Tibor Cinkler

cinkler@vik.bme.hu (Teams)

Communication Networks VITMAB06

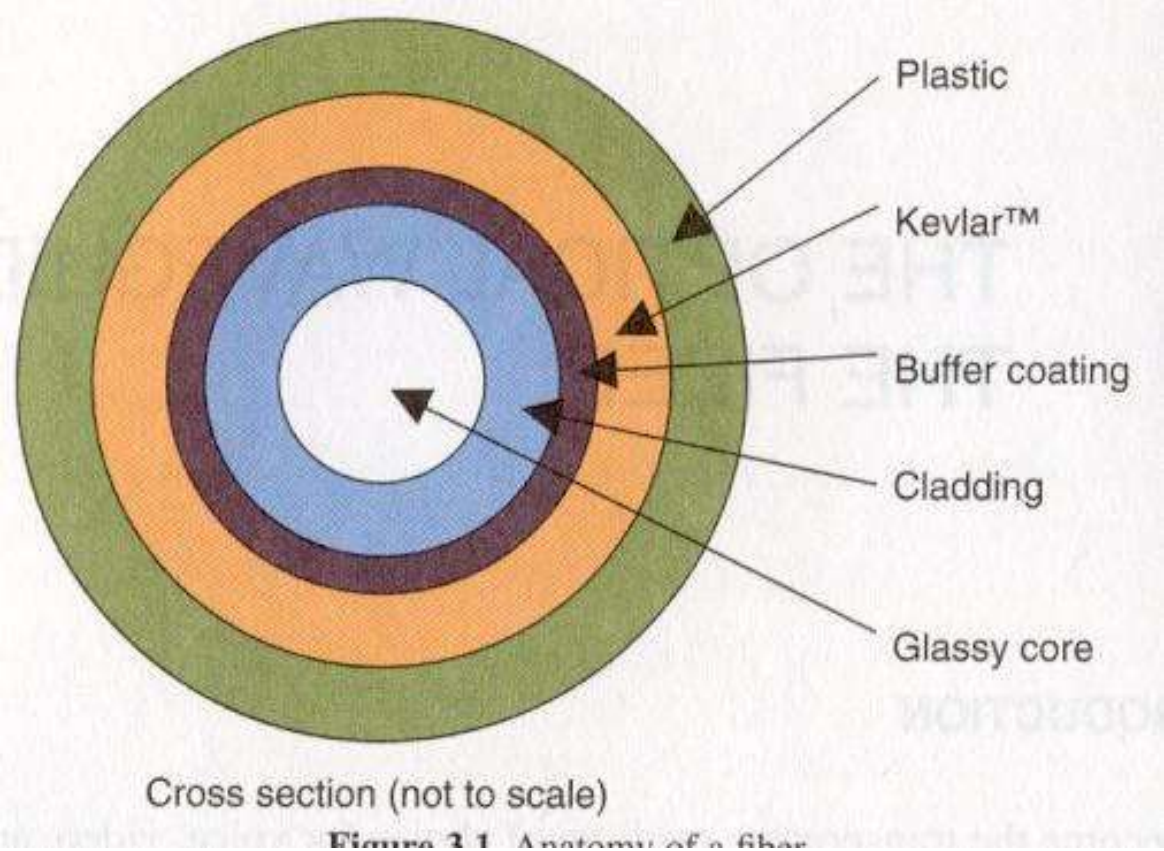
April 24 Wednesday 8:30-10:00

(Third presentation by TC)

Optical Networks

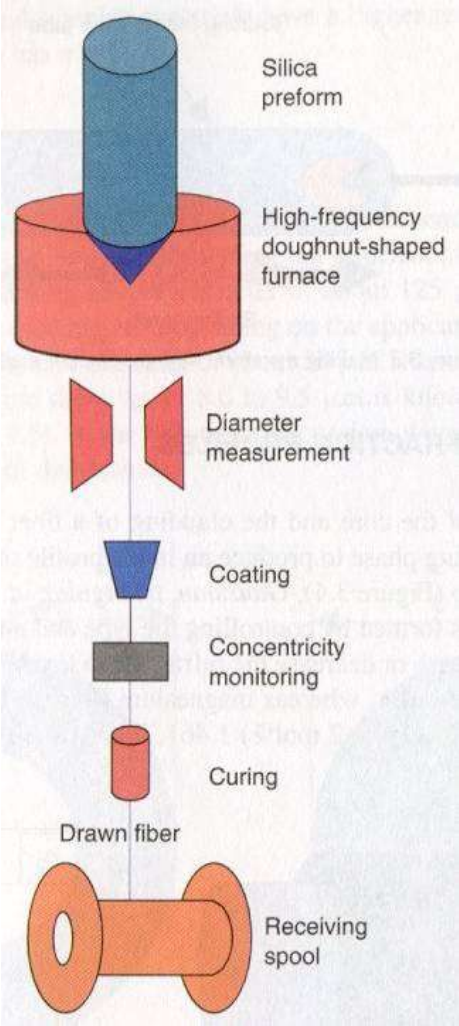
- Physical Layer for other networks
- Access – Metro – Core
- The Optical Fiber
- Some Network Examples
- Networking

Fiber Anatomy



Source: Shivkumar Kalyanaraman

Fiber Manufacturing

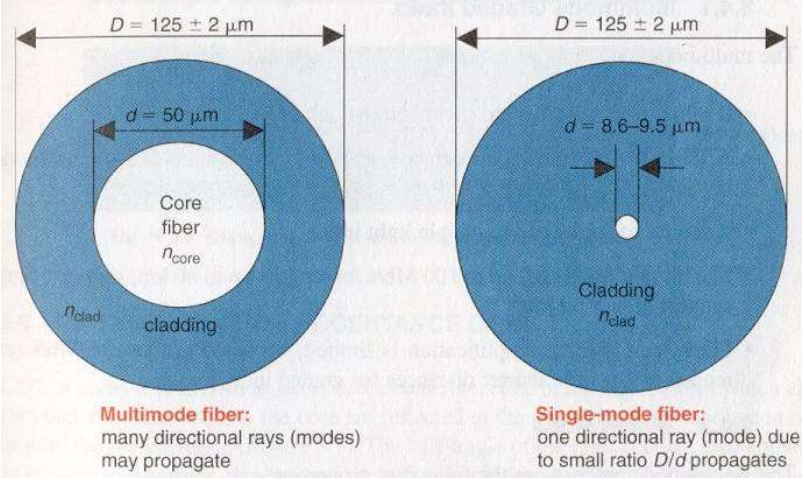


- Dopping by rare earth elements
  - Graded index
  - (Step Index)

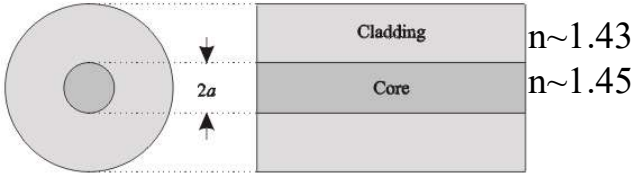
- Multiple cables per duct
- Up to 1000 fibers per cable
- Multi-core fibers?
- ~160 λ per fiber/core
- 10 Gbps or 100 Gbps per λ

Single and MultiMode Fiber

- Single-Mode Fiber (SMF) (8 to 10 μm core)
- Multimode Fiber (MMF) (50 to 85 μm core)
- SiO_2 (or plastic)
- 3 low attenuation bands (windows): 0.8, 1.3 , 1.55 μm



Refraction Index (RI):



Source:
Shivkumar Kalyanaraman

Absorption and Attenuation: Absorption Spectrum

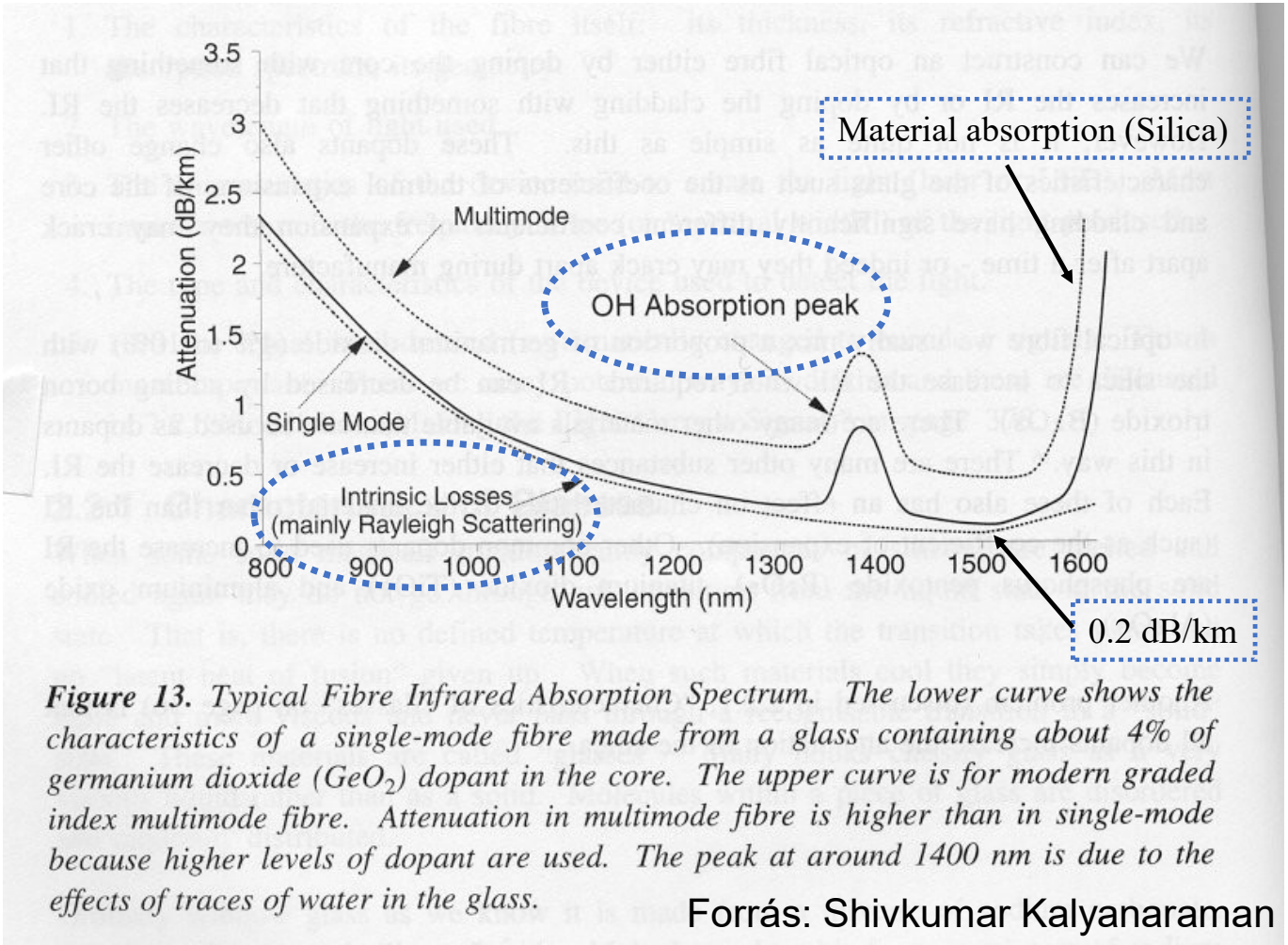
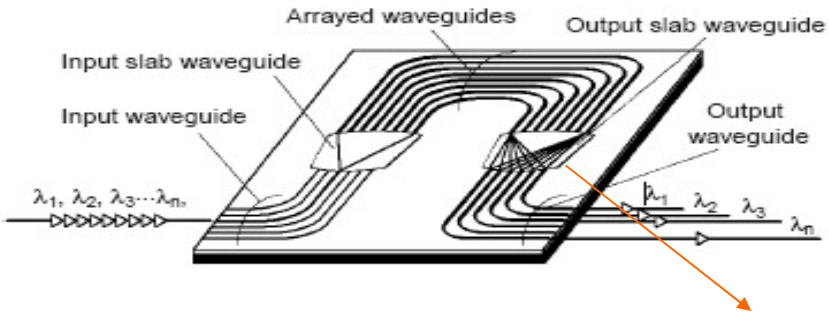


Figure 13. *Typical Fibre Infrared Absorption Spectrum. The lower curve shows the characteristics of a single-mode fibre made from a glass containing about 4% of germanium dioxide (GeO_2) dopant in the core. The upper curve is for modern graded index multimode fibre. Attenuation in multimode fibre is higher than in single-mode because higher levels of dopant are used. The peak at around 1400 nm is due to the effects of traces of water in the glass.*

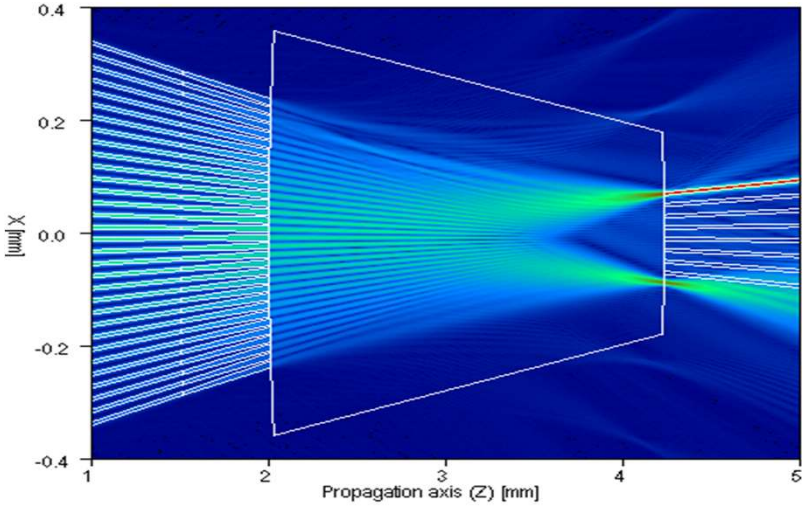
Forrás: Shivkumar Kalyanaraman

Arrayed waveguide grating



- AWG

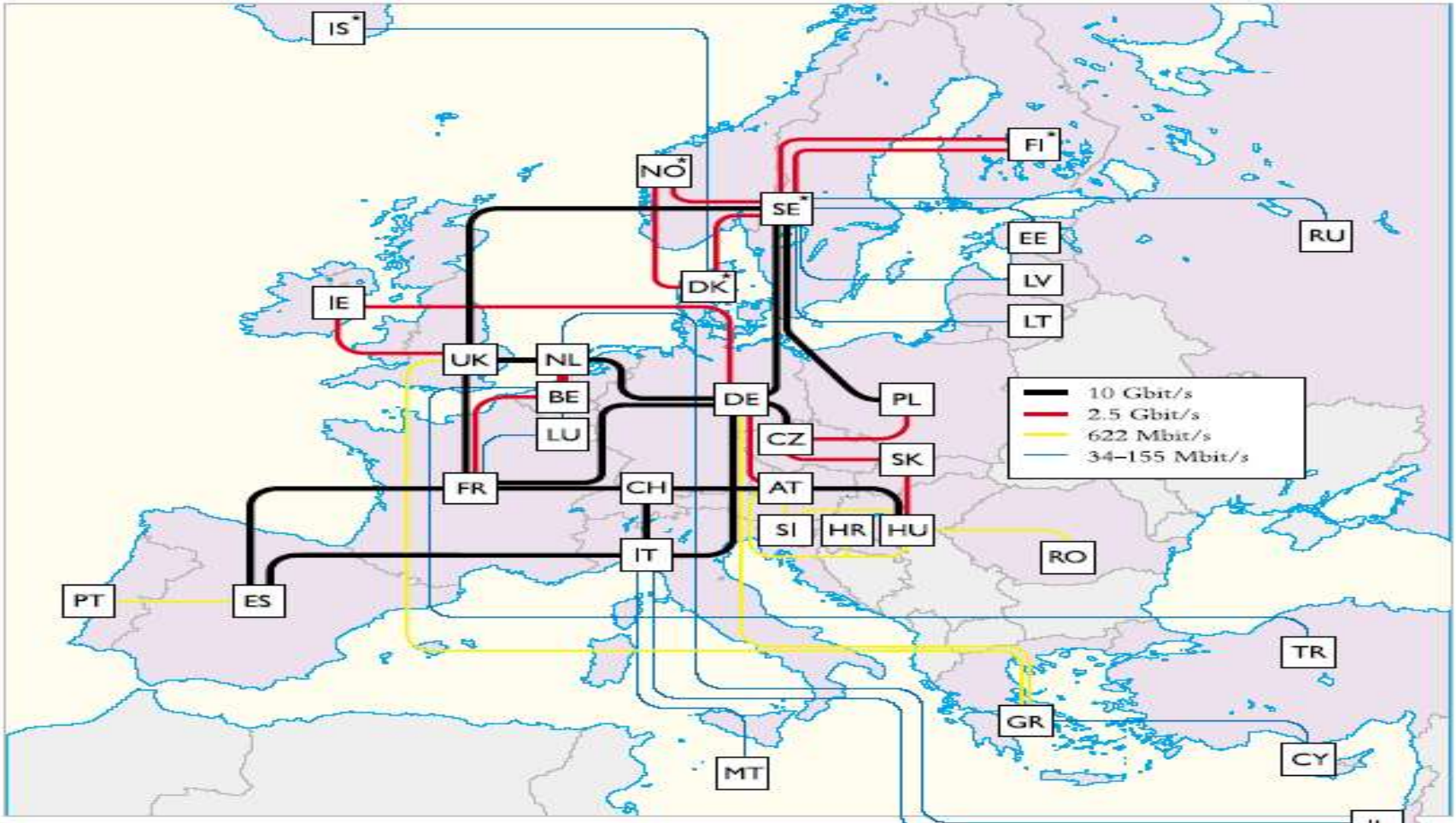
- Great scalability
- Low losses
- Non reconfigurable
  - It requires wavelength conversion



