users (researchers, vendors for interoperability tests). Such a testbed can serve as a real network or service. With respect to researches cycles and its support, CESNET Experimental Facility has provided to be very useful and more than 15 prototypes of the new optical equipment have been tested and then operated as pilot phases of practical deployment [17], [18].

What we have observed is a situation when users of the testbed are unaware of resources which can be provided. It is clear that something has to be done to motivate and encourage our users to exploit all possibilities of our future testbeds.

The CESNET Experimental Facility (EF) is shown in Figure 1. The EF uses 740 km of dark fibre, connected to the CESNET2, ACONET (Austria), PIONIER (Poland) and SANET (Slovakia) NRENs, to the GLIF and GÉANT2 lambda services system. GÉANT2 project serves European research and education community, for details see [32]. Open photonic n x 10 Gb/s Dense Wavelength Division Multiplex (DWDM) transmission systems are used in the EF.

The CESNET experimental facility is used for testing in real environments those things that are difficult to simulate in the laboratory (for example higher optical impairments, unstable Polarisation Mode Dispersion (PMD), different span lengths, remote monitoring and management, Out of Band (OOB) management, different housing environments offered by non-telecom fibre providers, and so on). One important purpose of field testing is to assure all partners of the functionality, reliability and serviceability of new technology. Some of the CESNET EF dark fibre lines are used to carry CESNET2 traffic for the purpose of evaluating open photonic DWDM transmission systems so these could be considered to be a long-term part of the CESNET2 network.

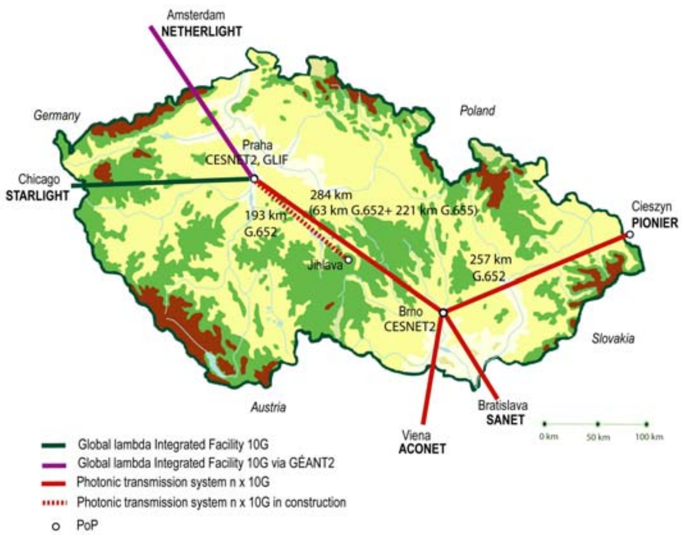

Figure 1. CESNET Experimental Facility

B. *Operational Networks*

CESNET2 is the network that serves the Research and Education community in the Czech Republic, using 4,700 km of fibre lines (including 980 km of single fibre lines). Coverage is rather high, given the size of the country and the population numbers. In addition to the Cisco 15454 MSTP n x 10 Gb/s DWDM transmission systems, nine lines (including two single fibre lines) in CESNET2 are lit by open photonic n x 10 Gb/s DWDM transmission systems, while six other lines will be lit in the second half of 2008 (including 4 single fibre lines). 10G transmission to Bratislava and Wien is realised by using experimental facility dark fibres and open photonic n x 10 Gb/s DWDM transmission systems. More details are available (see for example [30]).

Interoperability on the photonic layer was achieved (10 Gb/s rate wavelengths can go from one transmission system to another without Optical-Electrical-Optical (OEO) conversion). There is of course a limit to optical reach (now about 1000 km), but this value will be improved. Interoperability on the photonic layer was achieved due to the intrinsic adaptability of open photonic devices; no changes to the Cisco systems were needed (and thus there were no violations of the guarantee or service conditions). The reliability and serviceability of open photonic transmission systems was thus proved and was seen as a contribution to solution of multi-domain interoperability issues on the physical layer. (To avoid any confusion, it should be mentioned that open photonic transmission systems are delivered by three fibre providers, using products available on the open market and not manufactured by CESNET).

Open photonic DWDM transmission systems are also used for end-user 10 Gb/s wavelength connections, if needed (the particle physics research premises in Praha, along with a number of hospitals, are connected, while a 10 Gb/s wavelength interconnection to the Barrandov Studios is under construction). The deployment of open photonic transmission DWDM n x 10 Gb/s systems, implementing the concurrent bidirectional transmission on single fibre lines (giving beneficial cost advantages) is ongoing. Another advantage of open photonic DWDM transmission systems lies in the ability to make savings on energy consumption, housing space usage, travel to remote huts, and so on (the details are outside the scope of this report). Upgrades to 40 Gb/s wavelength rates for some lines have been evaluated and prepared.

