
12-13 June 2024. Lannion, France

EPIC Meeting on Specialty Optical Fibers:
New Designs and Novel Applications
at Photonics Bretagne

Potentialities of Hollow-Core Fibers for Optical Transport (WDM) and Access Networks (FTTx)

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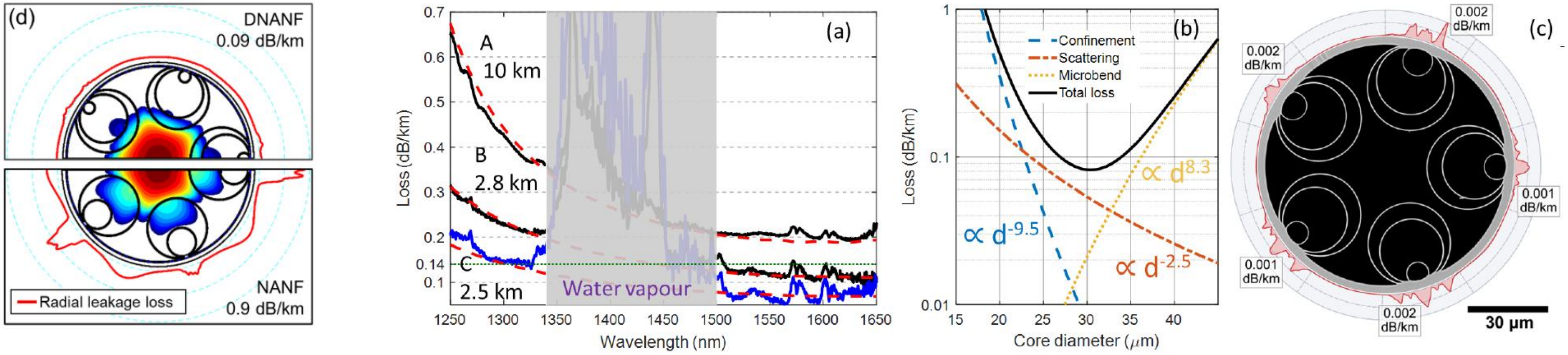
Orange Innovation Networks – WNI/FAN – WNI/AOT

12-13 juin 2024 - Lannion

Optical Transport Networks (WDM)

Hollow Core Fibers: a Revolution for Optical Transport?

- Since the beginning of 2020’s decade, the ORC of Southampton University and its spin-off, Luminesity, have hugely make evolved the domain of Hollow Core Fibers (HCF) and more particularly have introduced Nested Anti-resonant Nodeless Fibers (NANF) and Double-Nested Anti-resonant Nodeless Fibers (DNANF):
  - ✓ OFC’2024 [1]: DNANF with 0.11 dB/km @ 1550-nm & 0.15 dB/km @ 1310-nm,
  - ✓ OFC’2022 [2]: DNANF with 0.174 dB/km @ 1550-nm & 0.22 dB/km @ 1310-nm,
  - ✓ Optics Express 2014 [3]: ORC proposal for a new HCF combining the qualities of Photonic Band-Gap Fibers (PBGF) and Anti-Resonant Fibers (ARF): low propagation loss and bend robustness (PBGF) and wide bandwidth and low modal overlap with the cladding (ARF).



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[1] Y. Chen et al., ″Hollow Core DNANF Optical Fiber with <0.11 dB/km Loss,″ Postdeadline Paper, OFC’2024, San Diego

[2] G. T. Jasion et al., "0.174 dB/km Hollow Core Double Nested Antiresonant Nodeless Fiber (DNANF),″ Postdeadline Paper Th4C.7, OFC’2022, San Diego.

[3] Francesco Poletti, "Nested antiresonant nodeless hollow core fiber," Opt. Express 22, 23807-23828 (2014)

Hollow Core Fibers: a Revolution for Optical Transport?

- Three reasons explain the renewed interest for this new HCF type:

  - ✓ Low losses,
  - ✓ Low latency: reduction of one third of the fiber propagation duration → speed of light of 3x10^8 m/s in HCF instead of 2x10^8 in silica core fiber (SCF),
  - ✓ Low non-linear effects: the non-linear parameter γ is three order of magnitude less in HCF than in SCF → no Kerr effects, no Stimulated Raman Scattering (SRS) between amplification bands in multi-band WDM systems[4], as illustrated below.

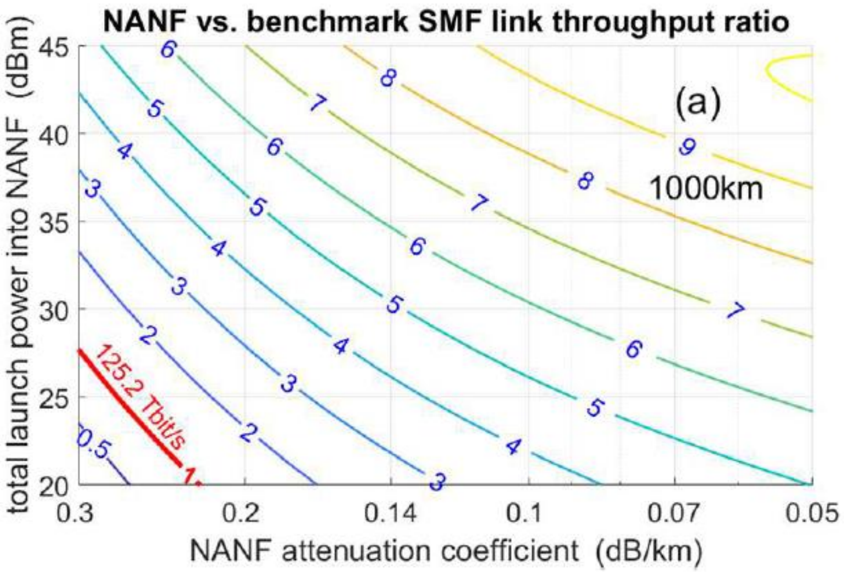

Fig: Data throughput ratio between NANF and SSMF over a C+L-band WDM system operating between 1530 and 1625-nm over 10x100-km versus NANF attenuation and total launch power inside NANF.

Baud rate = 64 Gbaud
Δf = 75 GHz
γ = 1.2 W^{-1}.km^{-1} , D = 17 ps/nm/km (SSMF)
γ = 5x10^{-4} W^{-1}.km^{-1} , D = 2.5 ps/nm/km (NANF)

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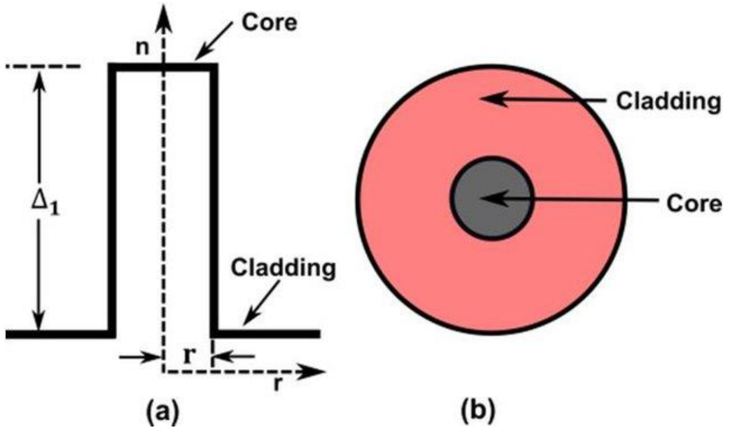
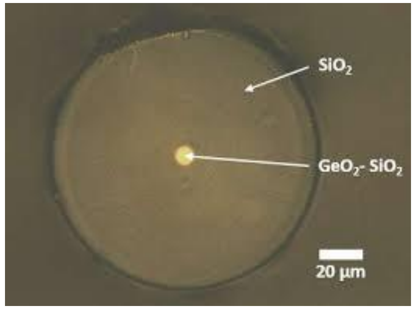
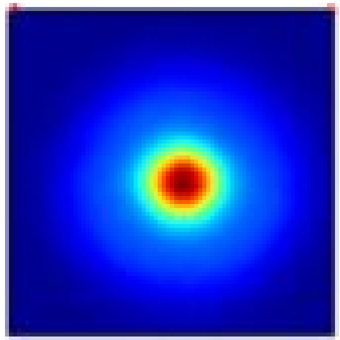
[4] P. Poggiolini and F. Poletti, "Opportunities and Challenges for Long-Distance Transmission in Hollow-Core Fibres," in *Journal of Lightwave Technology*, vol. 40, no. 6, pp. 1605-1616, 15 March15, 2022, doi: 10.1109/JLT.2021.3140114.