C2V animation

Source: Robotiker, Andrea Bianco Redondo
Networks 2008, Budapest

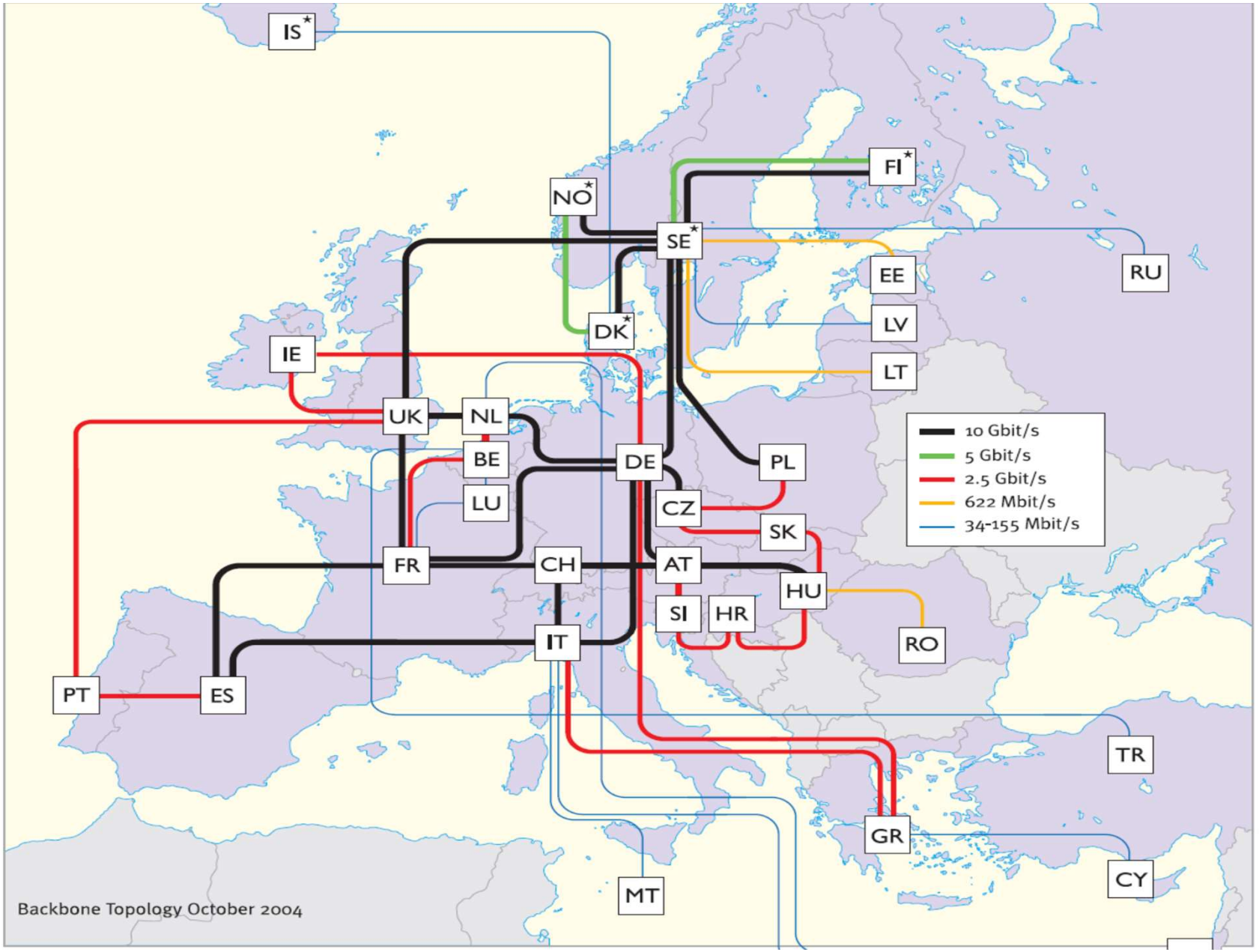
Geant Europan network

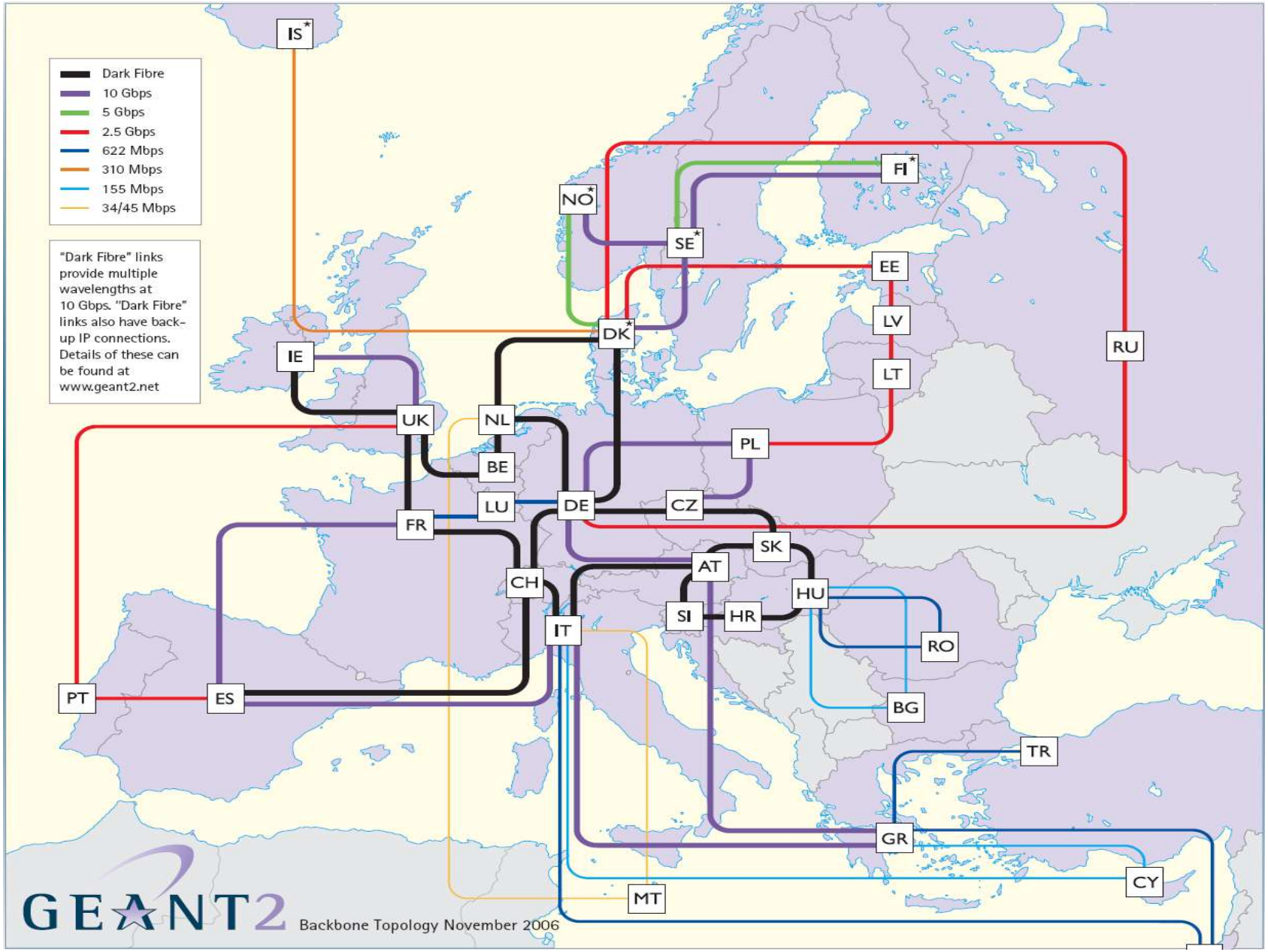


Backbone Topology November 2003

AT	Austria	CZ	Czech Republic	ES	Spain	HR	Croatia	IS	Iceland*	LV	Latvia	PL	Poland	SE	Sweden*
BE	Belgium	DE	Germany	FI	Finland*	HU	Hungary	IT	Italy	MT	Malta	PT	Portugal	SI	Slovenia
CH	Switzerland	DK	Denmark*	FR	France	IE	Ireland	LT	Lithuania	NL	Netherlands	RO	Romania	SK	Slovakia
CY	Cyprus	EE	Estonia	GR	Greece	IL	Israel	LU	Luxembourg	NO	Norway*	RU	Russia	TR	Turkey
														UK	United Kingdom

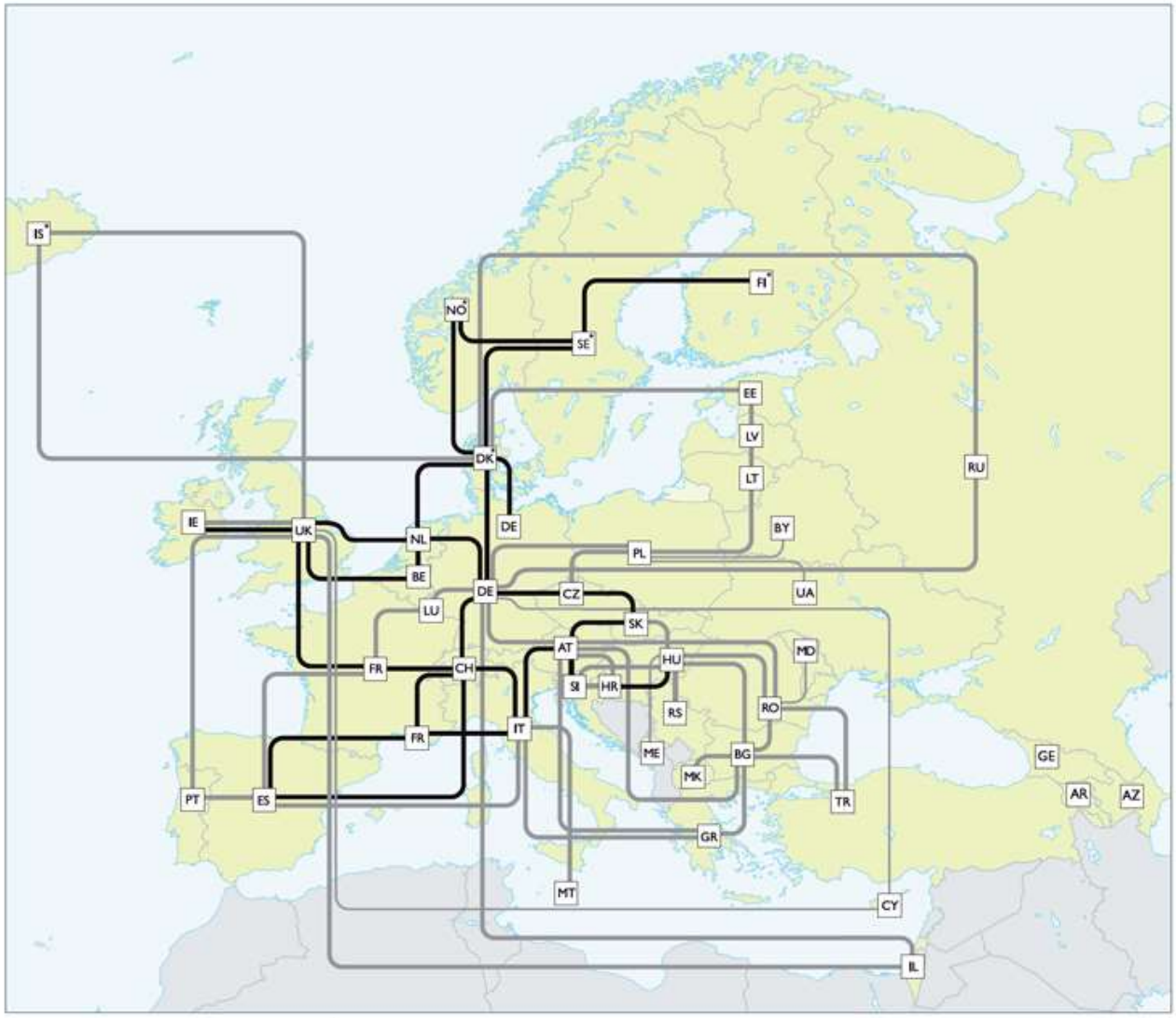
* Connections between these countries are part of NORDUnet (the Nordic regional network)


IS*
NO*
SE*
FI*
RU
EE
LV
LT
DK*
IE
UK
NL
BE
LU
DE
PL
CZ
SK
FR
CH
AT
HU
SI
HR
RO
IT
PT
ES
TR
GR
CY
MT
10 Gbit/s
5 Gbit/s
2.5 Gbit/s
622 Mbit/s
34-155 Mbit/s
Backbone Topology October 2004


Dark Fibre
10 Gbps
5 Gbps
2.5 Gbps
622 Mbps
310 Mbps
155 Mbps
34/45 Mbps
"Dark Fibre" links provide multiple wavelengths at 10 Gbps. "Dark Fibre" links also have back-up IP connections. Details of these can be found at www.geant2.net
IS
NO
SE
FI
EE
LV
LT
RU
DK
IE
UK
NL
BE
PL
LU
DE
CZ
FR
SK
AT
CH
HU
SI
HR
IT
RO
BG
PT
ES
TR
GR
CY
MT
GEANT2
Backbone Topology November 2006

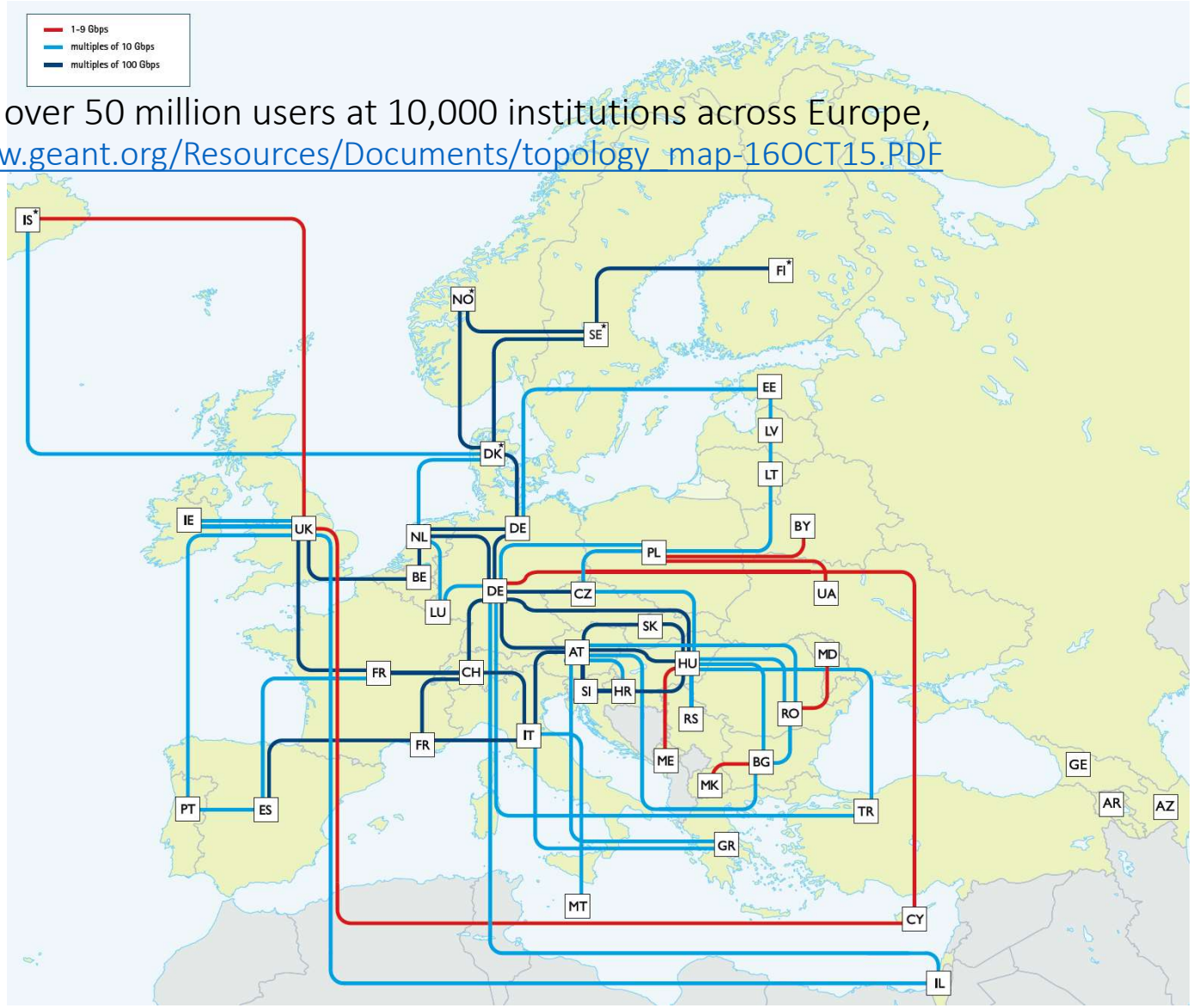
The Pan-European Research and Education Network