The results associated with the following are especially important:

- The early adoption of the new photonic technology in the production network.
- The risk management closely associated with nearly all early adoptions.
- The use of experimental dark fibre facilities (after laboratory testing) to verify feasibility of deployment in the production network.
- The use of some services of the experimental facility for CESNET2 or end-user wavelength connection (support of long term experiments with real usage).

Practical results are lambdas without OEO conversion in the CESNET2 network, 4 lines in CESNET EF and 4 lines in CESNET2 are lit by open photonic devices, 5 other lines will be lit in 2008. Interoperability without OEO has been achieved and single fibre bidirectional DWDM n x 10G is in operation (about 40% of fibre pair lease cost savings).

C. *Metropolitan DWDM End-to-End (E2E) connections*

Some important Research and Educational (R&E) premises are connected by dark fibres and lit by open photonic transmission DWDM systems to deliver E2E connection, see Figure 2. These connections support unique applications (e.g. High Energy Physics (HEP), uncompressed High Density (HD) or 4K video transmission) with high demands (bandwidth, low latency and jitter) and can also be used for low level tests and field trials (e.g. 40 Gb/s transmission or wavelength routing).

The Institute of Physics uses lightpaths to the USA and Taipei (via GLIF) and to Karlsruhe (via GÉANT2). The GLIF demo in Prague in 2007 used n x 10G open photonic DWDM to the premises of The Charles University, and deployment for the Barrandov cinema studios is prepared. Another 10G lightpath connection operates between Brno and Louisiana

State University. With FTTx deployment, usage of metropolitan fibres lit by high speed open photonic DWDM is expected to be common. Openness enables the solution of physical layer interoperability issues decreases expense and eliminates equipment delivery time problems as well.

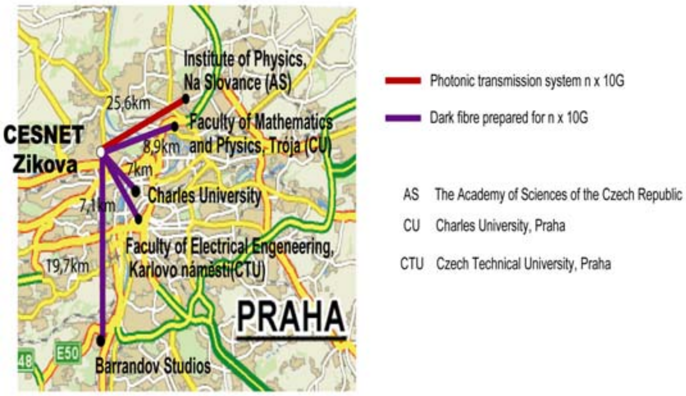

Figure 2. Metropolitan DWDM for E2E connections

III. FULL ACCESS TO THE PHYSICAL LAYER IS NEEDED

Open access to the physical layer gives the possibility to evaluate delays, jitter and latency without dependency on concurrent processes running in a network and to reproduce experiments, measurements etc.

A. Understanding of physical layer is crucial to enhance applications

There are no applications without physical layer. As a matter of fact we can note that the demands of present applications are still growing. But technology used in physical layer limits transmission speed and the applications (by latency, non-determinism etc.). To achieve fast, more deterministic and dynamic networks (offering ligtpath or even packet routing without OEO) understanding of physical layer is crucial. An influence of some transmission impairments grow faster than linearly with transmission speed (e.g. influence of CD grow quadratically [31]), so that for higher transmission speeds more impairments have to be take into account. There is electronic processing speed limitation expected (about 100 Gb/s per port), optical processing speed limitation will be about 1 Tb/s per port. Optical processing has significantly lower energy consumption [19]. So the savings of energy, space and costs must be solved primarily in the physical layer design.

B. Experimentation based on physical layer technology advances

The main source of possibilities to enhance applications lies in physical layer. Research and Development driven by experiments is important to verify and evaluate real possibilities, create new service offers for users, and find early adopters.

The CEF Network concept was used for Research and Education network CESNET2 first time in 2000 on the 324 km leased dark fibre pair Praha-Brno, implementing 2.5 Gb/s transmission, [20].

C. Devices for network research and experimentation

As mentioned above, CESNET has developed family of open photonic devices (CL family), enabling early adoption of the leading edge photonic technology.