HCF versus Silica Core Fiber Comparison

- Silica core fiber (SCF): ~5 billions of kilometers deployed on earth worldwide today.
- Speed of light in SCF: ~200 000 km/s → 50 ms to cross the Pacific Ocean.
- ~5 Euros → 1 km of SCF.
- Light guidance by refractive index (total internal reflection)
- Applications: FTTH, Optical transport (WDM, subsea)



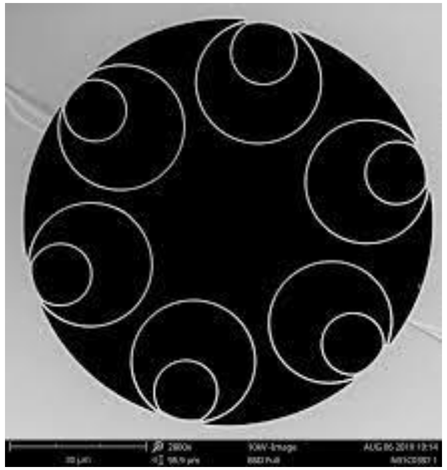


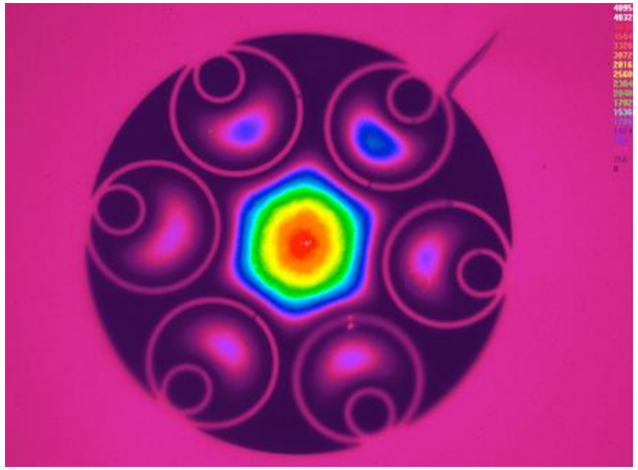


n ~ 1.47

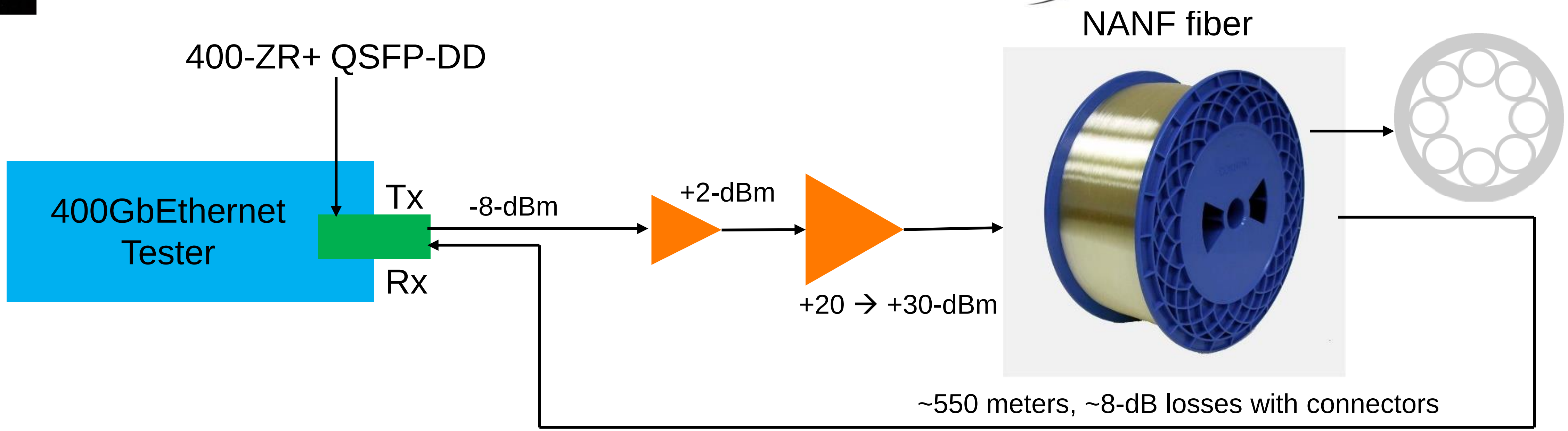
Δ_1~ 5x10^{-3}

- Hollow Core Fiber (HCF): several thousands of kilometers.
- Speed of light in HCF: ~300 000 km/s → 33 µs to cross 10-km of fiber between a US bank headquarter and Wall-Street (against 50 µs for a SCF).
- > 100 kEuros → 1 km of HCF.
- Light guidance: antiresonant phenomenon through a mechanism of inhibited coupling in the higher order modes.
- Applications: « fast trading », low latency, WDM transport, quantum communications (co-propagation QKD/WDM).





Experimental Set-Up



NANF fiber

400-ZR+ QSFP-DD

400GbEthernet Tester

Tx

Rx

-8-dBm

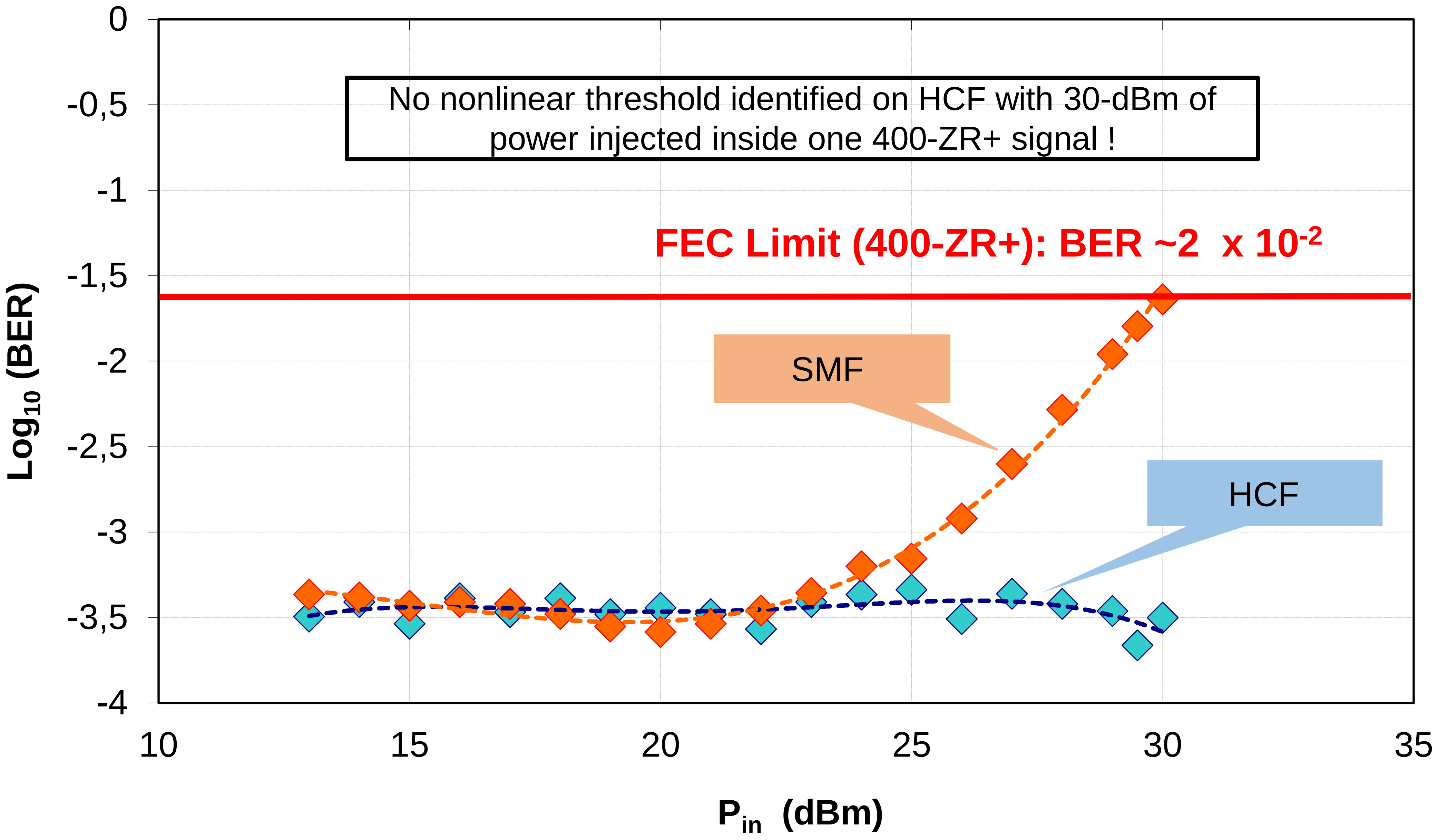
+2-dBm

+20 → +30-dBm

~550 meters, ~8-dB losses with connectors

- 550 meters of NANF manufactured by Photonics Bretagne in Lannion with ~5.5-dB losses at 1550-nm and ~8-dB losses with connectors.
- The 400-Gbps Pol-Mux 16QAM signal is generated by a 400-ZR+ QSFP-DD with -8-dBm output power.
- A cascade of two EDFAs, a micro-EDFA + a high-power EDFA, enables to explore the [+20 - +30]-dBm power range at the NANF input.
- The objective here is to show that the non-linear threshold in the NANF fiber is considerably shifted towards the high power compared to SSMF (ITU-T G652 fiber).