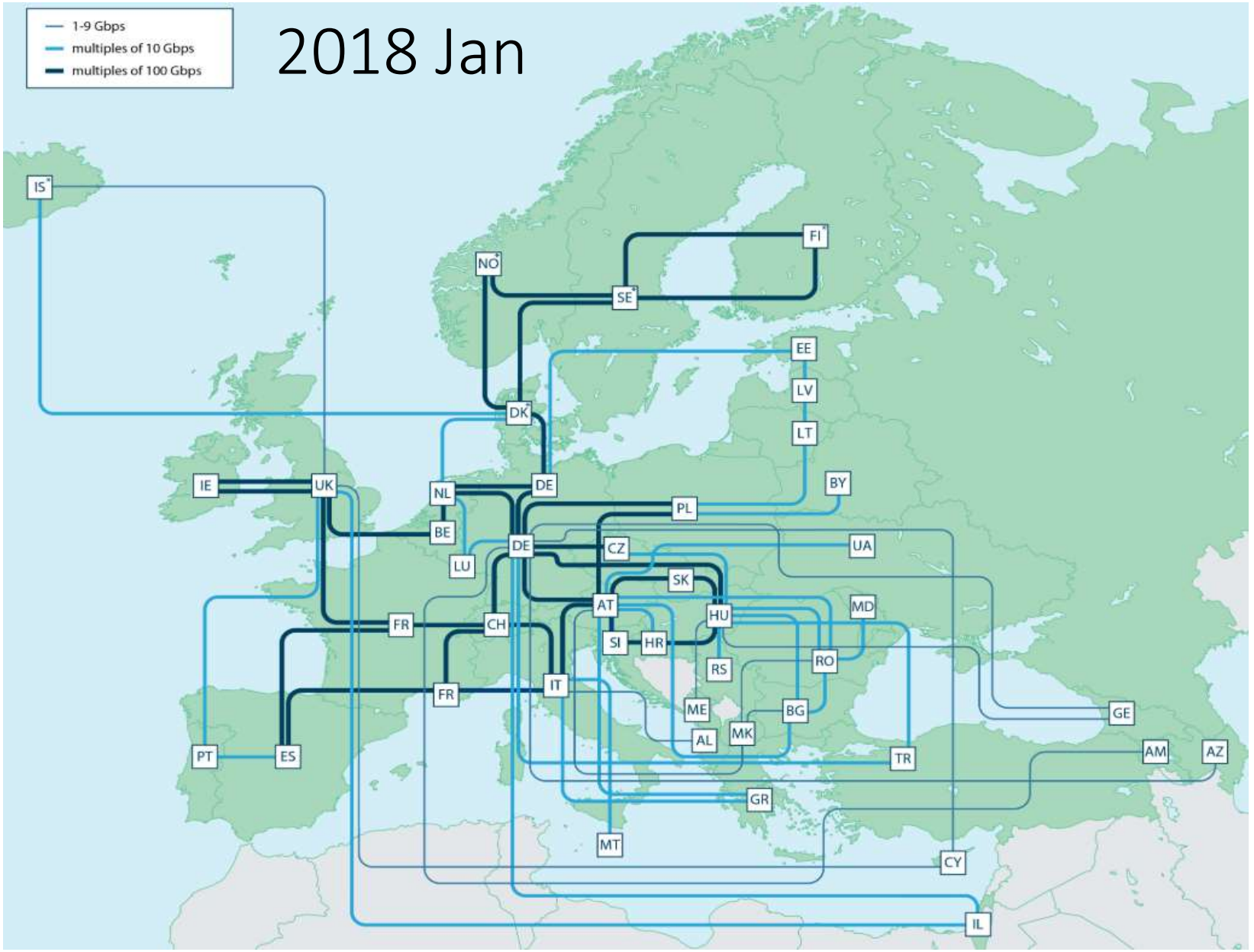
GÉANT interconnects Europe's National Research and Education Networks (NRENs). Together we connect over 50 million users at 10,000 institutions across Europe.



GÉANT connectivity as at September 2013. GÉANT is operated by DANTE on behalf of Europe's NRENs. Black lines indicate dark fibre.

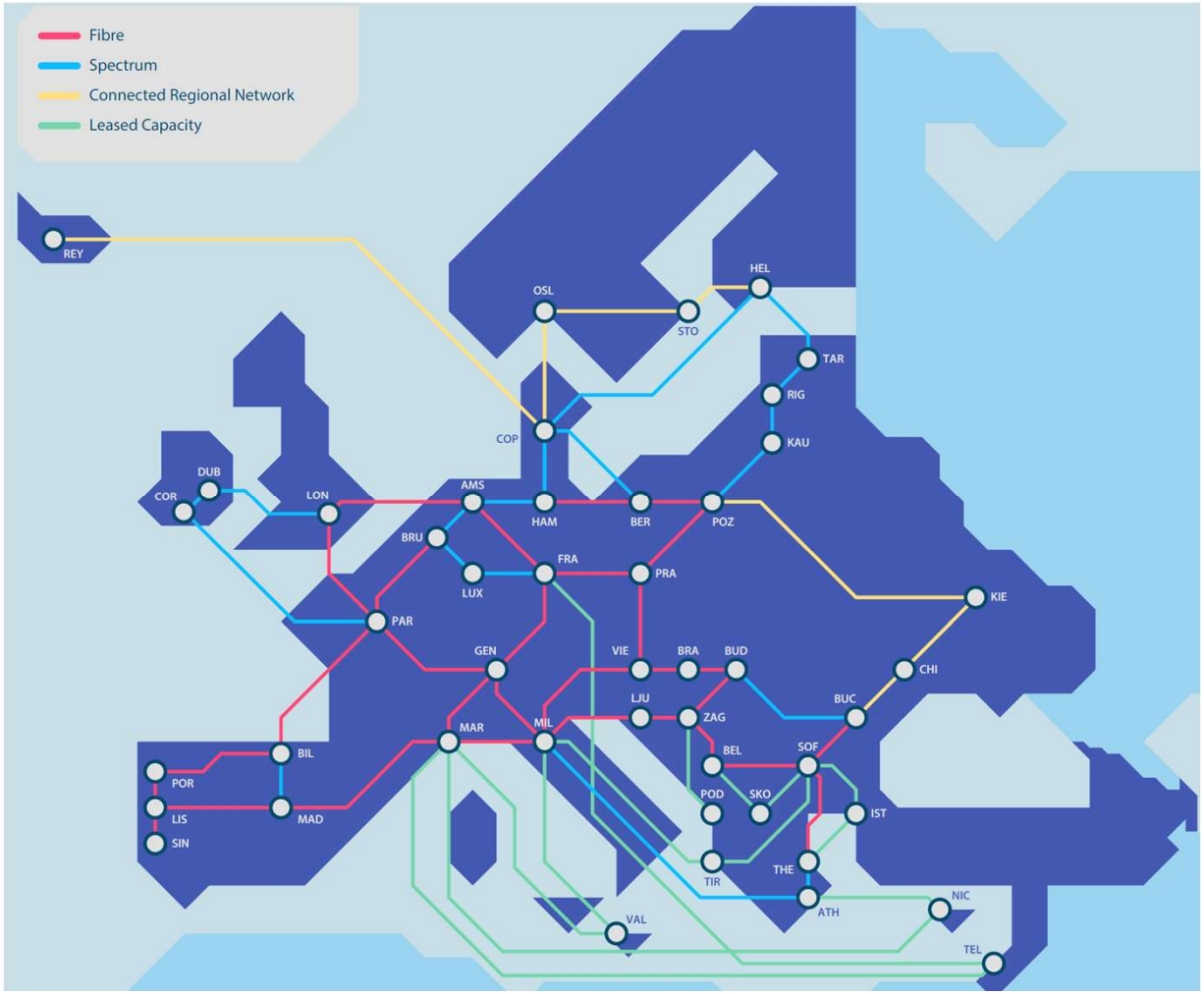
connects over 50 million users at 10,000 institutions across Europe,
http://www.geant.org/Resources/Documents/topology_map-16OCT15.PDF



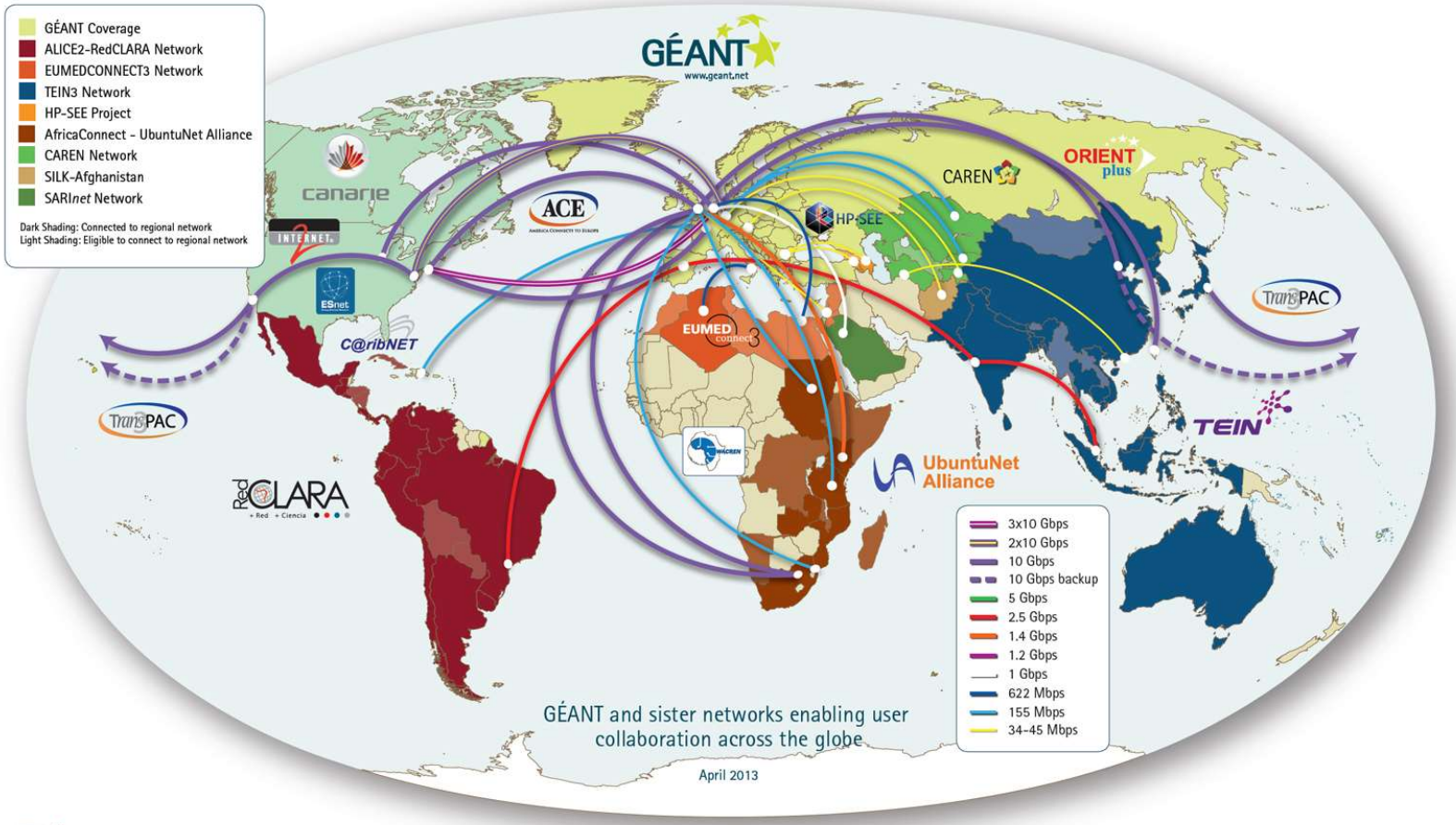

1-9 Gbps
multiples of 10 Gbps
multiples of 100 Gbps
2018 Jan
IS
NO
SE
FI
EE
LV
LT
DK
IE
UK
NL
DE
BY
PL
BE
DE
CZ
UA
LU
SK
AT
HU
MD
FR
CH
SI
HR
RO
RS
IT
FR
ME
BG
GE
MK
AL
PT
ES
TR
AM
AZ
GR
MT
CY
IL

2024 January

https://resources.geant.org/wp-content/uploads/2024/01/GN4-3N-Topology-Map-Jan2024.pdf



GÉANT At the Heart of Global Research Networking



DANTE www.dante.net GÉANT www.geant.net

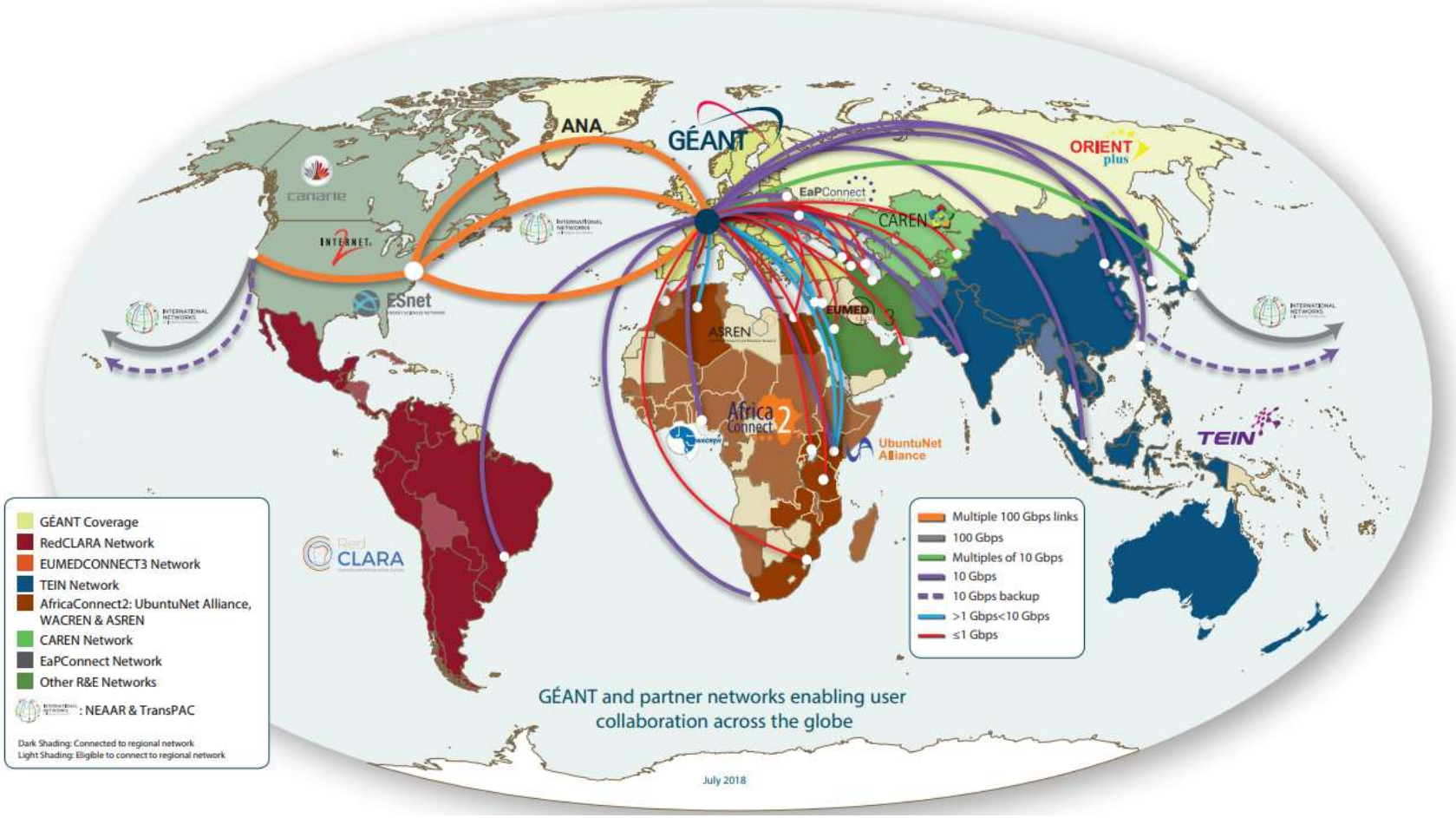
connect • communicate • collaborate

GÉANT is co-funded by the European Union within its 7th R&D Framework Programme.
This document has been produced with the financial assistance of the European Union. The contents of this document are the sole responsibility of DANTE and can under no circumstances be regarded as reflecting the position of the European Union.