The CL family of devices offers different advantages as freedom of the design, ability to meet user needs, easy to modify if necessary, avoid delays in innovations (low needs to save investments), photonic transmission and processing speed, low cost, saving energy, space and user care [16], [21], [22].

The CL family devices proved to be very useful not only for GLIF applications development, especially for dispersed end users (chapter III.E) but also for CESNET2 NREN and Experimental Facility development, including CBF lighting, FTTx deployment (chapter III.E), improvement of interoperability on the physical layer, as well as remote monitoring and control, low latency and deterministic multicast (chapter III.G).

The CL family offers main building elements of photonic networks, for example:

- Optical Amplifiers (CLA) – devices to allow necessary reach extension in both long-haul or wide local networks, including NIL and single fibre bidirectional transmission. Devices could be deployed both in digital or analogous systems, in terminal or inline applications
- Variable Multiplexers (CL-VMUX) - devices designed for optical variable multiplexing or demultiplexing of DWDM channels, with equalization of optical power
- Reconfigurable Optical Add/Drop Multiplexer (CL-ROADM) - devices designed for dynamical adding and dropping of WDM channels from/into continual optical WDM multiplex
- Tuneable CD Compensators (CLC) – tuneable devices allowing dynamic chromatic dispersion compensation for transmission speeds from 10 to 160 Gb/s
- Photonic Switches (CLS) – devices allowing transparent all-optical switching of full wavebands.
- Photonic Switches with Multicast Option (CLM) - devices delivering all optical multicasting without OEO conversion, speed and modulation format transparent, don't introduce non-deterministic delay
- Optical Channel Monitor (CL-OCM) - device for simultaneously monitoring power levels of DWDM signals and offers overview of present/non-present channels.

Delivery of CL open photonic devices is available from FTTx development company.

D. Connecting dispersed users to GOLEs

Suggested approach is based on dark fibres connecting end users and GOLE via photonic (all-optical) lightpaths (i.e. implemented without OEO conversions). It was successfully demonstrated (but not yet fully published) for example in GLIF2007 workshop in Praha as connection between the

Charles University and GOLE Praha, used for all demonstrations (chapter III.F). Photonic lightpath connected to GOLE Praha are available in CESNET2 NREN and in CESNET Experimental Facility, including CBFs. GOLE connections are shown in Figure 3. Commercially available transmission systems allow optical reach of 10G photonic lightpaths about 1000 km now and extension to about 2000 km is prepared, as well as upgrade to 40G transmission rate.

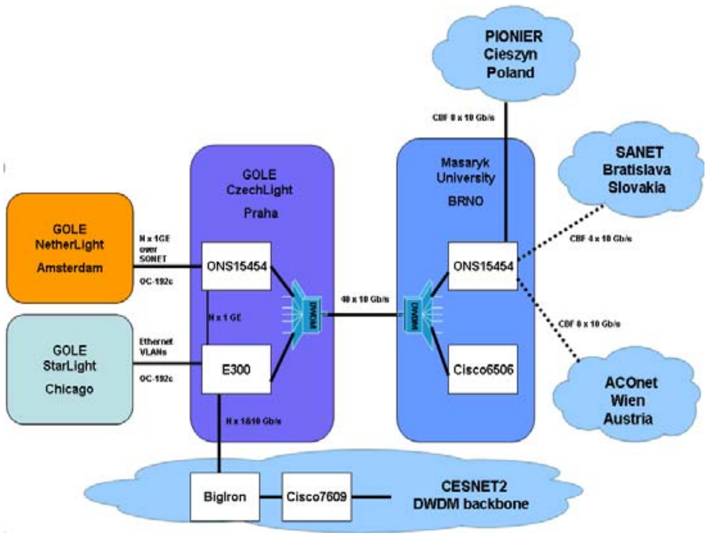

Figure 3. GOLE CzechLight connections

E. LTTx: Lightpaths To The x

FTTx development enables large change of network services [23]. Lightpaths to home or office will be very probably one type of a service on FTTx (LTTx is acronym suggested in 8th Annual Global LambdaGrid Workshop in 2008). These lightpaths (including home working) enables new applications and their wider deployment. Experiences from GLIF experiments using dedicated fibre last miles are important for FTTx development. Development of many applications based on lambda services depends on our ability to connect real end users in their office or home.

Openness of FTTx networks to all service providers and low transmission latency will be crucial [24] – (as the customer perceives him/herself to be the centre of the universe).