Compared performance between SSMF (SCF) and HCF

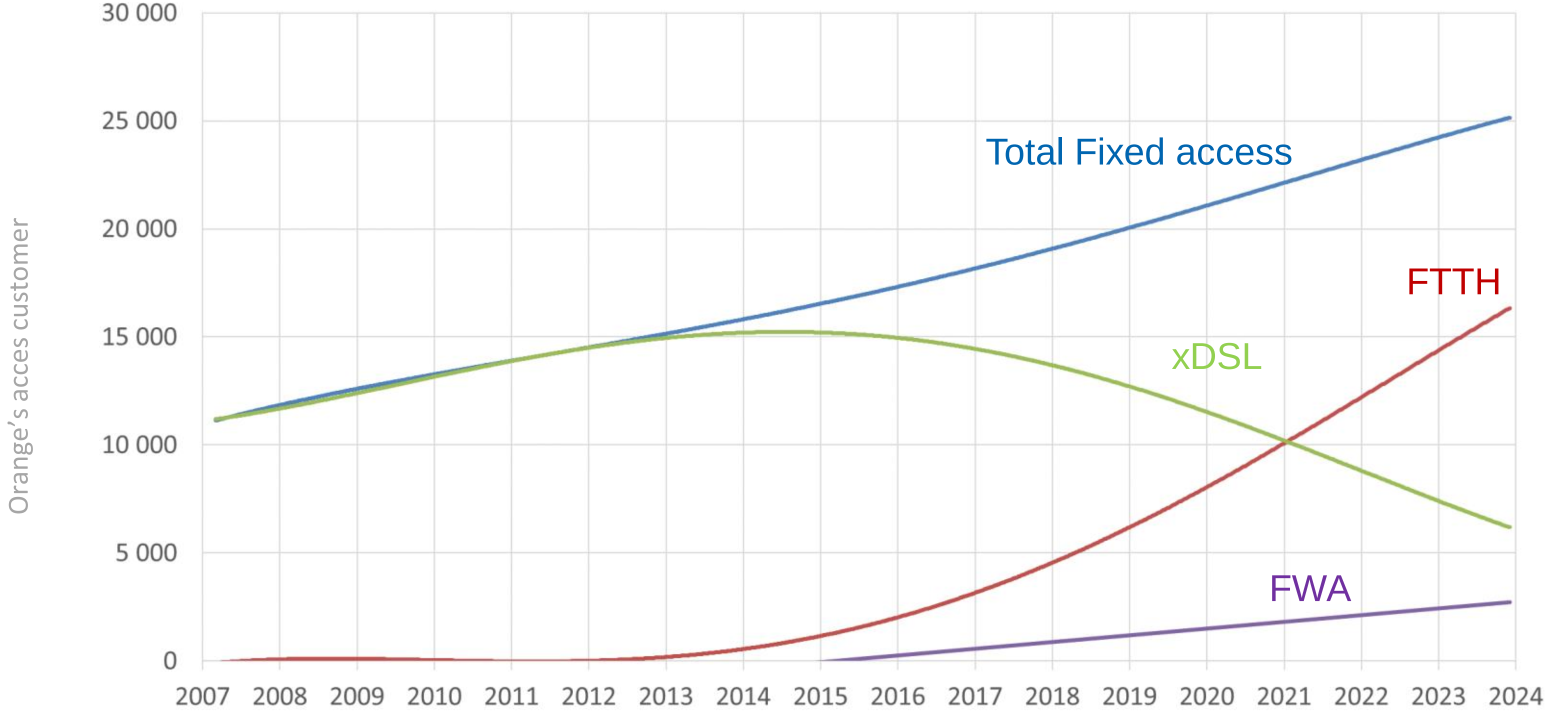


Optical Access Networks (FTTx)

Orange’s Fixed accesses customers

[customer base x 1000]

FWA: Fixed Wireless Access
FTTH: Fiber to The Home
xDSL : Digital Subscriber Line



Orange Fixed operations around the world

~ 25M

Broadband internet customers

~72M

FTTH Home Passed

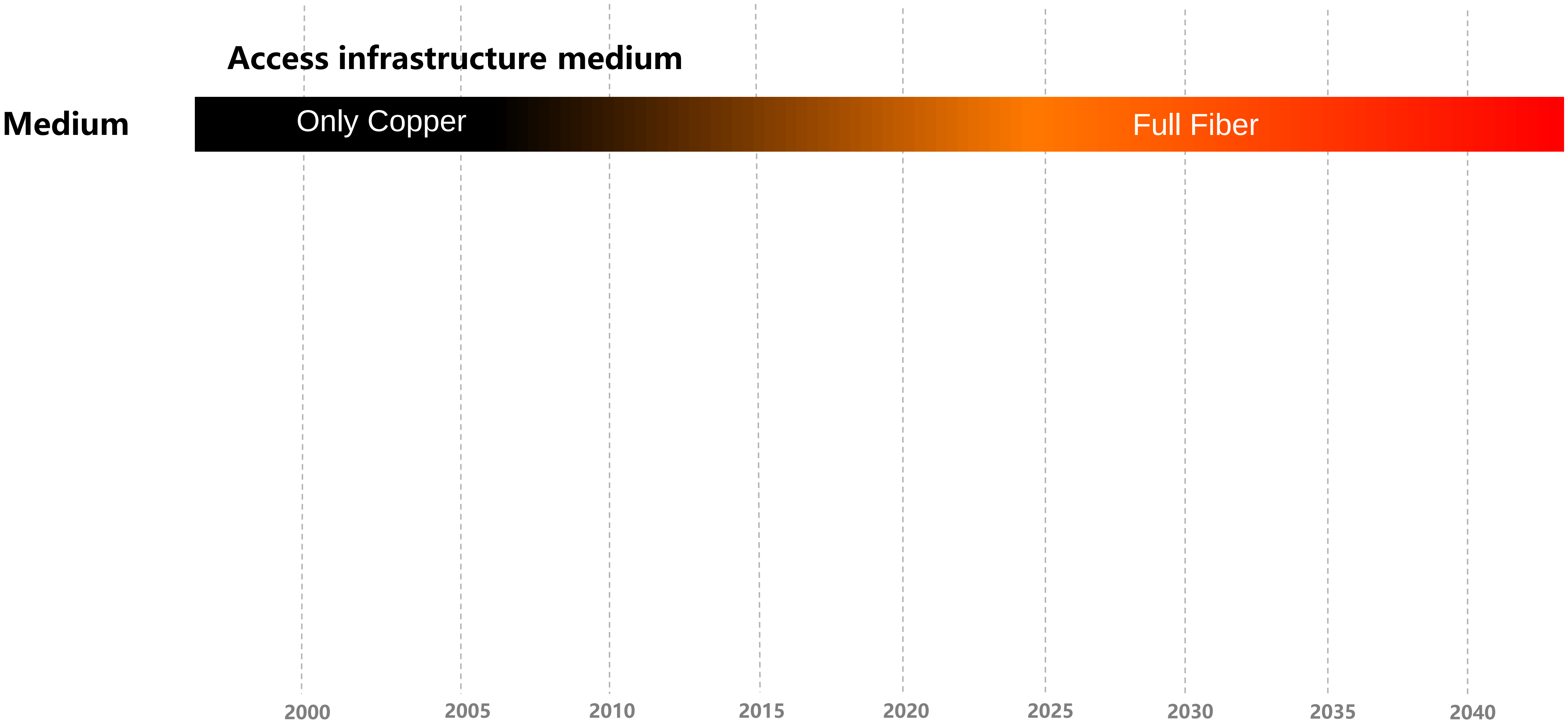
~17M

FTTH customers

17

FTTH networks in Europe (8) and MEA (9 and counting..

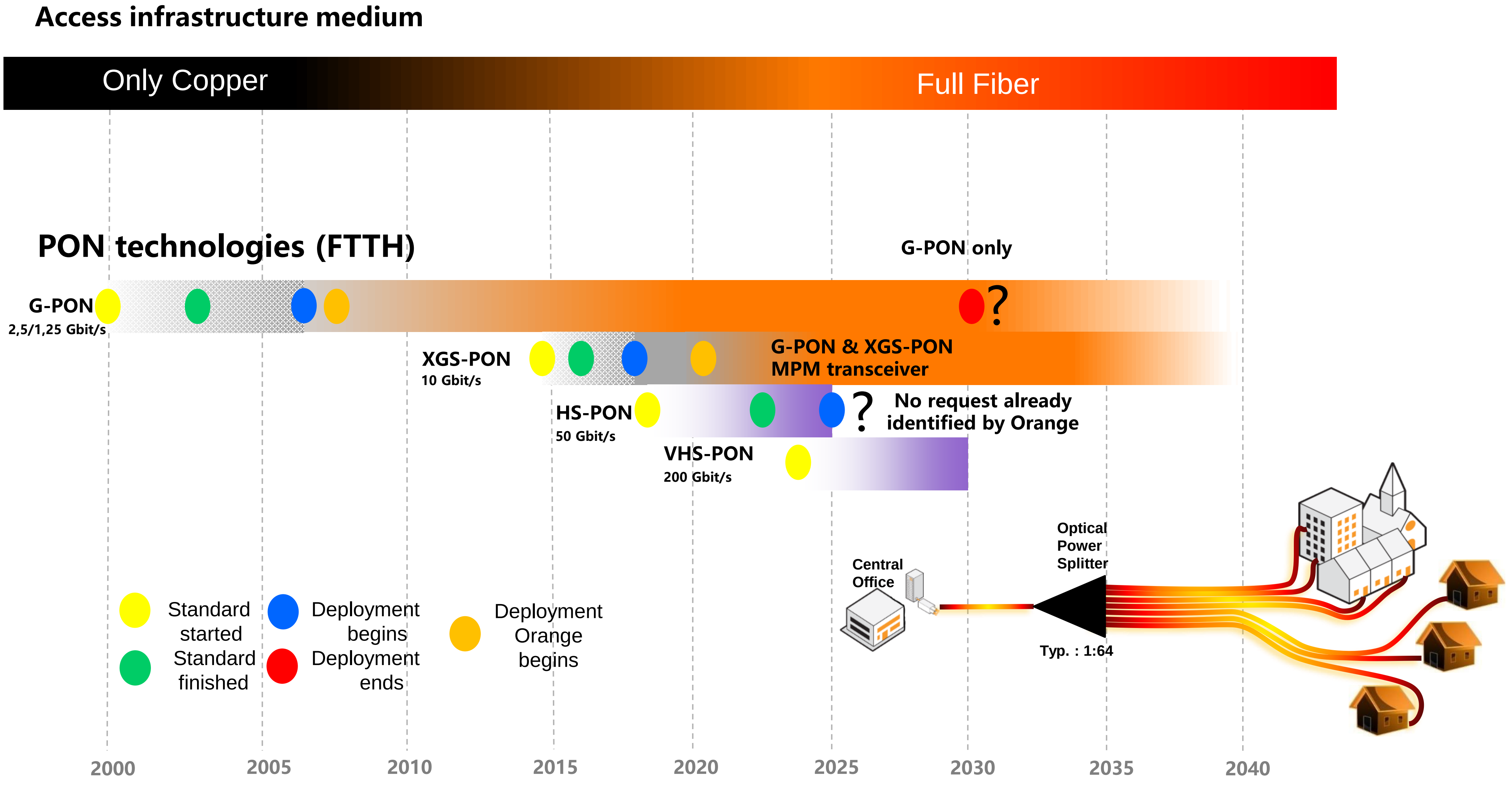
The right medium to maintain high quality fixed access network (FTTx)