SEVENTH FRAMEWORK PROGRAMME

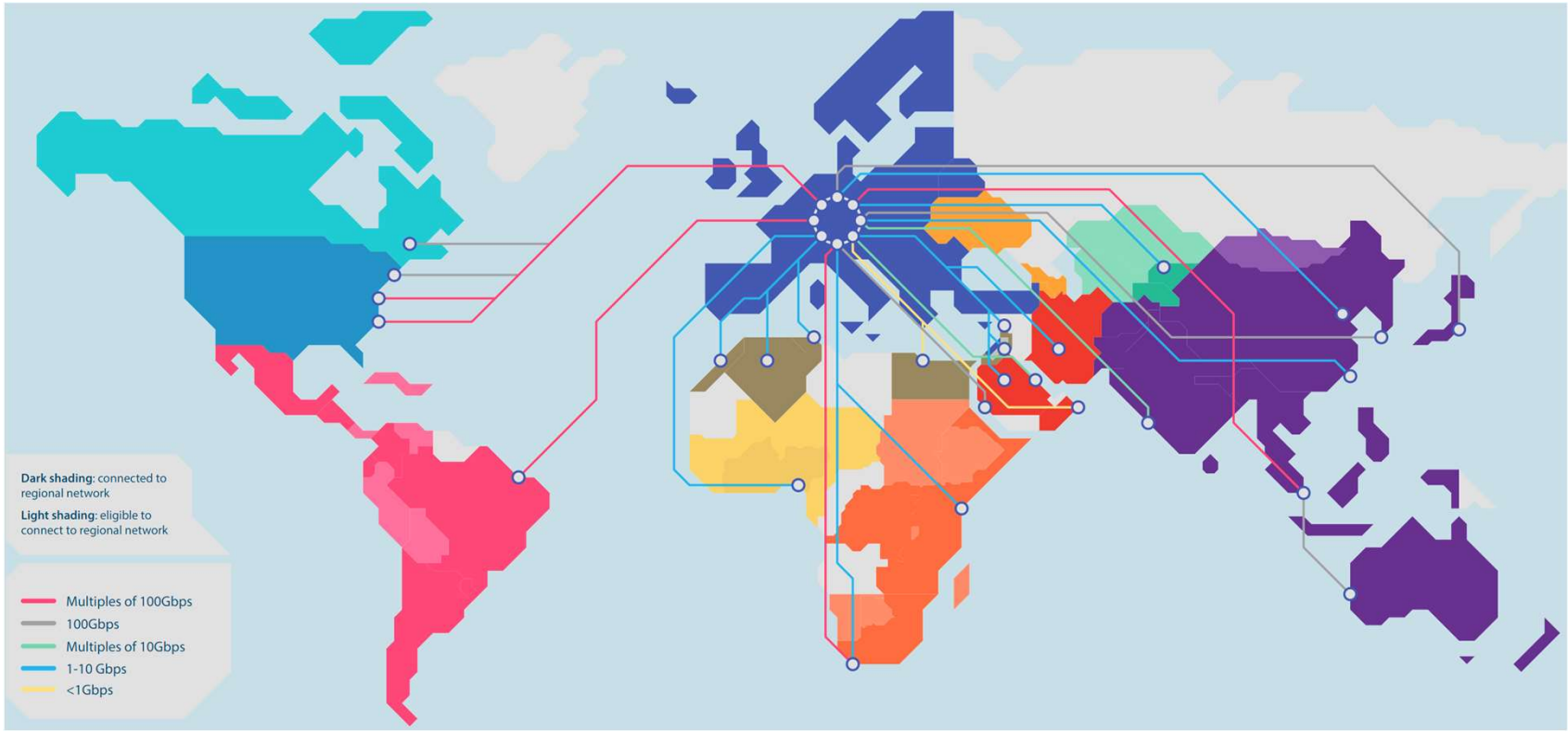
Co-funded by the European Union

2018 July GEANT and partner networks

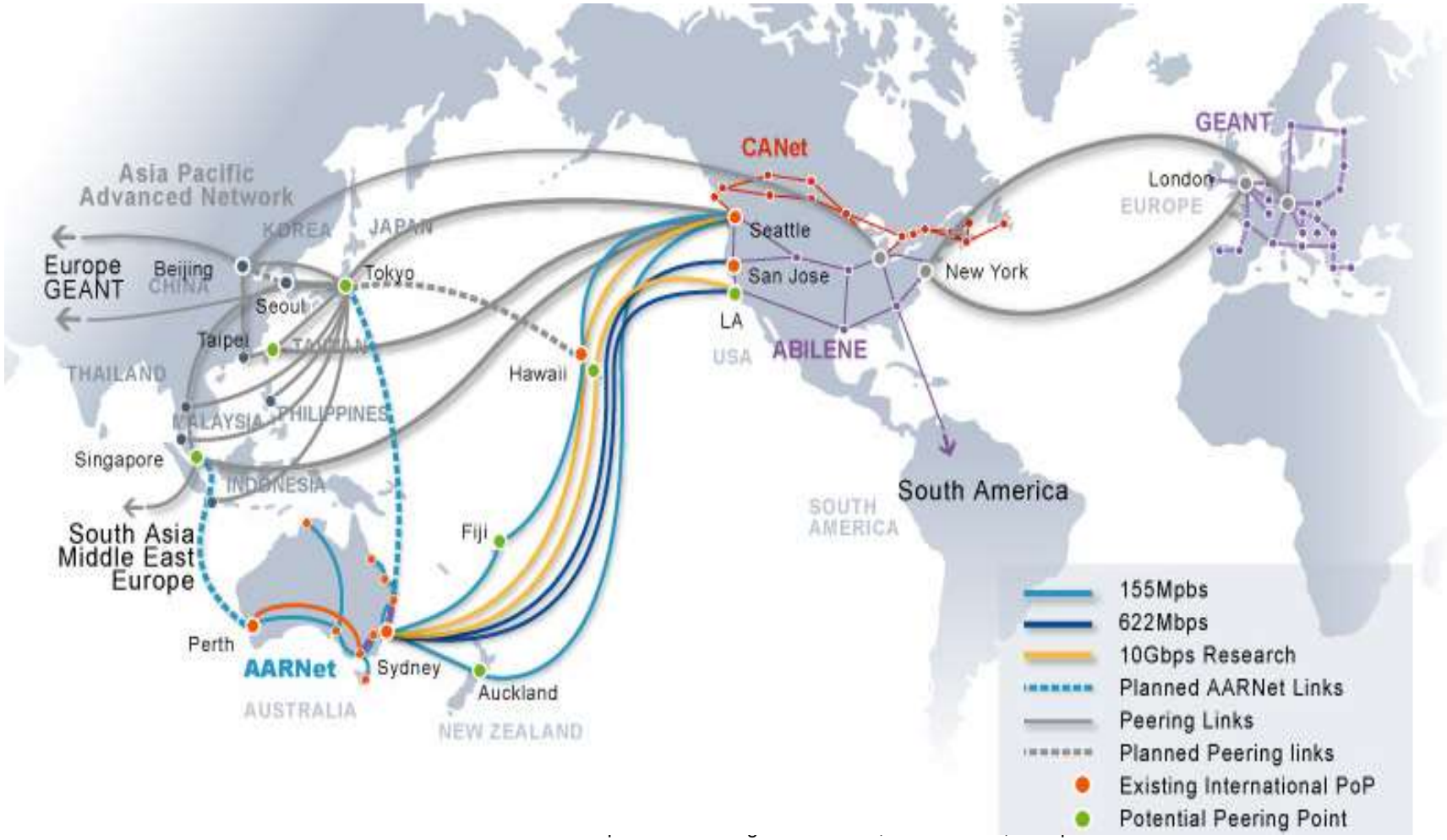


June 2023 Geant

https://resources.geant.org/wp-content/uploads/2023/06/GEANT-at-the-Heart-of-Global-Research-and-Education-Networking-Official-June2023.pdf



AArnet (Australia 2004) +
SXTransPORT (Trans Pacific Optical Research Testbed)



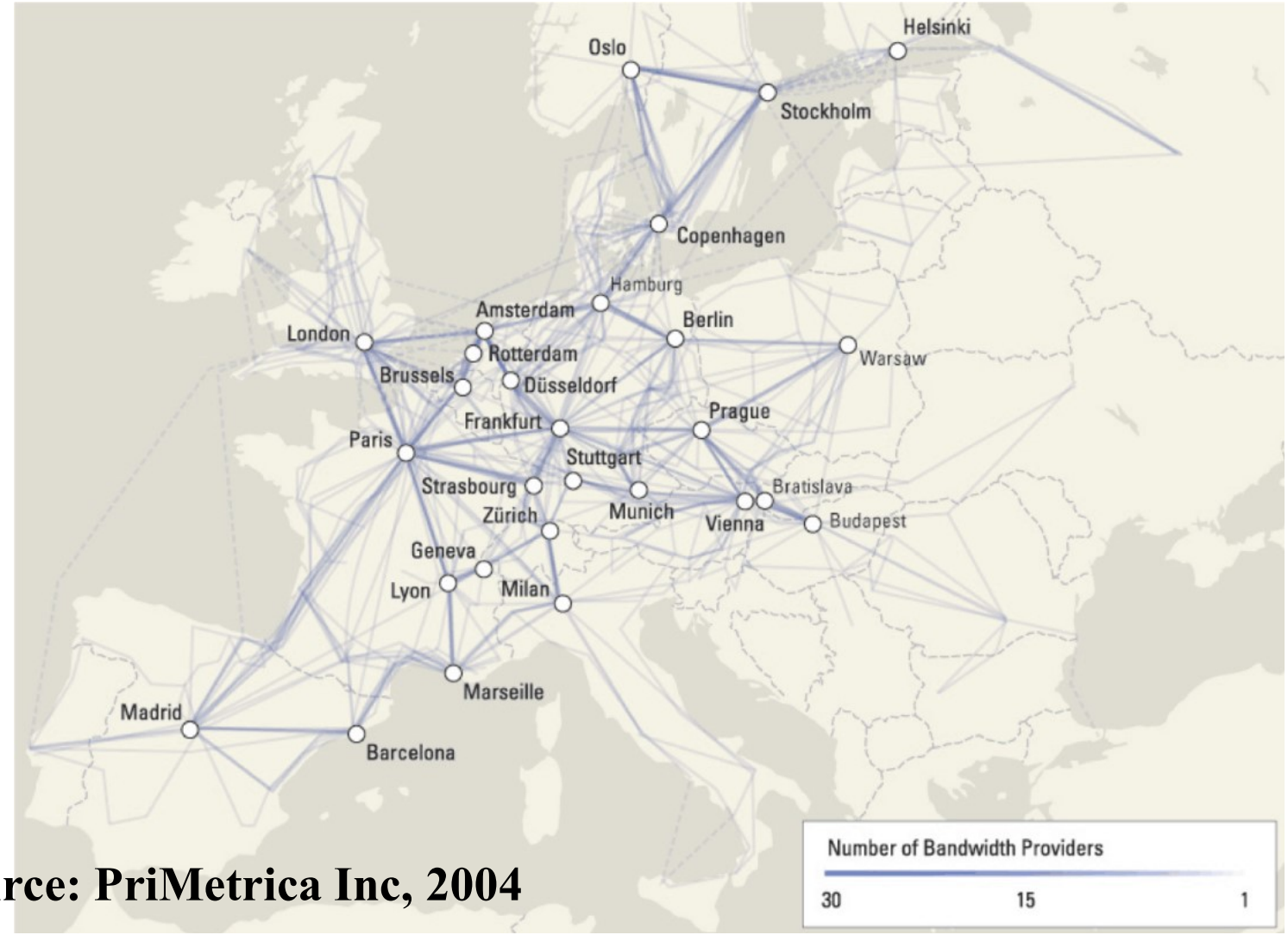
Optical cable systems of Americas

- Americas 1
- Americas II
- South American Crossing
- Columbus II
- Columbus III
- Emergia (Telefonica)
- ARCOS
- Maya-1
- 360 Americas

Source:

H.B.Newman, GNEW2004

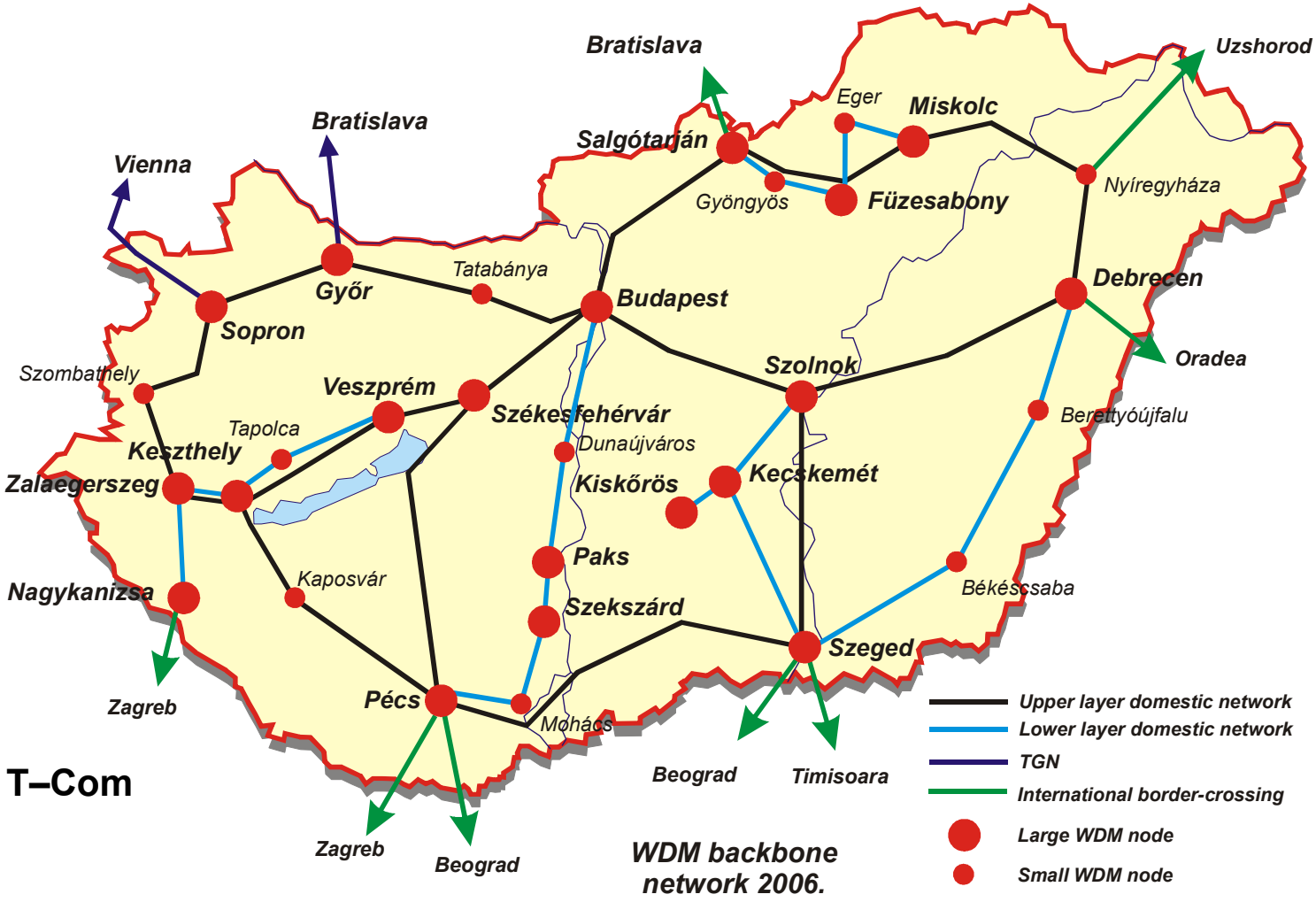
Pan-European Networks



Source: PriMetrica Inc, 2004

- 2001 óta folyamatos fejlesztés
- 24 /32 + 10 Gbit/s
- 100 GHz-enként

Magyar WDM gerinc



Forrás: T–Com

submarine-cable-map-201x Homework 2a:

https://submarine-cable-map-2024.telegeography.com/

https://submarine-cable-map-2023.telegeography.com/
https://submarine-cable-map-2022.telegeography.com/
…
https://submarine-cable-map-2019.telegeography.com
https://submarine-cable-map-2018.telegeography.com/
https://submarine-cable-map-2017.telegeography.com/
https://submarine-cable-map-2016.telegeography.com/
http://submarine-cable-map-2015.telegeography.com/
http://submarine-cable-map-2014.telegeography.com/
http://submarine-cable-map-2013.telegeography.com/

Interesting Videos
Homework 2b:

Optical cable production video:

https://www.youtube.com/watch?v=uSnjo5tOGQA

Laying undersea cables

https://www.youtube.com/watch?v=v1JEuzBkOD8
https://www.youtube.com/watch?v=XQVzU_YQ3IQ
https://www.youtube.com/watch?v=GUN9J9_HtbQ
https://www.youtube.com/watch?v=JLVFKHJcBMM old

Shark attacks a cable

https://www.youtube.com/watch?v=XMxkRh7sx84

Optical Orthogonal Frequency-Division Multiplexing (O-OFDM)

OFDM: Orthogonal Frequency-Division Multiplexing

O-OFDM: Optical OFDM

- **SpectrumElasticMukherjee_06148192_002.pdf**
- **G. Zhang, M. De Leenheer, A. Morea, B. Mukherjee**
- **A Survey on OFDM-Based Elastic Core Optical Networking**
- **IEEE COMMUNICATIONS SURVEYS & TUTORIALS**

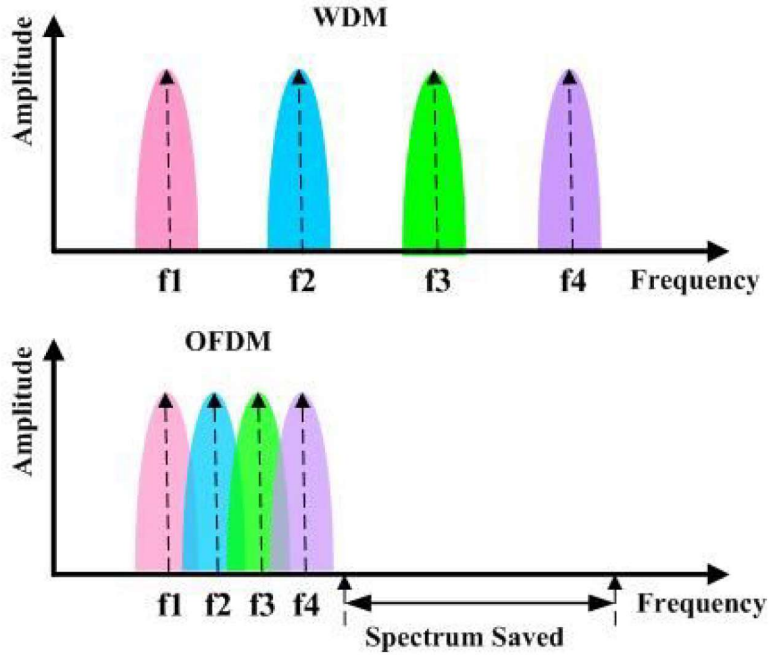
Already used:

- **IEEE 802.11 a/g WiFi**
- **WiMAX**
- **LTE**
- **DAB és DVB**
- **DSL**

How does OOFDM work?