F. GLIF Applications supported by LTTx in CESNET (selection)

- GLIF demos on the 7th Annual Global LambdaGrid Workshop in 2007 at the Carolinum, Prague, Czech Republic
- HEP - data access and processing for ATLAS and ALICE experiments on Large Hadron Collider (LHC) , D0 on Tevatron, STAR experiment on Relativistic Heavy Ion Collider (RHIC)
- First VIrtual Network Infrastructure (VINI) sites in Europe (Praha, Plzeň)
- Intercontinental Remote Education on High Performance Computing between Masaryk University Brno and Louisiana State University
- CESNET-TWAREN (NREN of Taiwan) Hinchu lightpath: peering CESNET-TWAREN, Multicasting and IPv6

More details and references to project pages are available in [14].

G. Multicasting device demonstration

The CLM (Multicast Switch) offers photonic multicasting (replicating) of optical signals. Output signals are thus exact deterministic copies of input signal, without jitter and delay. This is achieved without OEO conversion, without store and forward processing and without loading of switch by multiple tasks. Multicasting is remotely controllable via web interface.

Operation was demonstrated in CESNET during 7th Annual Global LambdaGrid Workshop in 2007 and outside CESNET at University of Washington (the 8th Annual Global LambdaGrid Workshop, 1 October 2008, Seattle), CLM was located at StarLight, Chicago and managed remotely [25], [26].

IV. Global support for Large-Scale Experimental Facilities

Understanding of the importance of Large-Scale Experimental Facilities or Open Testbeds for research of networking is quite general now, but few projects only enables access to dark fibres and enables control of photonic devices in physical layer.

A. Important projects

With the contemporary development of networks and applications, and the changes in the photonics industry and resulting increased competition, early prototyping and experimentation will become key means for driving the innovation and development of user-oriented solutions. In contrast to a traditional vendor, operator and technology-specific “closed” testbeds, the notion of “open” testbeds has emerged. To meet this need, major research and development programs have started around the globe, including Future Internet Research and Experimentation (FIRE) in Europe, New Generation Network (NWGN) in Japan and Global Environment for Network Innovations (GENI) in the USA, to establish large-scale experimental facilities.

JGN2plus is an advanced testbed that supports the NWGN programme promoted in Japan by the National Institute of Information and Communications Technology (NICT) and which enables leading-edge demonstrative experiments for network R&D and various applications to be conducted. JGN2plus provides access to an optical testbed based on field dark fibres and this service is open to general researchers for R&D purposes.

By comparison, “A Strategic Plan for the Internet2 Community. 2008-2013” suggests that research and education community network users will be given access to fibres (Part I, items A and D):

A. “Operate a cost-effective network backbone that provides ’production’ research and education network services and operational performance data to the members, while enabling ’breakable’ testbed capability for network researchers who are inventing the future Internet in partnership with government and industry.”

D. “Create an open, inclusive and transparent process involving researchers, connectors, other regionals, campuses, and other stakeholders to define future Internet2 network architectures including assessment of the value of operating a physical network, in anticipation of the end of the current Level3 contract.”

In Europe, experimental facilities allowing access to the wide-area photonic layer for universities and research institutions are available in some countries [27], [28], [29].

B. *Lessons learned*

1. The traditional top-down network design approach should be used in combination with the bottom-up approach.
2. The attention paid to photonic transmission and processing should be increased. Advances in the New Generation Network (NWGN) project are important, especially because:
    - o The importance of photonic (all-optical) networking and processing is growing.
    - o Above a certain speed limit, all-optical transmission and processing are the only known possibility.
    - o Below certain energy consumption limits, all-optical transmission and processing is the only known possibility.
    - o Speed, energy saving, space saving, and cost saving issues all must be solved primarily by the physical layer network design: the possibility of addressing them on the higher layers is very limited.
3. The design of E2E lightpath services took the global networking community from single to multi-domain scenarios and to interoperability issues at network layers below that of the Internet Protocol (IP) layer. We must assume that different domains will use equipment delivered by different vendors. Therefore the community ought to place a lot more emphasis on this aspect of cross-vendor optical layer interoperability. The complexity of the optical parts of any network equipment is growing significantly. This changes the position in a relation to network equipment vendors because:
    - o Interoperability on the physical layer is an important requirement
    - o The community should specify their interoperability and other requirements independently of vendors sufficiently in advance to have an influence on the product development road maps of vendors.
    - o FTTx equipment vendors should be taken into account when implementing E2E lightpath services (to maintain affordability).
    - o Understanding based on theoretical knowledge and experimental verification should be supported.
4. Open transmission systems should be investigated and deployed if they:
    - o Improve interoperability on the physical layer.
    - o Enable early adoption of leading edge photonic transmission technology and thus allow higher transmission speeds and/or energy, space and cost savings.
    - o Enable and support experimental applications requested by users or field experiments on dark fiber lines to verify feasibility of network improvements.
    - o Avoid impact of other vendor delays in innovations (often caused as they seek to maximize returns on their investments).
5. The development and interconnection (federalization) of country-wide experimental facilities (open testbeds) enabling field technology testing and user participation should be supported. Field evaluation and deployment of 40 Gb/s transmission technologies should continue and field testing of 100 Gb/s transmission technologies should started immediately when such transmission devices become available.