Access infrastructure medium

Medium

The right technology to maintain high quality fixed access



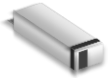
Access infrastructure medium

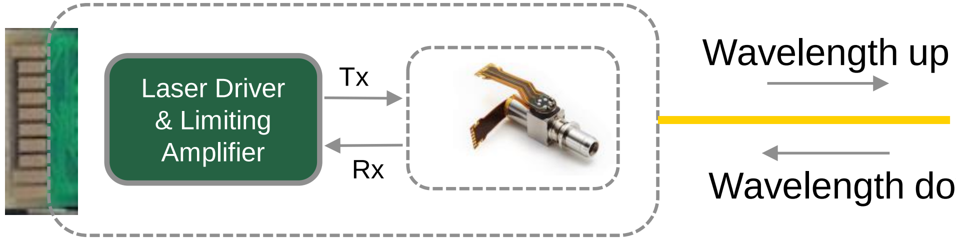
PON technologies (FTTH)

🟡 Standard started
🟢 Standard finished
🔵 Deployment begins
🔴 Deployment ends
🟠 Deployment Orange begins

The right technology to maintain high quality fixed access

G-PON



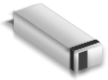


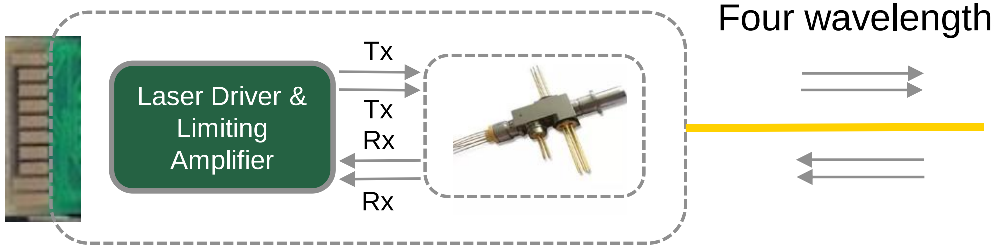
Two wavelengths (1490 / 1310 nm):

Wavelength up

Wavelength down

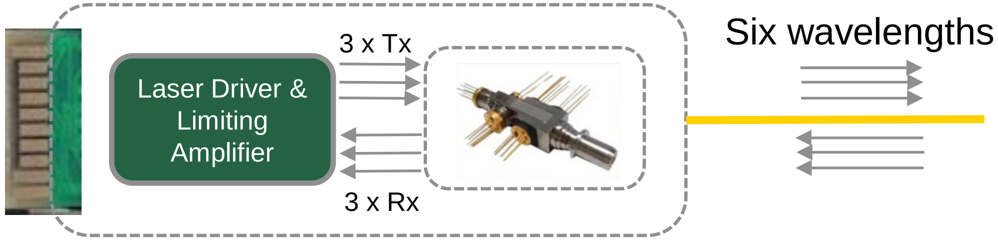
Combo
G-PON & XGS-PON





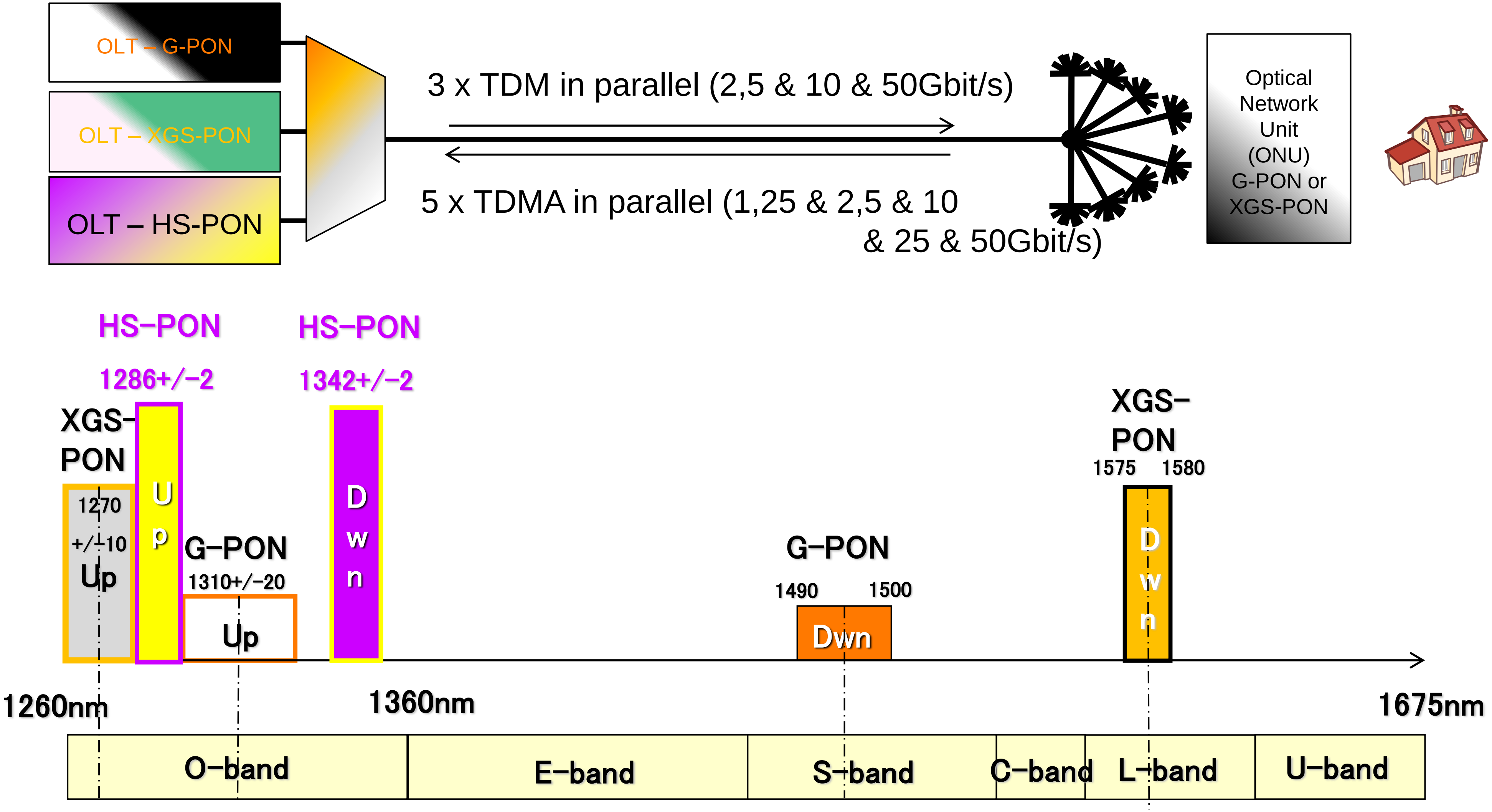
Four wavelengths (1577 / 1270 + 1490 / 1310 nm):

Tri-Combo
G-PON & XGS-PON & 50G-PON



Six wavelengths (1342 / 1286 + 1577 / 1270 + 1490 / 1310 nm):

The right technology to maintain high quality fixed access



OLT – G-PON

OLT – XGS-PON

OLT – HS-PON

3 x TDM in parallel (2,5 & 10 & 50Gbit/s)

5 x TDMA in parallel (1,25 & 2,5 & 10 & 25 & 50Gbit/s)