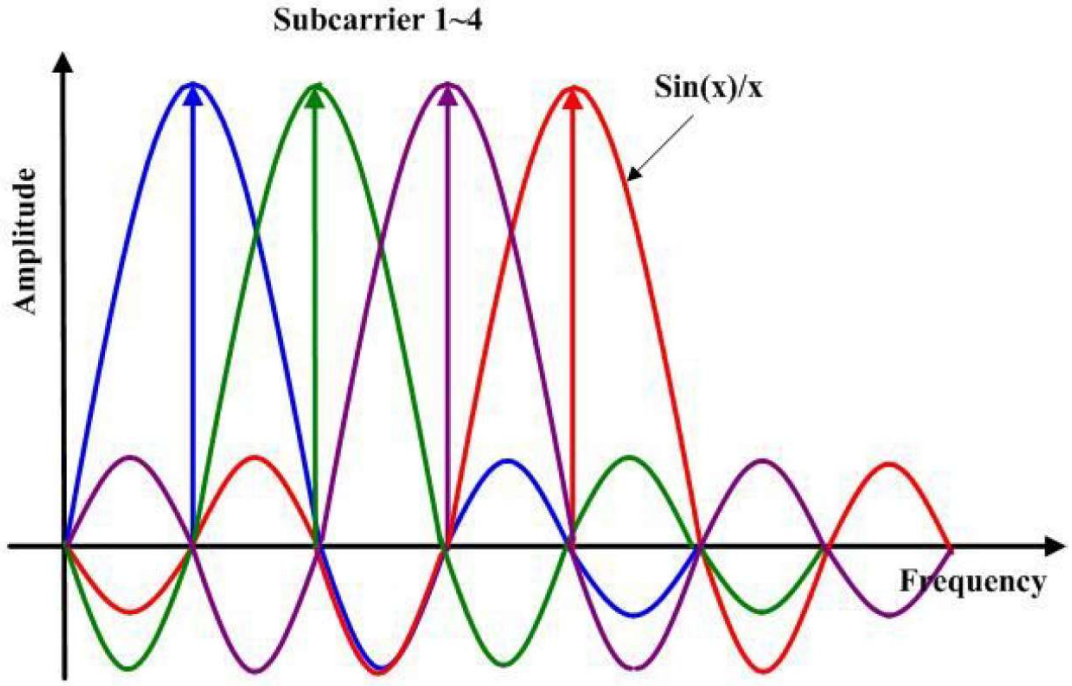
- Multi-Carrier Modulation
- Each carrier carries lower data rate stream
- In WDM large frequency gap needed
- In OFDM frequency banc

WDM and O-OFDM spectrum

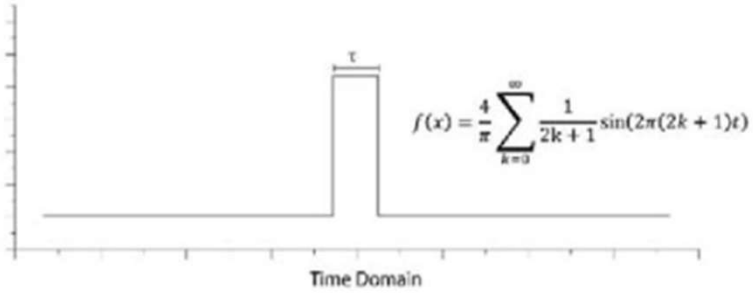


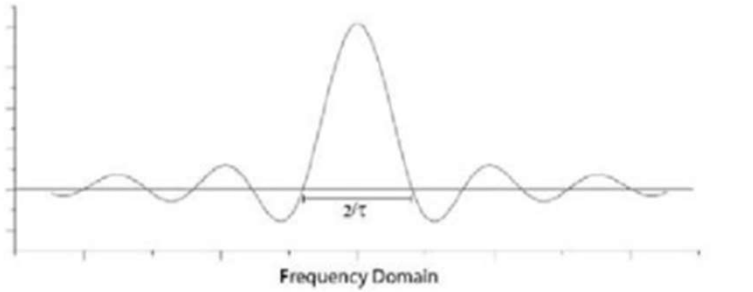
Ortogonality

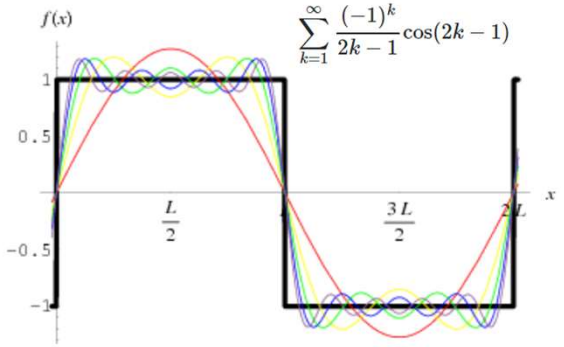
- Where the peak of subcarrier spectrum is
- There other subcarrier spectrums have 0
- Sampling at those frequencies
- Ortogonality → Efficient use of the Spectrum

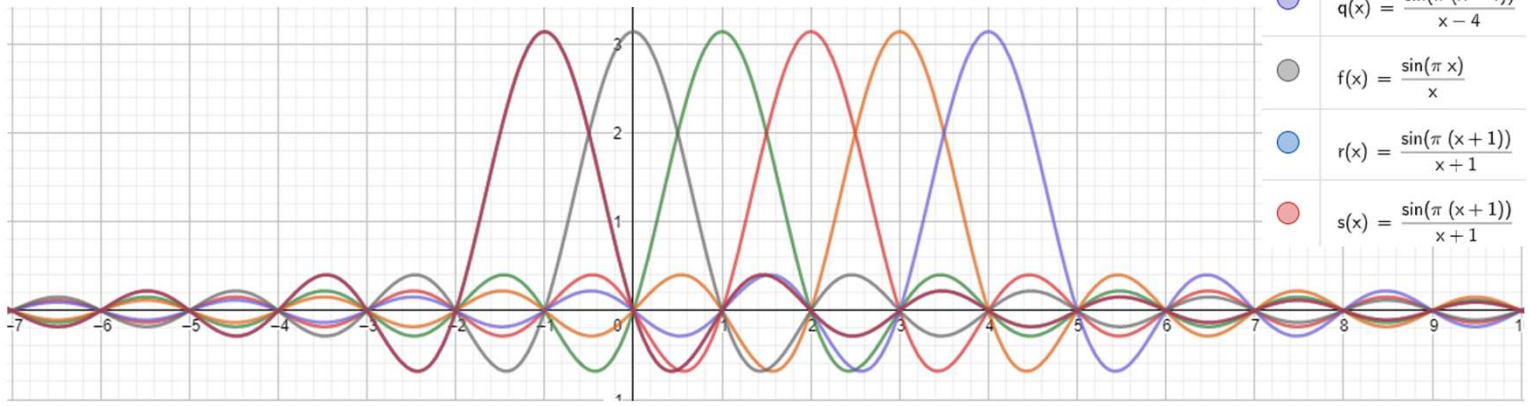


geogebra.org – homework – draw it yourself! ☺



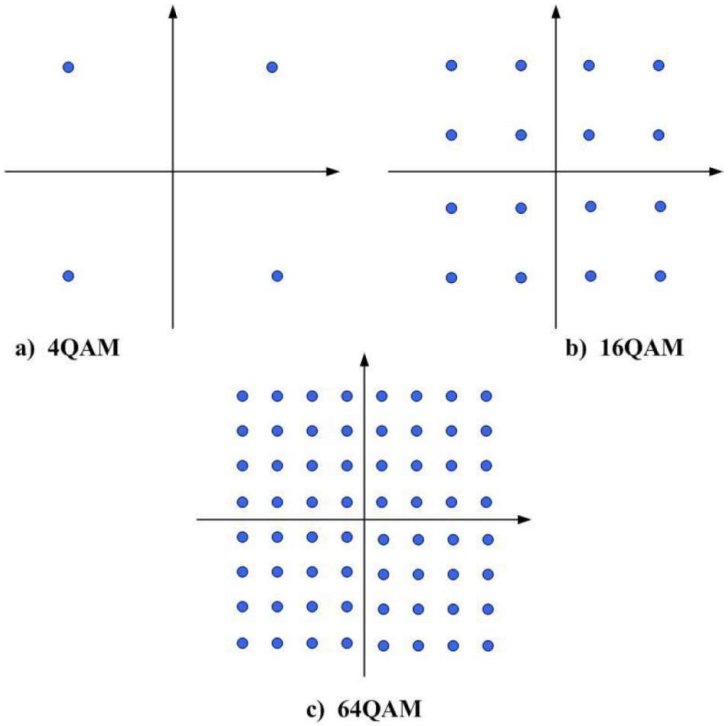






QAM

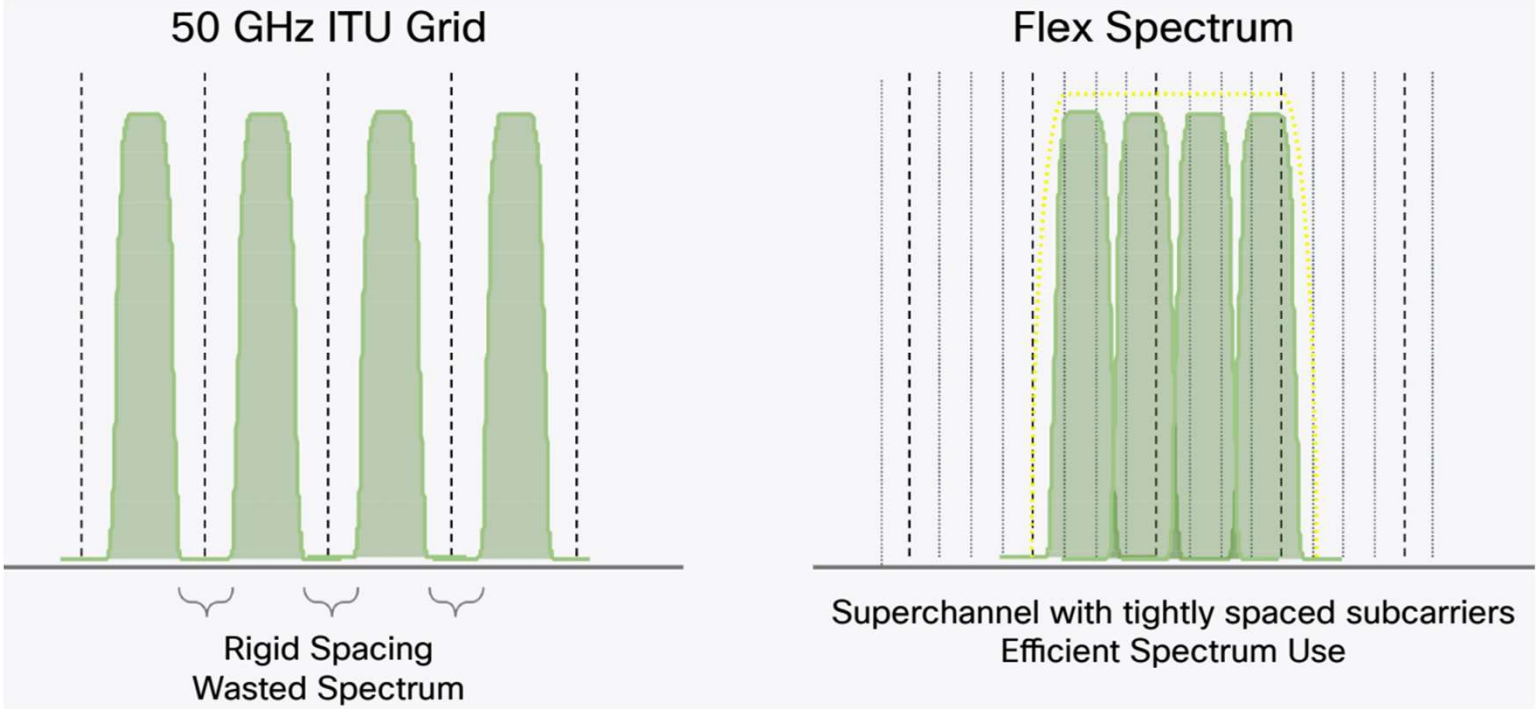
- Quadrature Amplitude Modulation
- 4, 8, 16, 32, 64



Flex Channels of Flex Grid

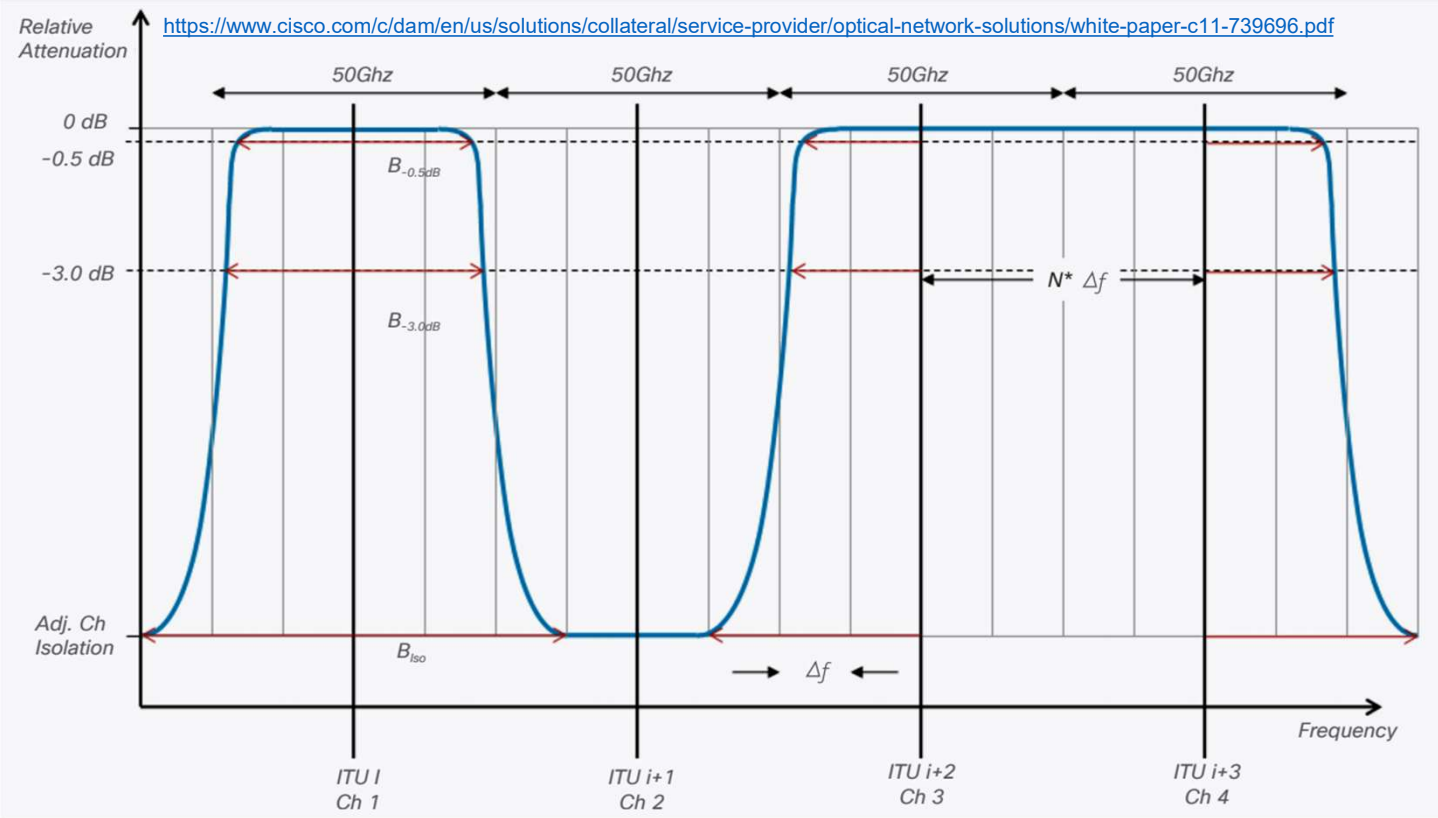
- 12,5 GHz subcarriers
- Typically 37,5 -100 GHz channels
  - Generrally 3-8 subcarriers
  - 4, 6, 8 is most typical… (50-75-100 GHz)

https://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/optical-network-solutions/white-paper-c11-739696.pdf