V. SUGGESTED GOALS

We believe federated dark fiber Experimental Facilities are important to improve the position of Europe in networking and to help in preparation of new global projects. Suggested goals are:

- To build a sustainable, adaptable, geographically dispersed large scale dark fibre Experimental Facility in Europe by gradually federating existing and new dark fibre facilities of NRENs and fibre providers for emerging or future Internet technologies. EFs should be sustainable in the similar way as IP services and wavelength circuit services delivered by GLIF or GÉANT.
- EF should be able to support development research projects whether they are funded by the EU, national governments or users groups, including Future Internet Research and Experimentation projects requiring provisioning of clean slate e-Infrastructure, long-term and experimentally-driven research projects, application projects requiring guaranty of response time, deterministic behaviour of transmission, higher security, etc.
- To give researchers an experimental environment for validating innovative – and potentially disruptive – architectures and technologies including physical layer. It is well known, that many issues are only

discovered when technology, devices or systems are deployed in "real-life" situations. Practical experiments are needed to give credibility and raise the level of confidence in the research findings; furthermore, the experimentation must be performed on a large scale to be representative, convincing, and to prove scalability.

- To interconnect available dark fiber experimental facilities of NRENs, enabling researchers access directly to the fibers. There is potential to reach European scale in few years.
- To interconnect EF with fibers of appropriate FTTx/FTTH projects to support experiments with very high speed E2E applications, etc.
- To support deployment of cutting edge technology. Such technology frequently looks beneficial, but management responsible for network operation may be afraid of lower reliability or open issues (e.g. warranty, maintenance). Previous experimental deployment in EF strongly alleviates this issue.
- To use EF in large environment by early adopters of new technologies and for experimental transmission of NREN traffic (or copy of them) in some cases for “near to real life technology testing”.

VI. Conclusions

Important concepts used in preparation and building of CESNET experimental facility are summarised in the paper. The necessity of access to the physical layer has been addressed. The results achieved and lessons learned in the field of dark fibre experimental facilities building and open photonic systems deployment in CESNET are summarized here, with emphasis on the global approach in R&E networking. Goals for further development of Experimental Facilities are suggested for analysis and discussion.

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LIST OF ACRONYMS

ACONET	Austrian NREN
ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC Apparatus
CBF	Cross Border Fibres
CD	Chromatic Dispersion
CL	CzechLight
CLA	CL Optical Amplifier
CLC	CL CD Compensator
CLS	CL Optical Switch
CEF	Customer Empowered Fibre
DWDM	Dense Wavelength Division Multiplexing
E2E	End-to-End
EF	Experimental Facility
FBG	Fibre Bragg Grating
FIRE	Future Internet Research and Experimentation
FTTH	Fibre To The Home
FTTx	Fibre To The x
GENI	Global Environment for Network Innovations
GLIF	Global Lambda Integrated Facility
GOLE	GLIF Open Lightpath Exchange
HD	High Definition
HEP	High Energy Physics
IP	Internet Protocol
JGN2plus	Japanese testbed network for R&D
LHC	Large Hadron Collider
MUX	Multiplexor
NICT	National Institute of Information and Communications Technology
NIL	Nothing In Line
NREN	National Research and Education Network
NRZ	Non Return to Zero
NWGN	NeW Generation Network
OA	Optical Amplifier
OOB	Out of Band
OEO	Optical-Electrical-Optical
PIONIER	Polish NREN
PMD	Polarisation Mode Dispersion
RHIC	Relativistic Heavy Ion Collider
ROADM	Reconfigurable Optical Add-Drop Multiplexer
SANET	Slovak NREN
STAR	Solenoidal Tracker At RHIC
Tevatron	1 TeV synchrotron at Fermi National Accelerator Laboratory
TWAREN	Taiwanese NREN
VINI	VIrtual Network Infrastructure
VMUX	Variable MUX