Optical Network Unit (ONU) G-PON or XGS-PON

HS-PON 1286+/-2 Up

HS-PON 1342+/-2 Dwn

XGS-PON 1270 +/-10 Up

G-PON 1310+/-20 Up

G-PON 1490 1500 Dwn

XGS-PON 1575 1580 Dwn

1260nm

1360nm

1675nm

O-band

E-band

S-band

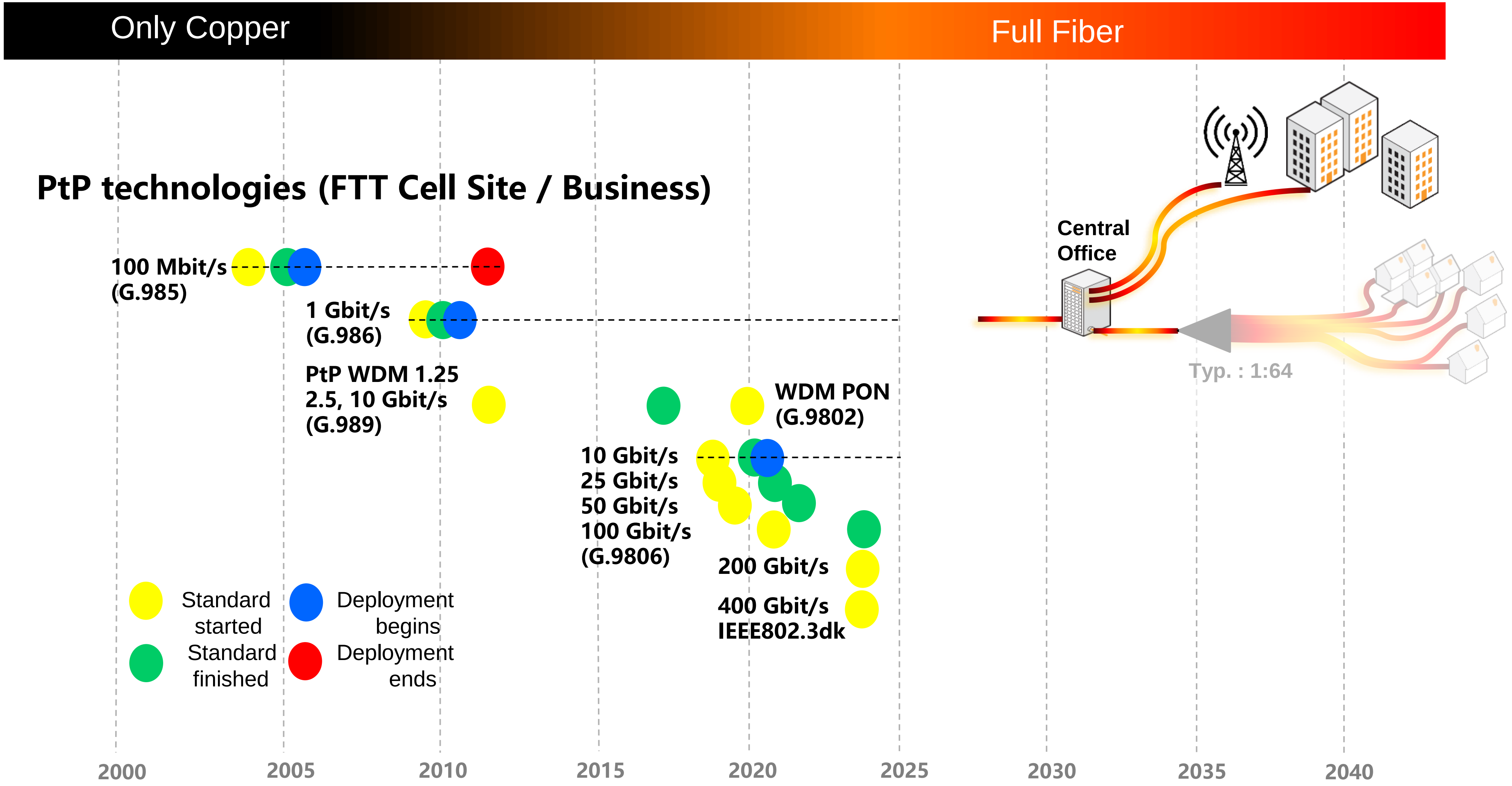
C-band

L-band

U-band

The right technology to maintain high quality fixed access

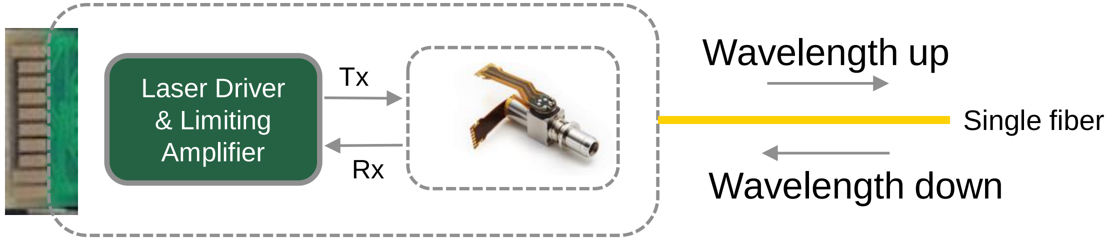
Access infrastructure medium



PtP technologies (FTT Cell Site / Business)

The right technology to maintain high quality fixed access

PtP bidirectional


Laser Driver & Limiting Amplifier

Tx

Rx

Single fiber

Two wavelengths:

Wavelength up

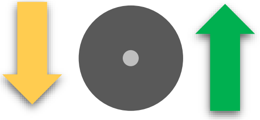
Wavelength down

ITU-T	Line Rate	Wavelength Down (nm)	Wavelength Up (nm)
G.985	100 Mbit/s	1530 +/-50	1310 +/-50
G.986	1 Gbit/s	1490 +/-10	1310 +/-50
G.9806	10 Gbit/s	1330 +/-10	1270 +/-10
G.9806	25 Gbit/s	1314 +/-8	1289 +/-8
G.9806	50 Gbit/s (PAM4)	1314 +/-8	1289 +/-8
G.9806	100 Gbit/s (PAM4)	1309.1 +/1	1304.6 +/-1

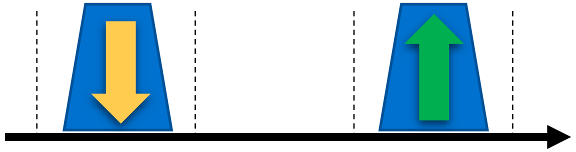
Requirements for new optical fiber in access (FTTH) 1/2

PON and PtP technologies require single fiber bidirectional transmission

Single Mode Fiber
Bidirectional

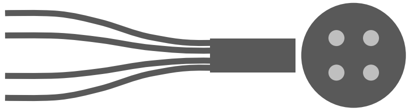


Two
Wavelengths



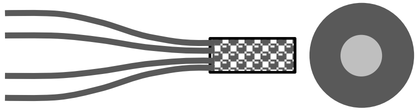
New Fiber
Bidirectional

Multi-core



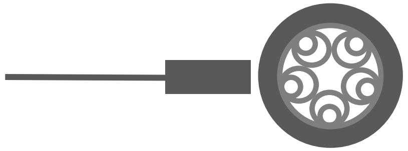
FAN In / Out
Must be bidirectional compatible

Few-mode



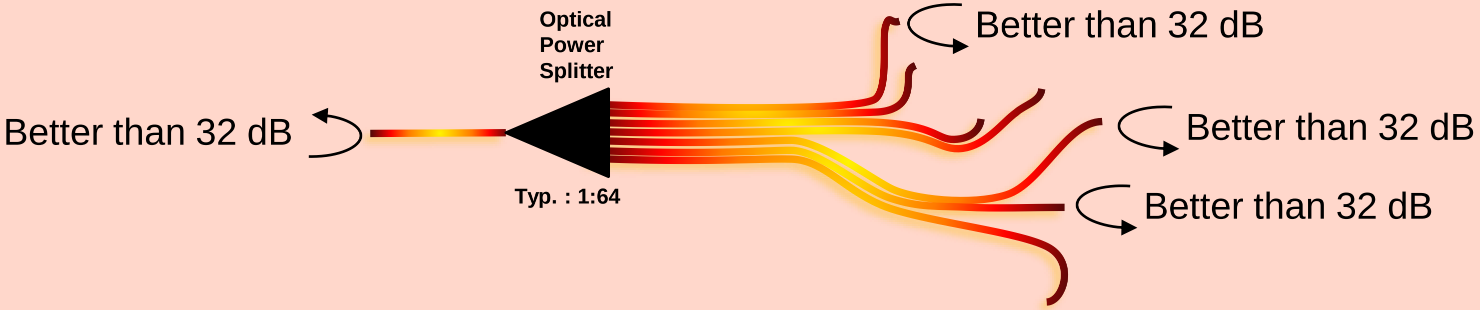
Few-mode multiplexer
Must be bidirectional compatible

Hollow core



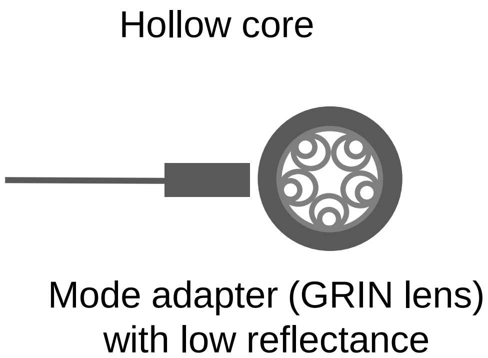
Mode adapter (GRIN lens)
Must be bidirectional compatible