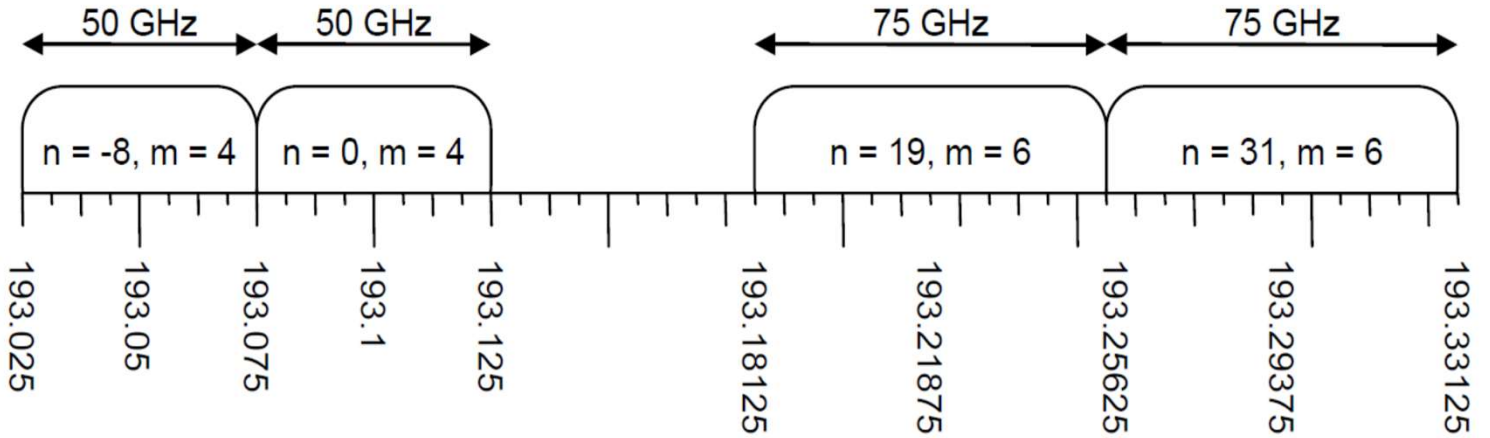
WSON vs SSON

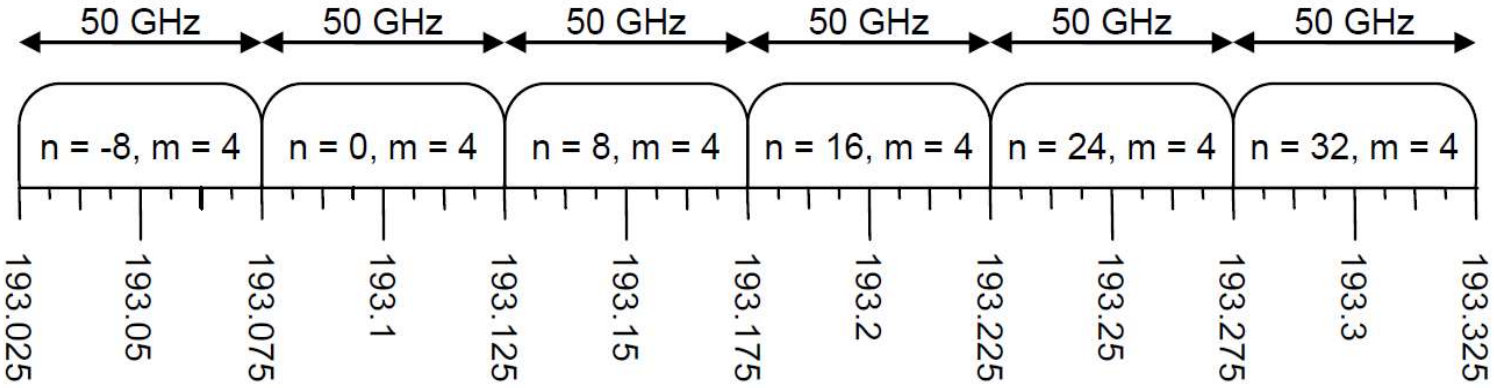
- WSON vs SSON
  - Wavelength Switched Optical Networks (WSON)
  - Spectrum Switched Optical Networks (SSON)



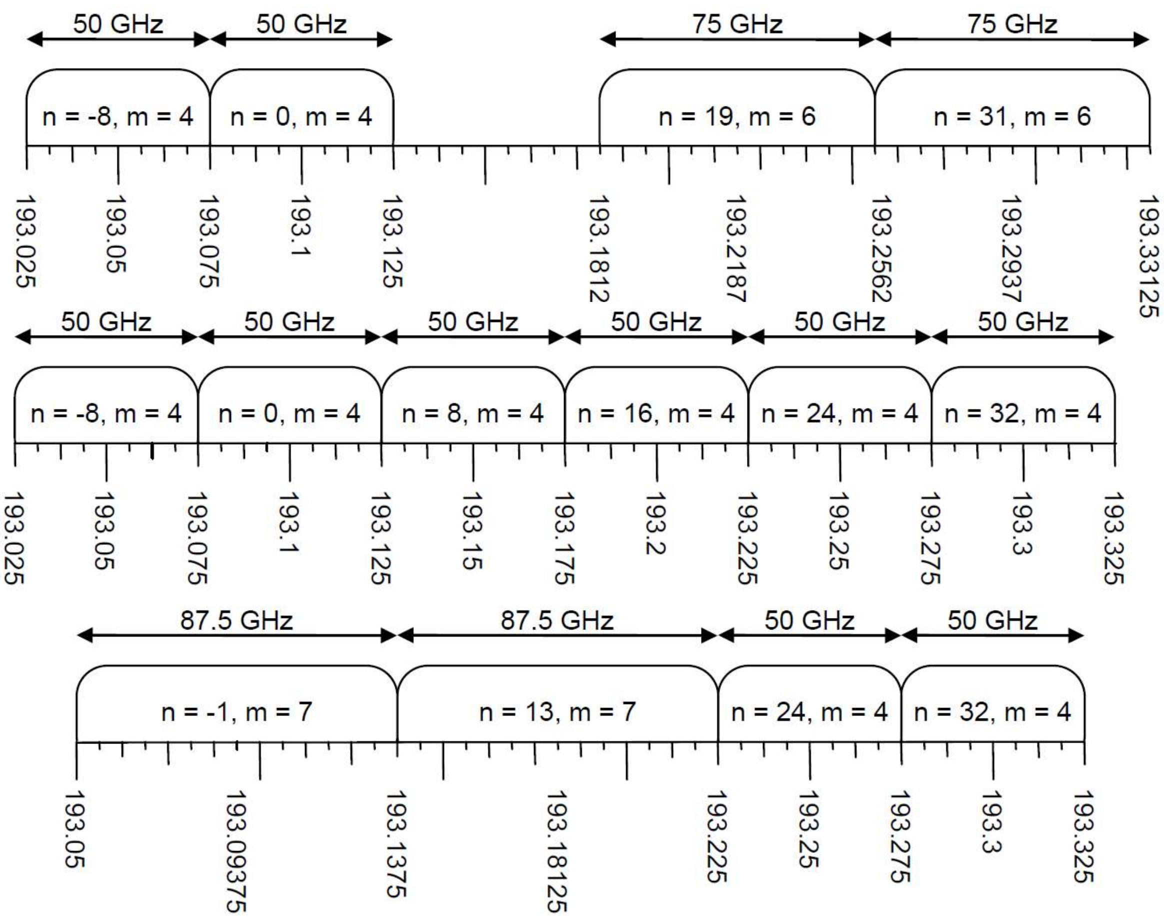
Recommendation ITU-T G.694.1

$$193.1 + n \times 0.0125 \text{ THz}$$





https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.694.1-201202-I!!PDF-E&type=items



50 GHz
50 GHz
75 GHz
75 GHz
n = -8, m = 4
n = 0, m = 4
n = 19, m = 6
n = 31, m = 6
193.025
193.05
193.075
193.1
193.125
193.1812
193.2187
193.2562
193.2937
193.33125
50 GHz
50 GHz
50 GHz
50 GHz
50 GHz
50 GHz
n = -8, m = 4
n = 0, m = 4
n = 8, m = 4
n = 16, m = 4
n = 24, m = 4
n = 32, m = 4
193.025
193.05
193.075
193.1
193.125
193.15
193.175
193.2
193.225
193.25
193.275
193.3
193.325
87.5 GHz
87.5 GHz
50 GHz
50 GHz
n = -1, m = 7
n = 13, m = 7
n = 24, m = 4
n = 32, m = 4
193.05
193.09375
193.1375
193.18125
193.225
193.25
193.275
193.3
193.325

Bitrate–Modulation–Bandwidth–Reach

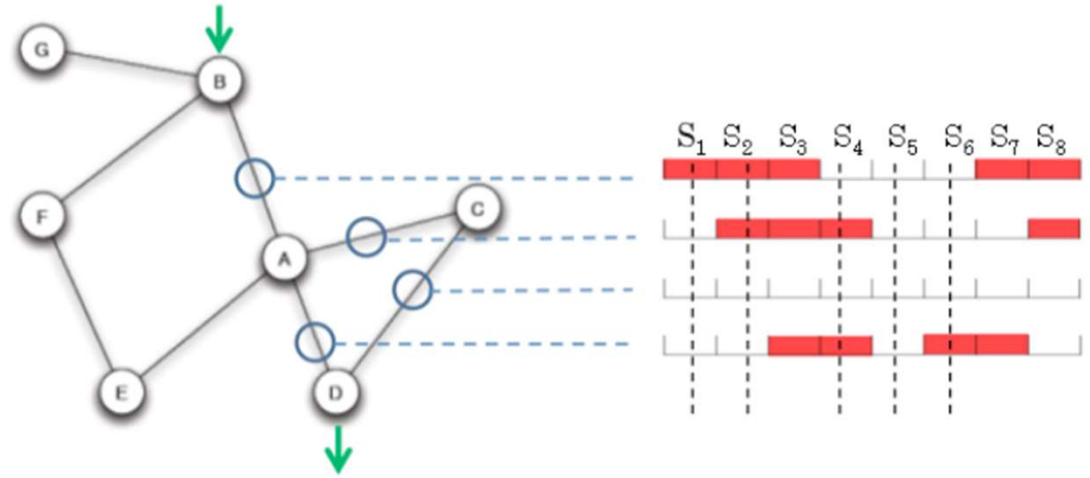
Thierry Zami, Annalisa Morea, Giovanni Bellotti, B. Lavigne:
Is Mixing 50 GHz-Spaced 32 GBaud Channels and 75GHz-Spaced 64 GBaud Ones Useful in a WDM Elastic Network? September 2018, OI: 10.1109/ECOC.2018.8535149, Conference: 2018 European Conference on Optical Communication (ECOC)

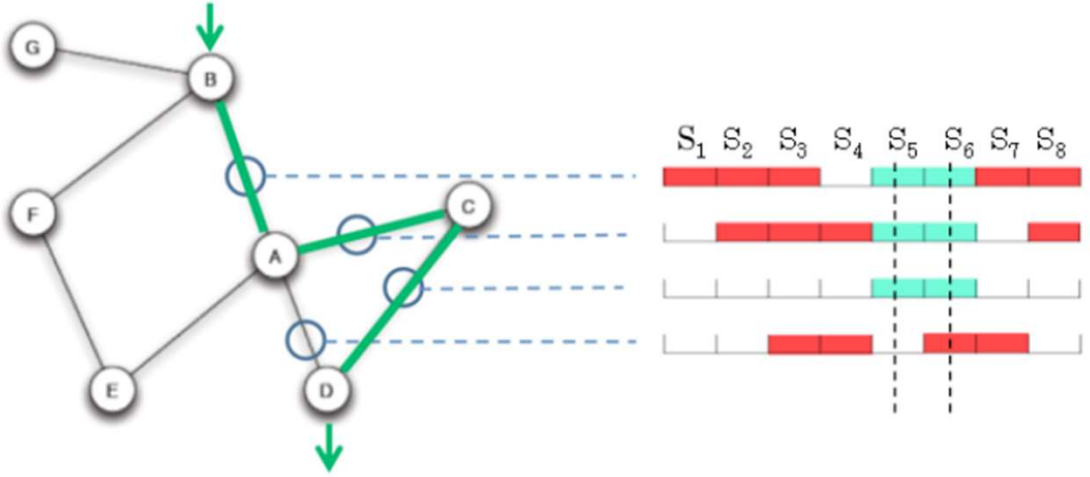
Carrier modulation *with lower FEC code rate	**Channel space (GHz)**	**Reach (km)**
100 Gb/s **32** GBaud PDM-QPSK	**50 or 75**	**4200**
150 Gb/s **32** GBaud PDM-8QAM	**50 or 75**	**1600**
200 Gb/s **32** GBaud PDM-16QAM	**50 or 75**	**800**
250 Gb/s **32** GBaud PDM-32QAM	**50 or 75**	**300**
200 Gb/s **64** GBaud PDM-QPSK	**75**	**2500**
250 Gb/s **64** GBaud PDM-8QAM*	**75**	**1600**
300 Gb/s **64** GBaud PDM-8QAM	**75**	**1100**
350 Gb/s **64** GBaud PDM-16QAM*	**75**	**700**
400 Gb/s **64** GBaud PDM-16QAM	**75**	**500**
450 Gb/s **64** GBaud PDM-32QAM*	**75**	**300**
500 Gb/s **64** GBaud PDM-32QAM	**75**	**200**

Bitrate–Reach–Bandwidth–N.Channels

•	Bit-Rate [Gbit/s]	Distance (Reach) L [km]	Optical Band [GHz]	Max. No. of Channels
a	100	4200	50	96
b	200	800	50	96
c	300	1100	75	64
d	400	500	75	64
e	500	600	100	48