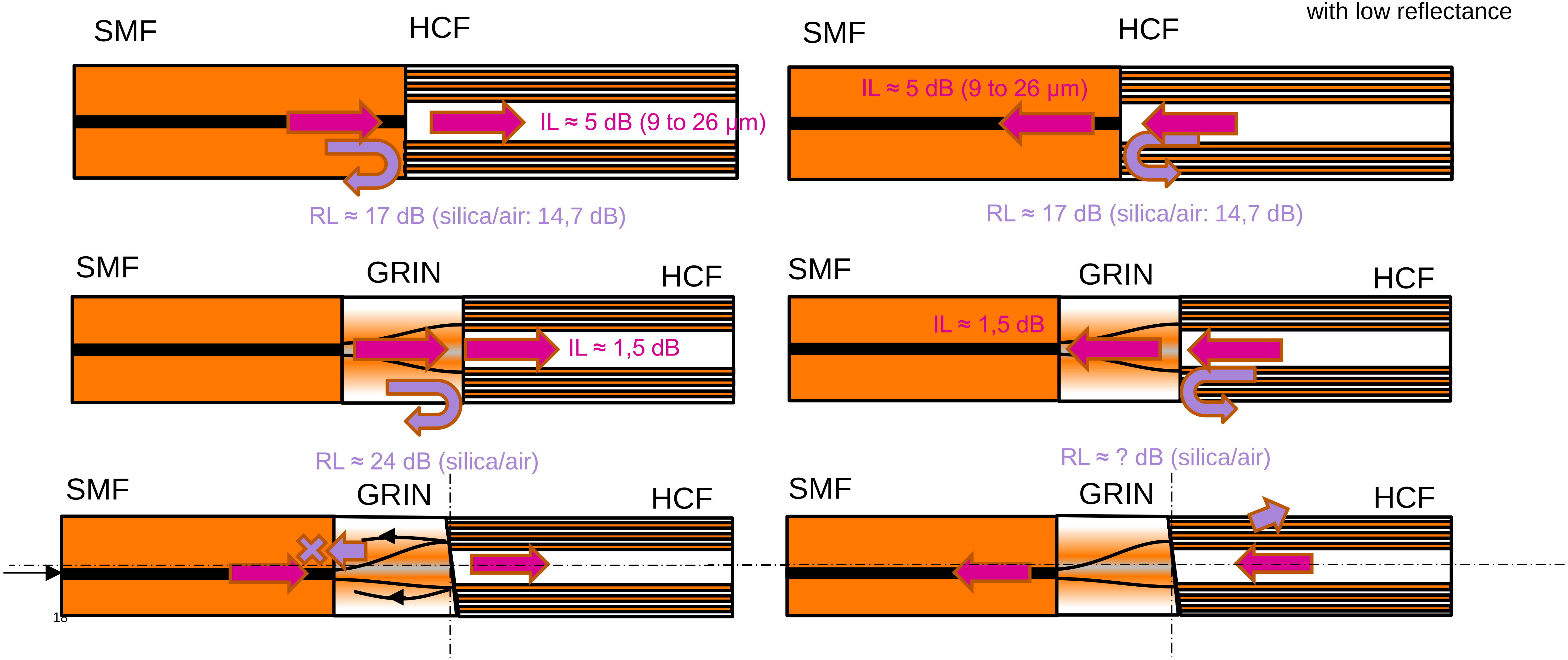
Requirements for new optical fiber in access (FTTH) 2/2

PON technologies	
Wavelength band	1260 to 1675 nm (1610 OTDR)
Chromatic dispersion range (for maximum 20km reach)	XGS PON - @1577 nm : 0 to 400 ps/nm - @1260 nm : 0 to -140 ps/nm 50G PON - @1342 nm : 0 to 77.1 ps/m - @1286 nm : 0 to -77.1 ps/nm
Optical return loss	 All discrete reflectances shall be better than −35 dB

Exemple: Orange innovation –1/2

GRIN lens for mode adaptation and low reflectance between SMF and NANF

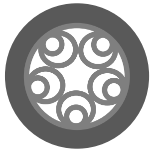




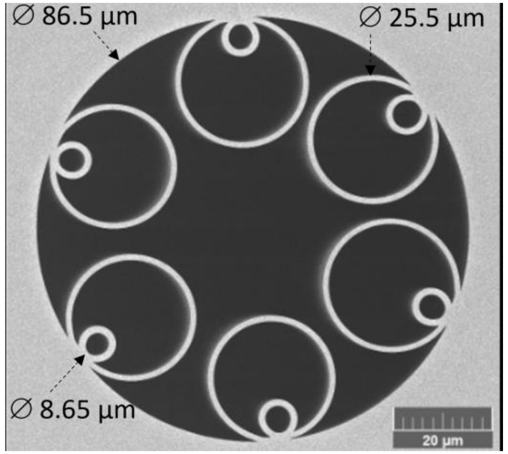
Exemple: Orange innovation 2/2

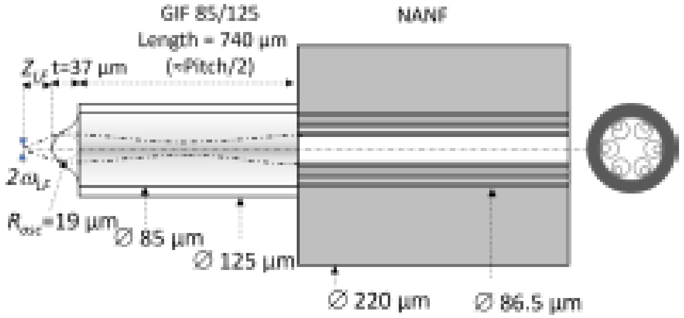
GRIN lens for mode adaptation for « direct » coupling between NANF and Laser

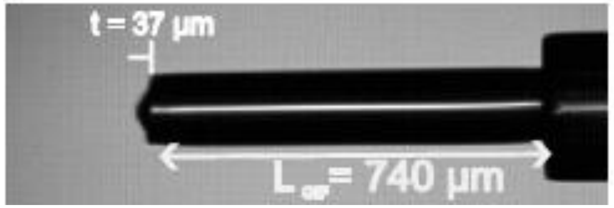
Hollow core

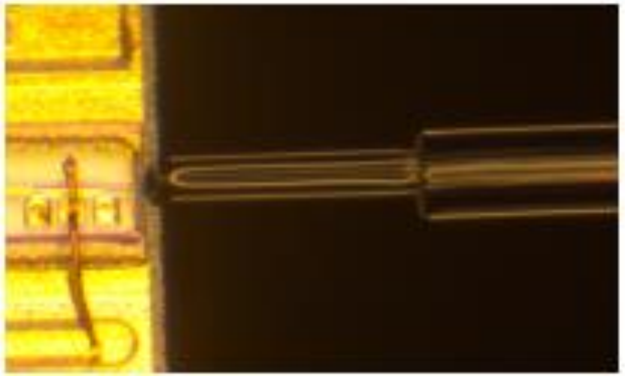


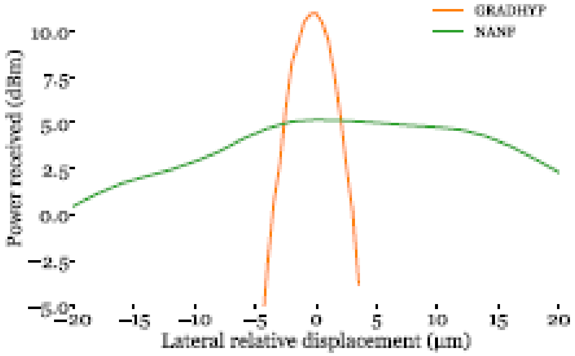
Mode adapter (GRIN lens) with low reflectance











New optical fiber in access (FTTH) for what?

New fiber to decrease nonlinear noise caused by high optical power? :

FTTx needs to ensure the safe operation in the fiber infrastructure (for 11µm SMF)

- Class 1M for OLT (max. +24.4 dBm @ 1310 nm / +25.7 dBm @ 1550 nm)
- Class 1 for ONU (max. +22.2 dBm @ 1310 nm)

New fiber to decrease chromatic dispersion?

Recent PON and PtP systems use O-band to limit chromatic dispersion. This spectrum area in now full.

One option is to have a fiber with limited chromatic dispersion for a large wavelength band (300 nm).

Other option is either to use coherent technology for next generation or take the place of previous PON generation with DSP.

New fiber to decrease loss dB/km?

- PON optical budgets are typically 32 dB (class C+) and 35 dB (class D). For O-band, we have about 0.35 dB/km. If we have a new fiber with 0.1 dB/km, we have a gain of 5 dB for 20 km. Most of the insertion loss is due to optical splitter (1:64 ≈ 20 dB)
- PtP optical budget for 40 km is up to 25 dB. For O-band, we have about 0.35 dB/km. If we have a new fiber with 0.1 dB/km, we have a gain of 10 dB for 40 km.

New optical fiber in access (FTTH) for what?

New fiber to decrease latency?

- Standard fiber and Hollow-core fiber have respectively 5 µs/km and 3,3 µs/km propagation latency: 100 µs and 66 µs for 20 km.
- G-PON system has latency 25 µs downstream and 80 µs [26 to 400 µs] upstream (for 0 km).
- PtP systems have latency about 20 µs (for 0 km).

	SMF 20 km (5 µs/km)	**Hollow-core fiber 20 km (3,3 µs/km)**	**G-PON (0 km)**	**PtP (0 km)**	**G-PON (20 km)**	**PtP (20 km)**
Latency	100 µs	66 µs (gain 33 µs)	Down: 25 µs Up: 80 µs [26-400 µs]	20 µs	Down SMF: 125 µs HCF: 91 µs (-27%) Up SMF: 180 µs HCF: 146 µs (-18%)	SMF: 120 µs HCF: 86 µs (- 28%)

For FTTH, WiFi latency is about 10 ms (PON latency is about <1 ms). No interest to decrease fiber latency.
For PtP to serve Mobile backhaul, the use of HCF between cell site and Data Center (CORE) could decrease latency (-28%?)

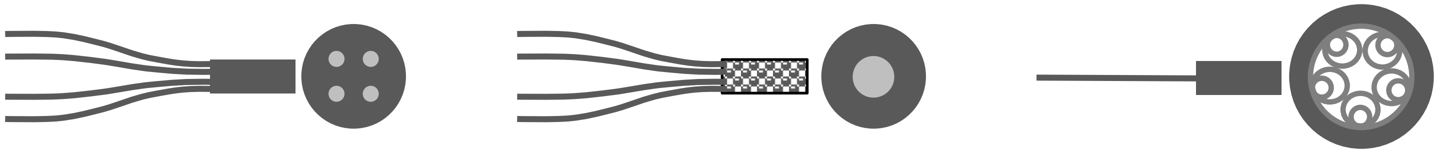
New fiber for sensing application?

Optical fiber sensing is under investigation over telecom infrastructure using :
- dedicated fiber with dedicated systems (ex. DTSS, DAS, DTS) : New fiber could be considered but cost expensive solution
- shared fiber with dedicated wavelength for sensing applications (ex. DTSS, DAS)
- shared fiber and transmission system which uses coherent transmission mechanism (SoP)

The business model of sensing over telecom infrastructure is very challenging (return of investment?).

Brillouin : Strain and Temperature sensing (DTSS)
Rayleigh : Acoustical sensing (DAS)
Raman : Temperature sensing (DTS)
State of Polarization variation (SoP)

Conclusion : SMF vs new fiber



Properties :

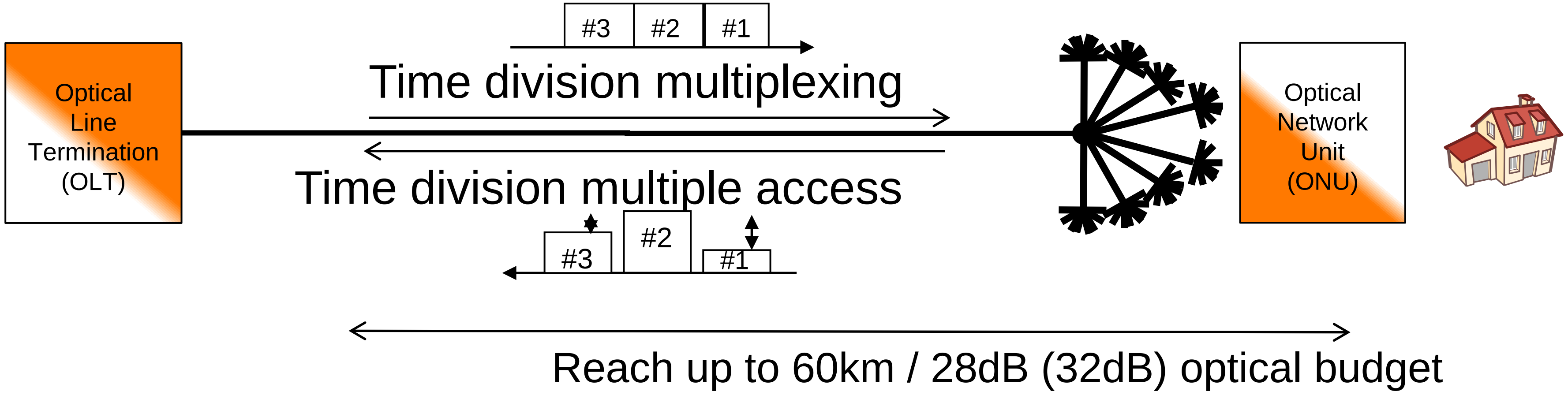
SMF vs. new fiber	Multi-core	Few-mode	Hollow core
Bidirectional	=	Bidi ok but maybe not for the full wavelenght band Impact of the reflection in other mode?	
Wavelength band	=	-	+
Chromatic dispersion	=	+	+
Optical return loss	Angled connector?	Angled connector?	Angled connector?

Use-cases :

SMF vs. new fiber	Multi-core	Few-mode	Hollow core
decrease nonlinear noise	=	+	++
decrease chromatic dispersion	=	+	+
decrease loss dB/km	=	-	+
decrease latency	=	=	++

Thank You

G-PON : Gigabit capable Passive Optical Network



Optical Line Termination (OLT)

#3 #2 #1

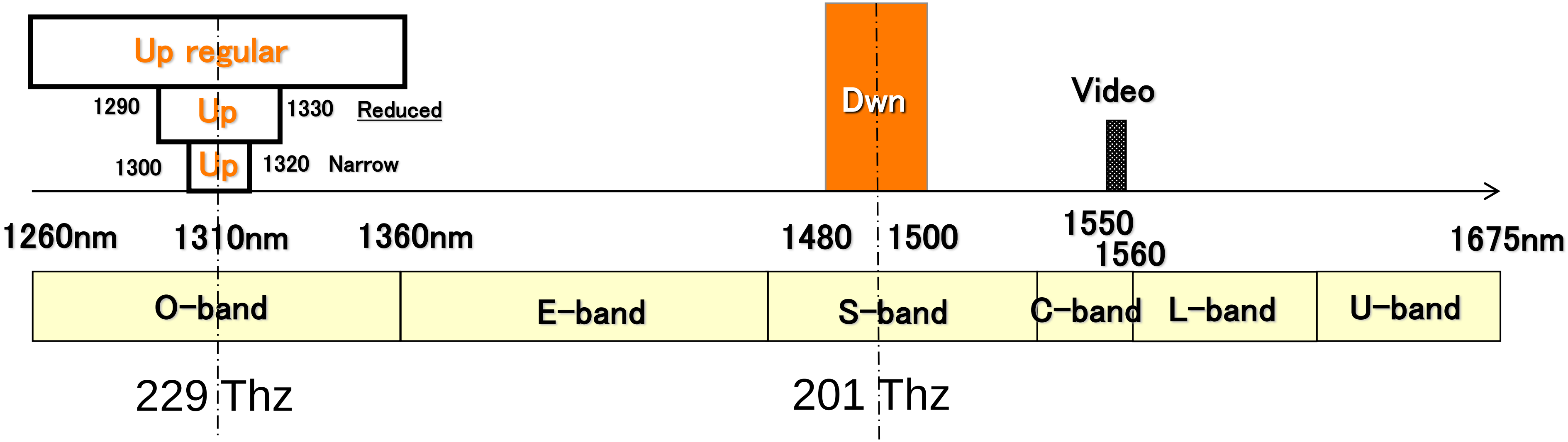
Time division multiplexing

Time division multiple access

#3 #2 #1

Optical Network Unit (ONU)

Reach up to 60km / 28dB (32dB) optical budget



Up regular

1290 Up 1330 Reduced

1300 Up 1320 Narrow

Dwn

Video

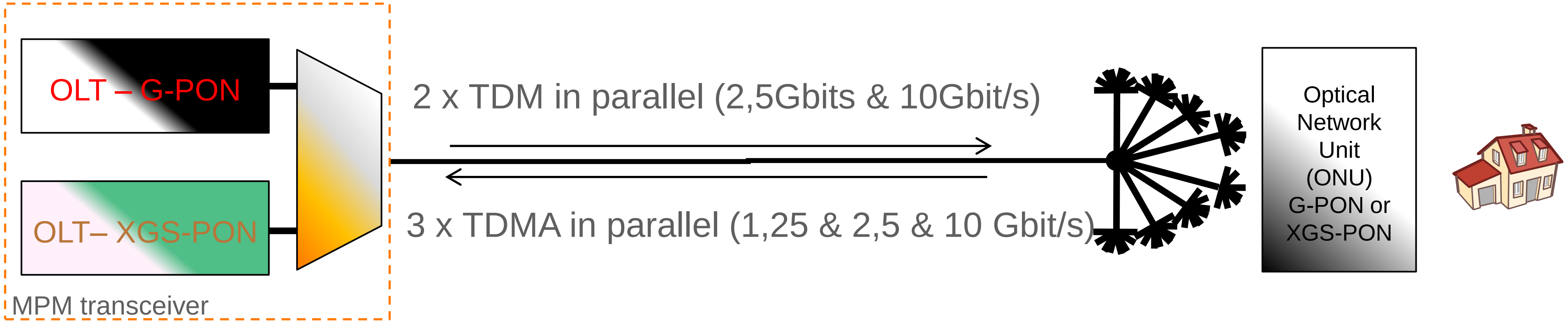
1260nm 1310nm 1360nm 1480 1500 1550 1560 1675nm