Routing one B⟶D demand : WSON - SSON

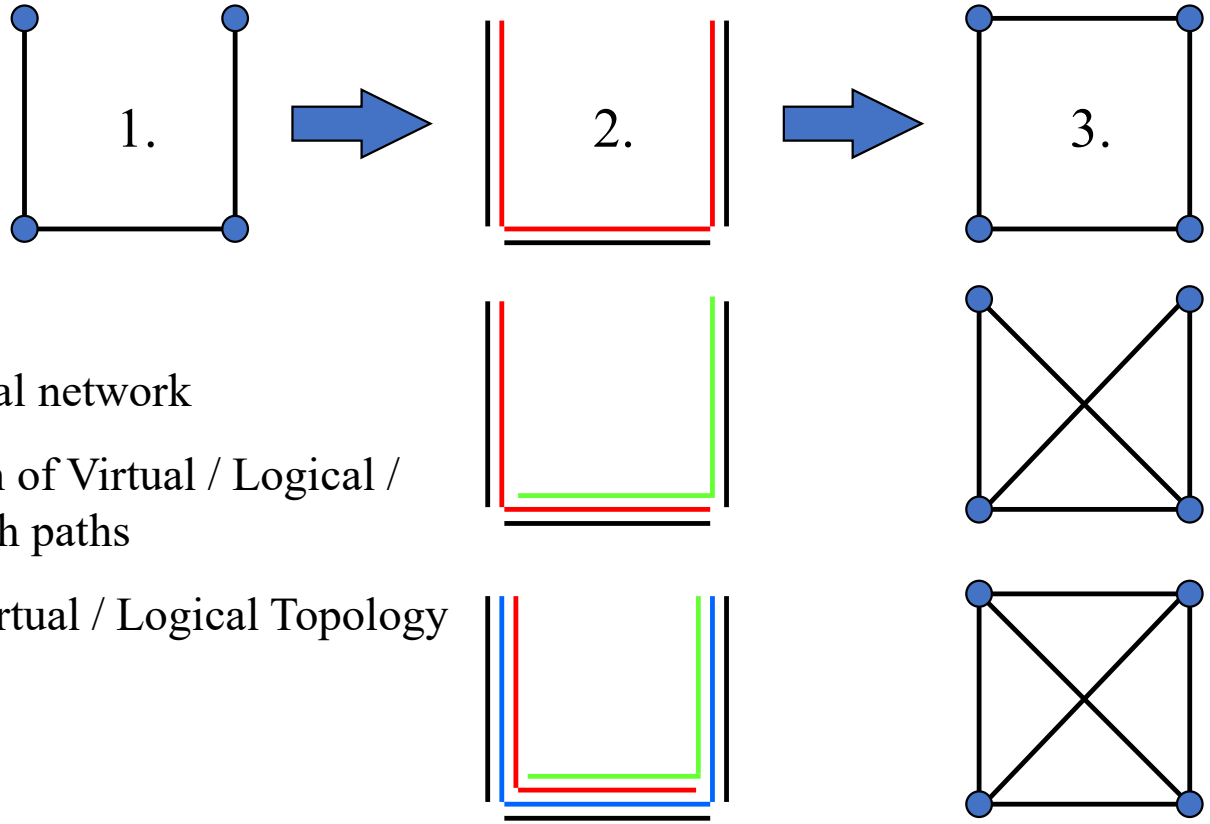




- Spectrum Selective Switching
- Spectrum Selective Network
- Routing and Spectrum Assignment

- Shortest path if sufficient subcarriers
- Longer path if along the shortest one not enough free subcarriers available…

Denser Virtual Topology



1. Physical network
2. System of Virtual / Logical / Wavelength paths
3. The Virtual / Logical Topology

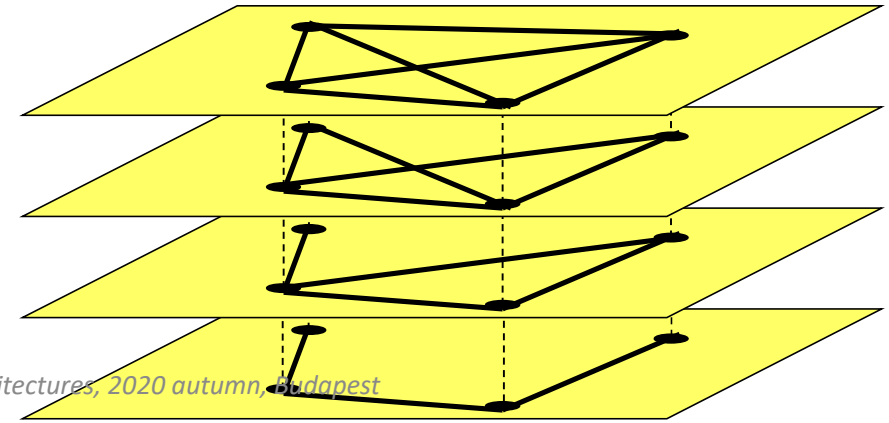
GMPLS/ASTN

Dynamic (Switched) & Multilayer

IETF GMPLS: Generalised Multiprotocol Label Switching

ITU-T ASTN: Automatic Switched Transport Network

PSC	(Packet Switching Capable, e.g., IP)
L2	(Layer 2 SC, e.g., GbEth)
TSC	(TDM SC, e.g., SDH VC-4-4c)
λSC	(Wavelength SC)
WBSC	(WaveBand SC)
FSC	(Fiber SC)



Optical Orthogonal Frequency-Division Multiplexing (O-OFDM)

OFDM: Orthogonal Frequency-Division Multiplexing

O-OFDM: Optical OFDM

- **SpectrumElasticMukherjee_06148192_002.pdf**
- **G. Zhang, M. De Leenheer, A. Morea, B. Mukherjee**
- **A Survey on OFDM-Based Elastic Core Optical Networking**
- **IEEE COMMUNICATIONS SURVEYS & TUTORIALS**

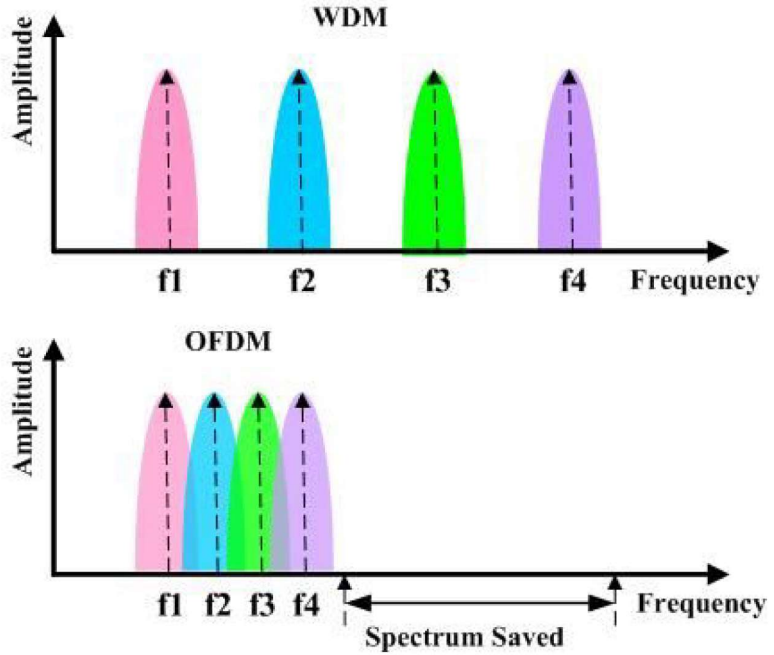
Already used:

- **IEEE 802.11 a/g WiFi**
- **WiMAX**
- **LTE**
- **DAB és DVB**
- **DSL**

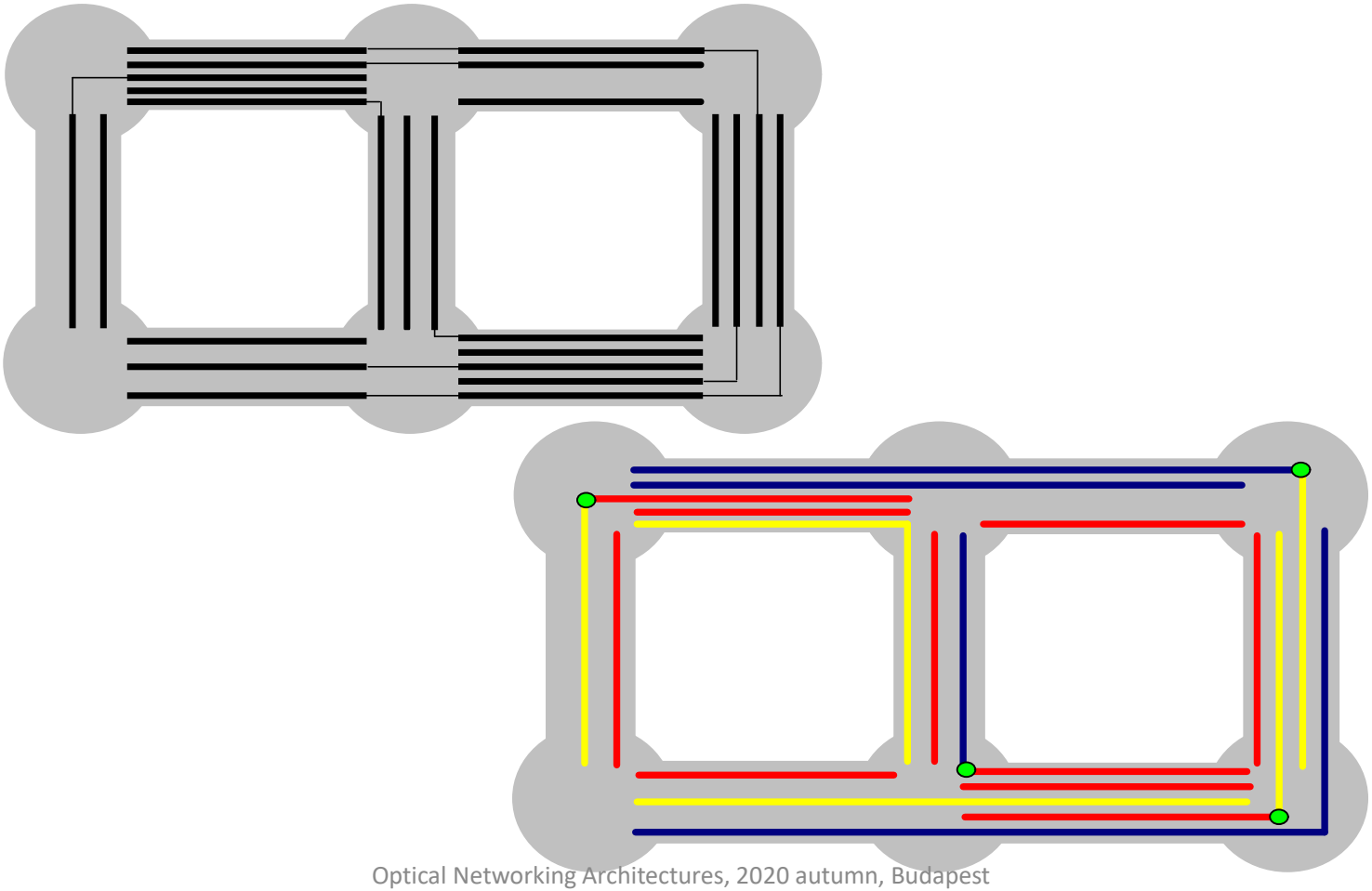
How does OOFDM work?

- Multi-Carrier Modulation
- Each carrier carries lower data rate stream
- In WDM large frequency gap needed
- In OFDM frequency banc

WDM and O-OFDM spectrum

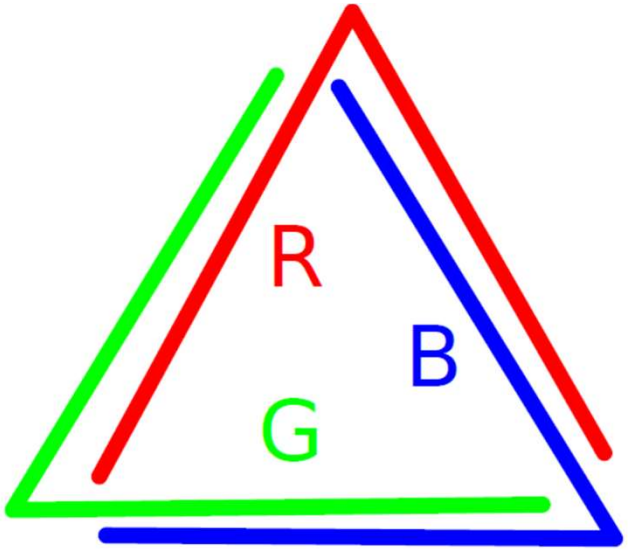


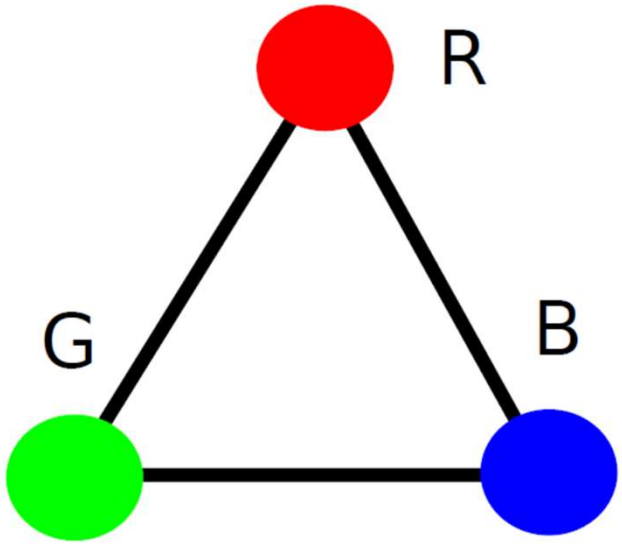
Using wavelengths…



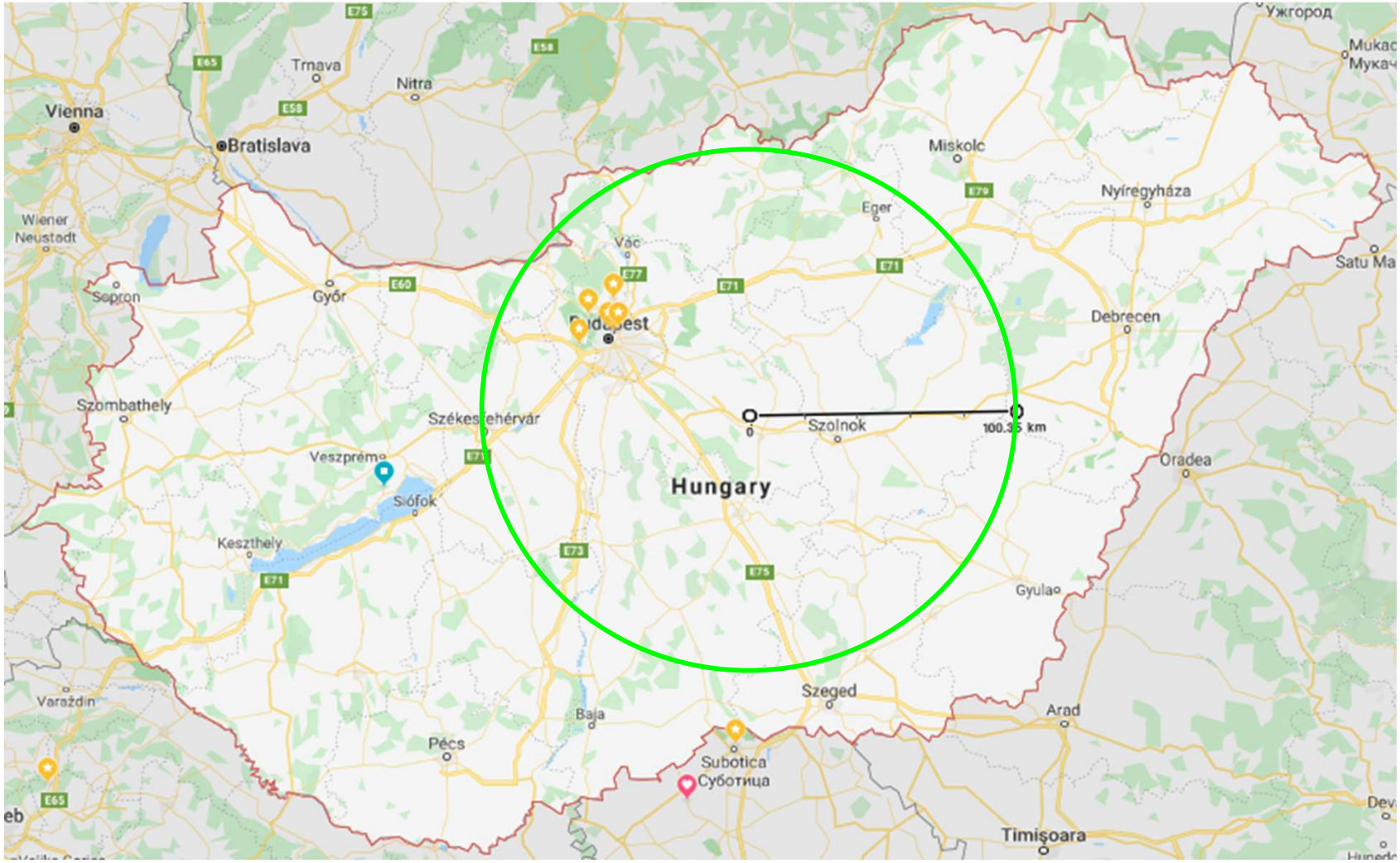
„Colouring”

- Spectrum (Wavelength) Assignment
- Colouring graph
- Graph colouring



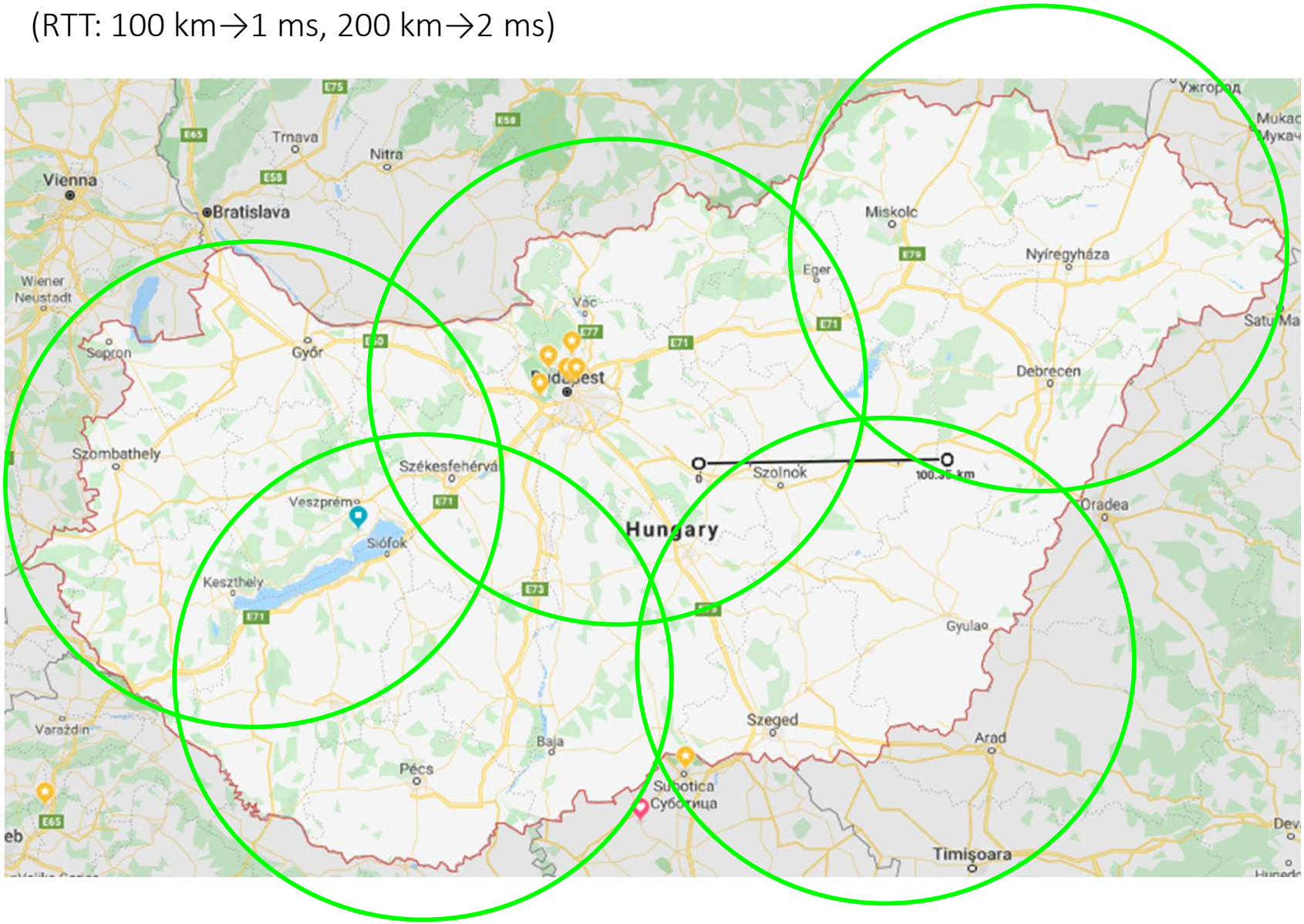


Round-Trip Times in Hungary (RTT: 100 km→1 ms, 200 km→2 ms)

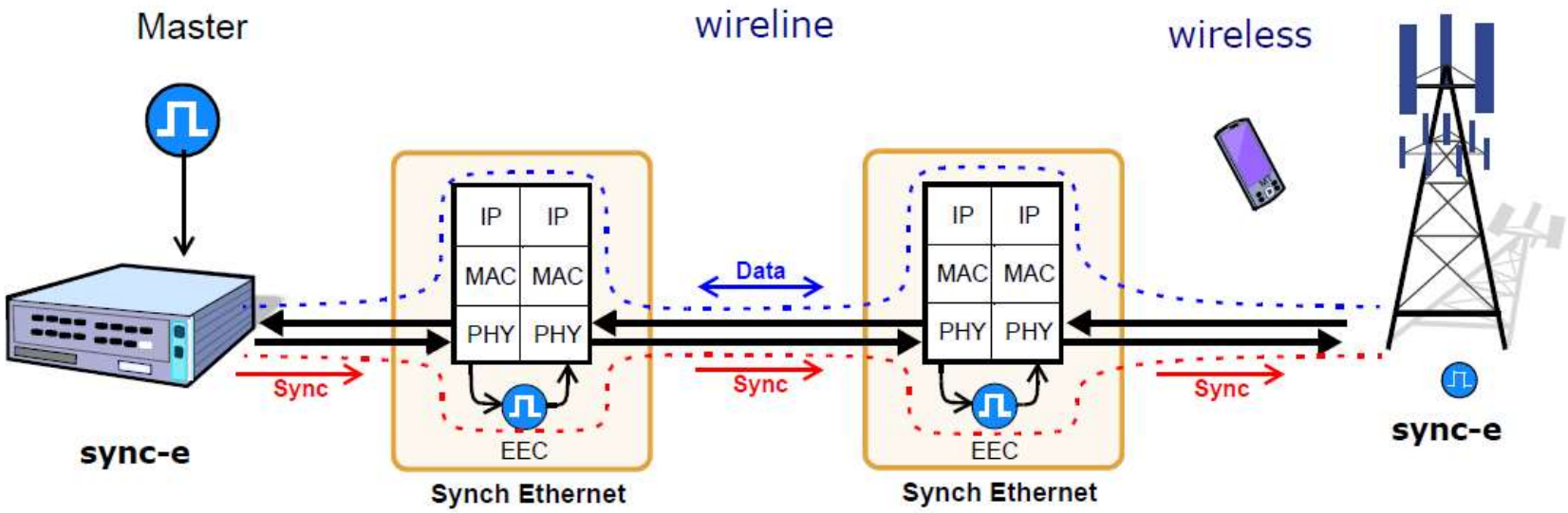


Optical cables are longer than the air-distance!

(RTT: 100 km→1 ms, 200 km→2 ms)

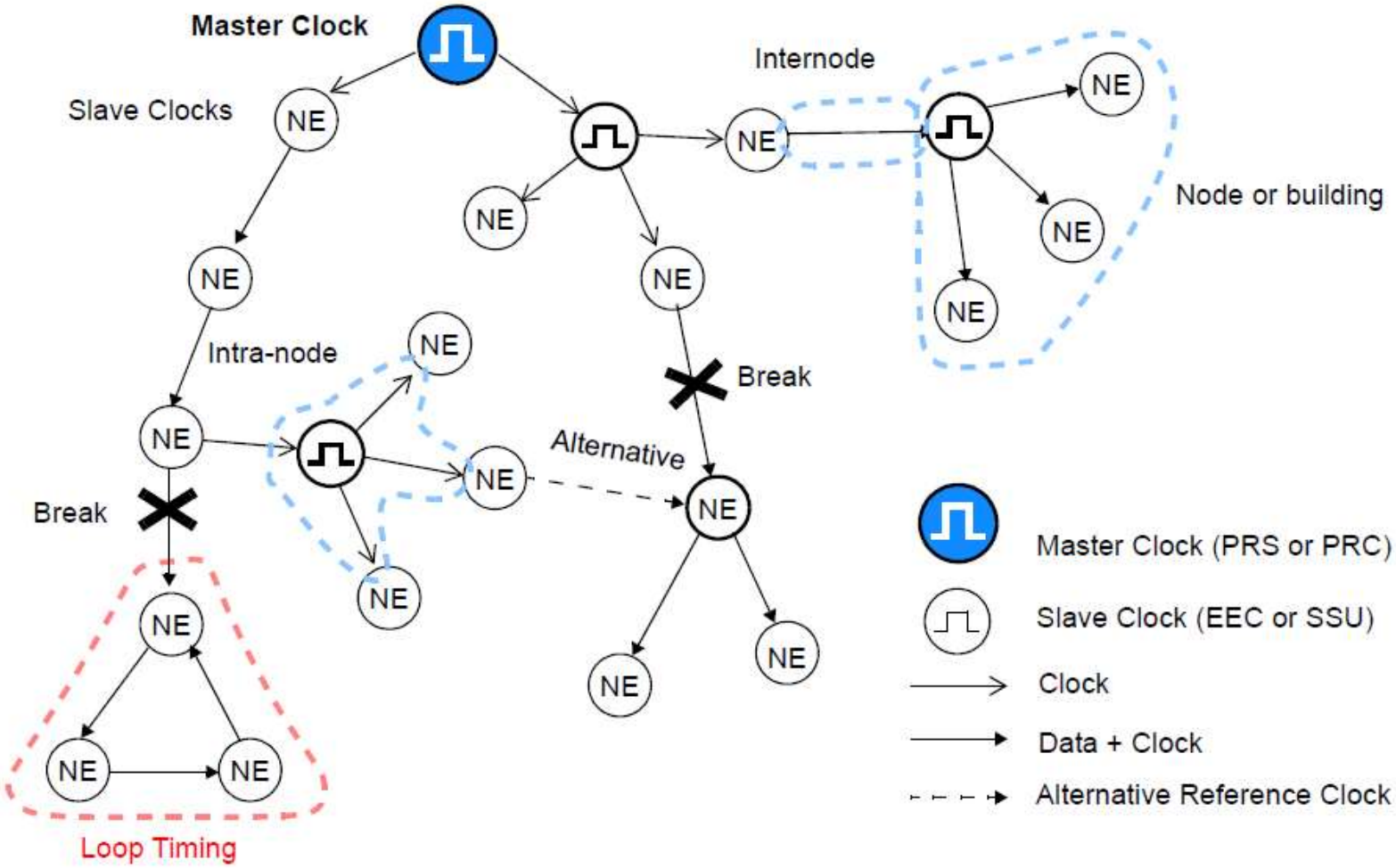


SyncE: Synchronous Ethernet



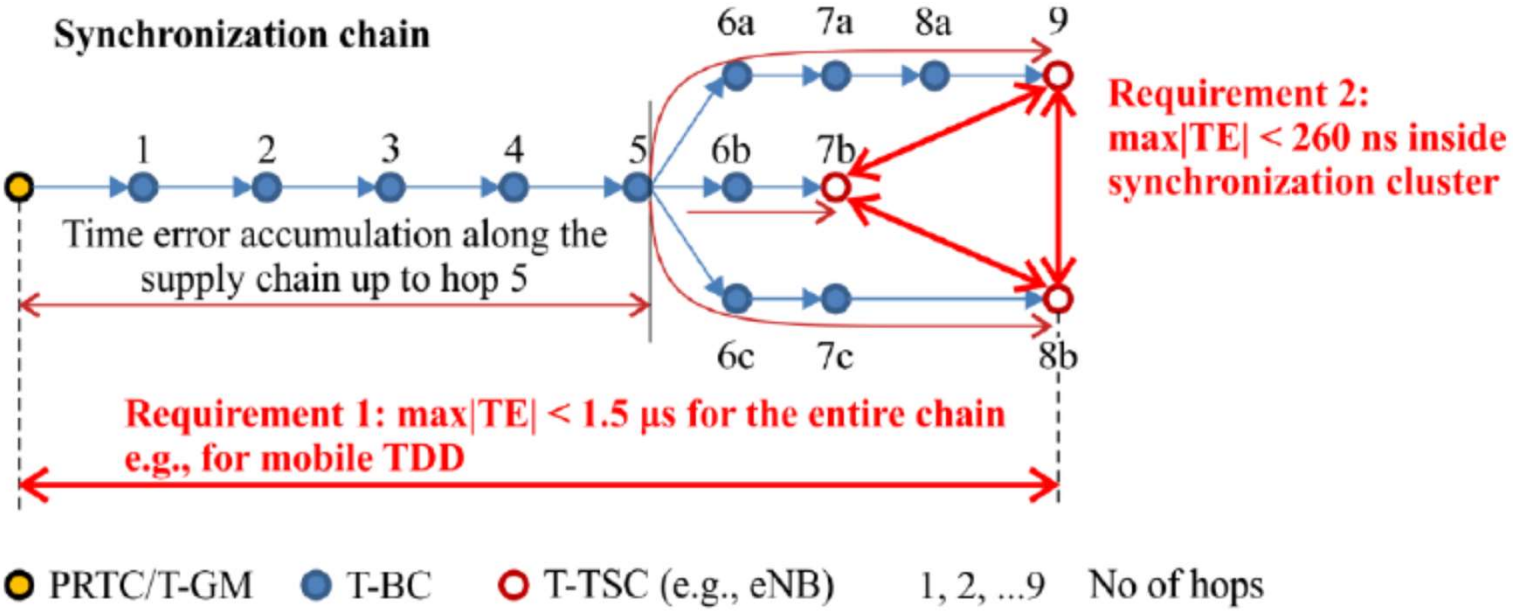
- ITU-T Rec. G.8261, 8262, 8264
- PRS: Primary Reference Source (accuracy 10^{-11})
- PRC: Primary Reference Clock (PRC/PRS)
- SSU: Synchronization Supply Unit (EEC-nél pontosabb)
- EEC: Ethernet Equipment Slave Clock ±4.6 ppm

SyncE (WikiPedia)



- Clock and data paths may differ!!!!

Synchronization Chain

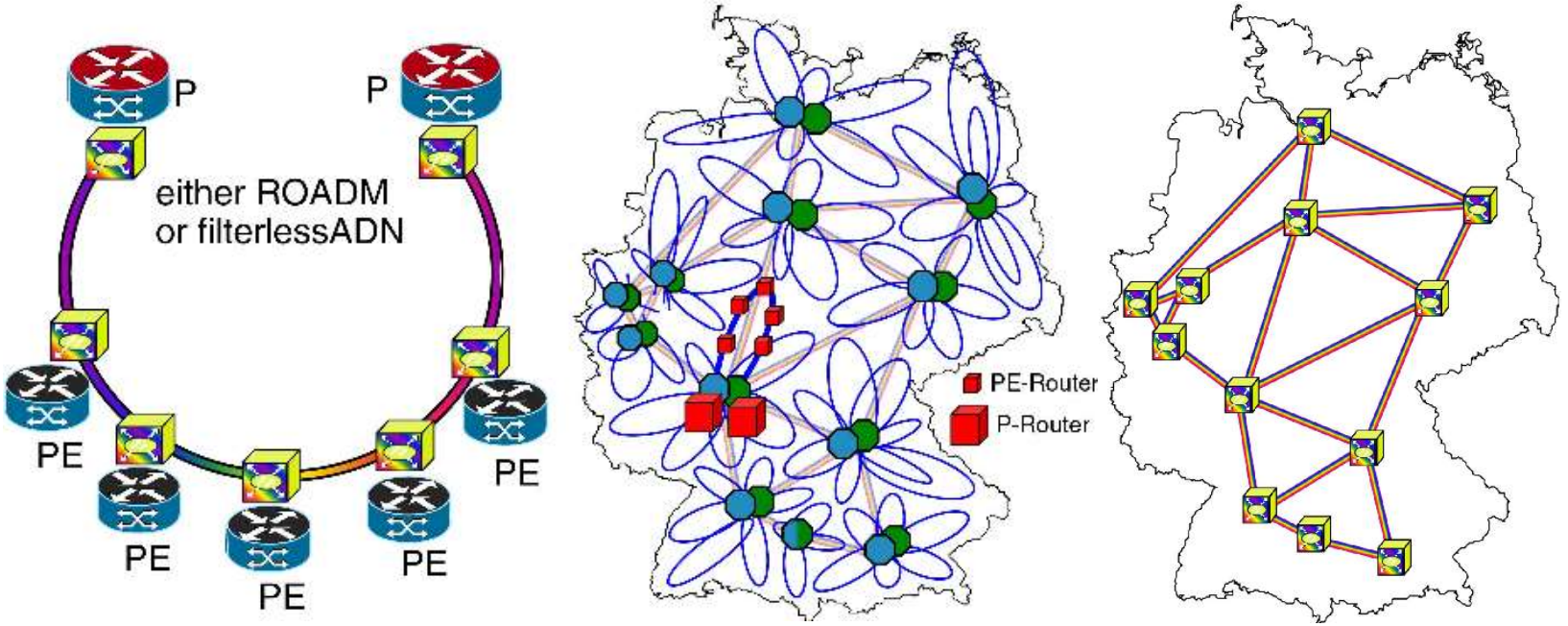


Sync. Specification (ITU-T G.8271):

- Frequency synchronization accuracy within 50ppb (10^{-9})
- Phase:
  - TDD (level of accuracy: 4): TE < 1,5 µs (E2E)
  - CarrierAggregation (level of accuracy 6A): TE < 260 ns(rel)
    - TE: Time Error

Germany example – Filterless Optical Network - HorseShoes

Vendor-interoperable elastic optical interfaces: Standards, experiments, and challenges [Invited], Matthias Gunkel, Arnold Mattheus, Felix Wissel, Antonio Napoli, João Pedro, Nélson Costa, Talha Rahman, Gianluca Meloni, Francesco Fresi, Filippo Cugini, Nicola Sambo, Marc Bohn, Published in IEEE/OSA Journal of Optical Communications and Networking, 2015, DOI:10.1364/JOCN.7.00B184



European DC Interconnect

- 4 DCs (Data Centers)
- 3 locations
- DC nterconnect
  - Two-failure Protected
- All other nodes
  - One-Failure Protected

- Length limitations!
- Cheapest Topology Sought!