O-band E-band S-band C-band L-band U-band

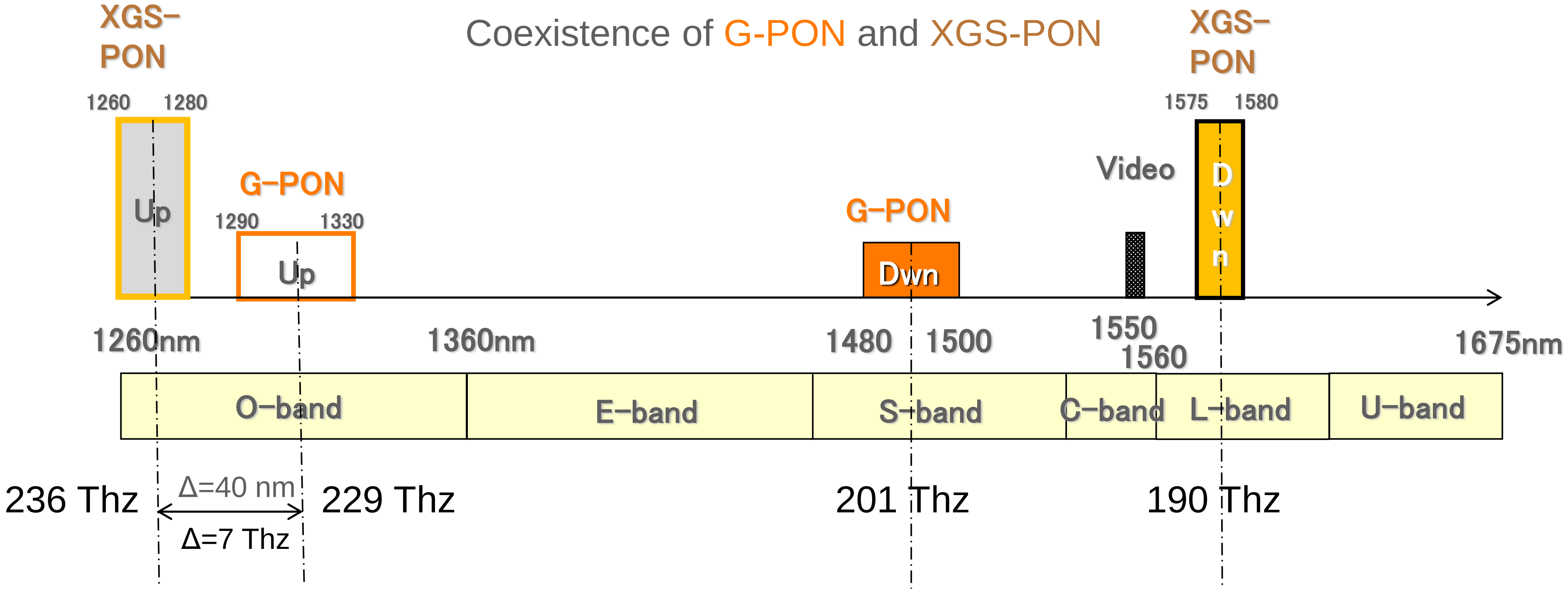
229 Thz

201 Thz

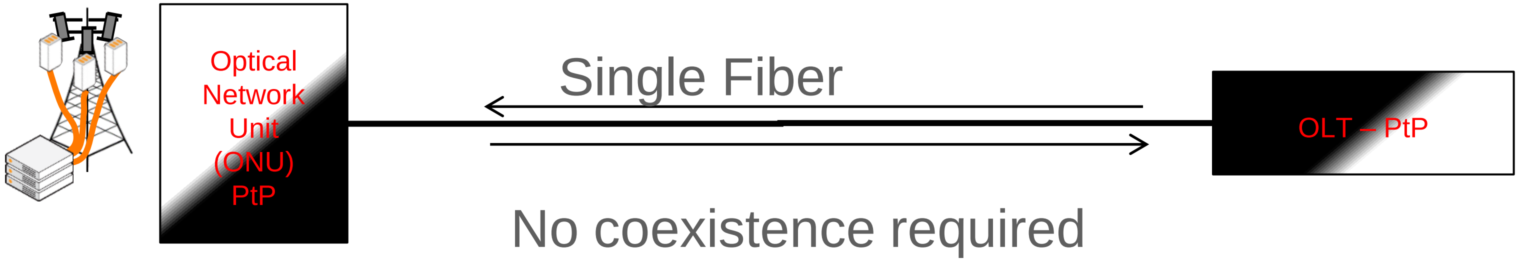
XGS-PON : 10 Gigabit Symetrical capable Passive Optical Network



Coexistence of G-PON and XGS-PON



PtP bidirectional optical fiber



No coexistence required

Optical Budget class

	Class S	Class SL	Class SU	Class A	Class BL	Class B-	Class B
Minimum loss	0 dB	0 dB	5 dB	5 dB	10 dB	10 dB	10 dB
Maximum loss	15 dB	10 dB	15 dB	20 dB	20 dB	23 dB	25 dB

Nominal distance considered 10, 20, 40 km

ITU-T	Line Rate	Wavelength Down (nm)	Wavelength Up (nm)
G.985	100 Mbit/s	1530 +/-50	1310 +/-50
G.986	1 Gbit/s	1490 +/-10	1310 +/-50
G.9806	10 Gbit/s	1330 +/-10	1270 +/-10
G.9806	25 Gbit/s	1314 +/-8	1289 +/-8
G.9806	50 Gbit/s (PAM4)	1314 +/-8	1289 +/-8
G.9806	100 Gbit/s (PAM4)	1309.1 +/1	1304.6 +/-1

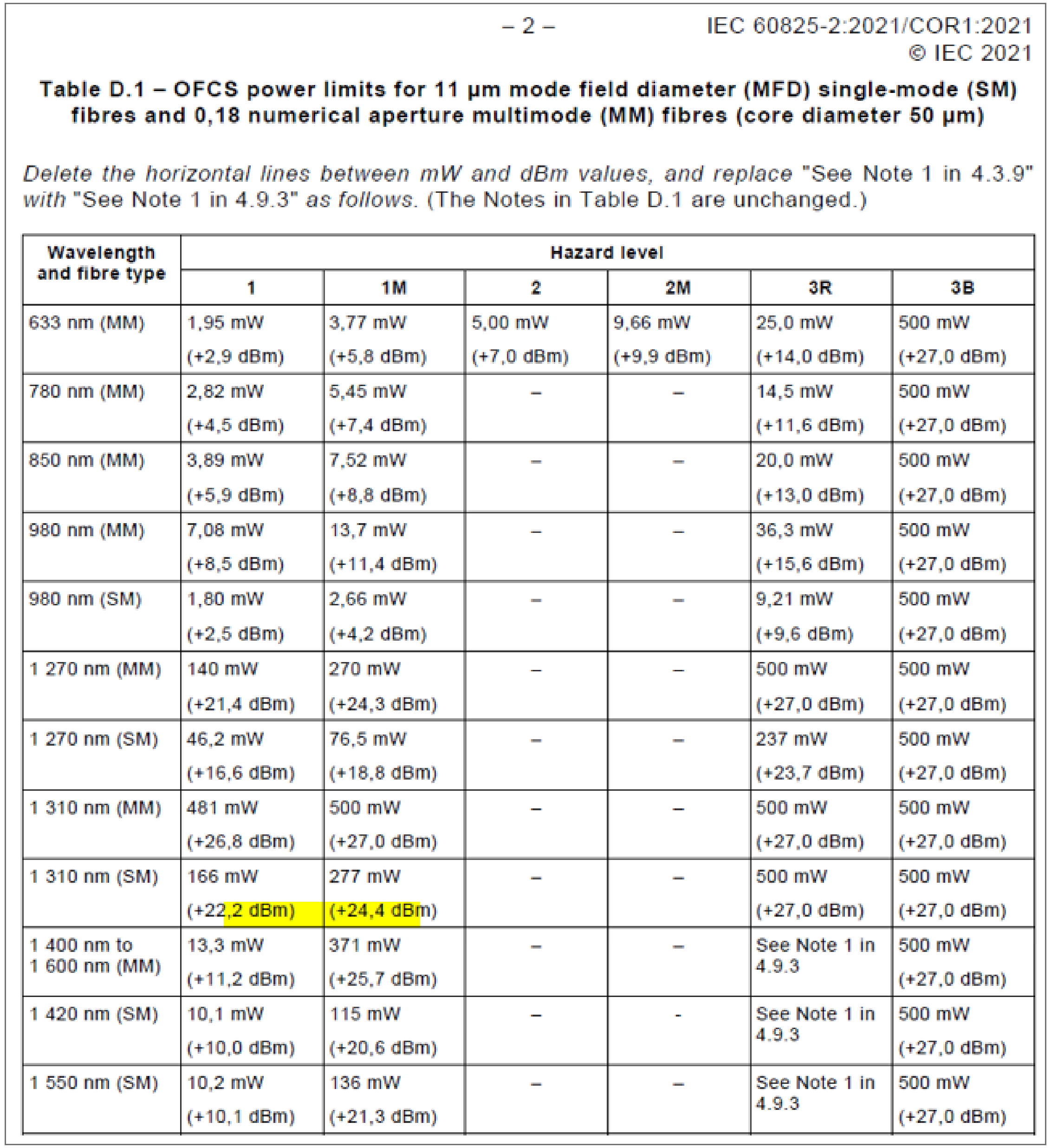


Table D.1 – OFCS power limits for 11 µm mode field diameter (MFD) single-mode (SM) fibres and 0,18 numerical aperture multimode (MM) fibres (core diameter 50 µm)

Delete the horizontal lines between mW and dBm values, and replace "See Note 1 in 4.3.9" *with* "See Note 1 in 4.9.3" *as follows.* (The Notes in Table D.1 are unchanged.)

Wavelength and fibre type	**Hazard level**					
	1	**1M**	**2**	**2M**	**3R**	**3B**
633 nm (MM)	1,95 mW (+2,9 dBm)	3,77 mW (+5,8 dBm)	5,00 mW (+7,0 dBm)	9,66 mW (+9,9 dBm)	25,0 mW (+14,0 dBm)	500 mW (+27,0 dBm)
780 nm (MM)	2,82 mW (+4,5 dBm)	5,45 mW (+7,4 dBm)	–	–	14,5 mW (+11,6 dBm)	500 mW (+27,0 dBm)
850 nm (MM)	3,89 mW (+5,9 dBm)	7,52 mW (+8,8 dBm)	–	–	20,0 mW (+13,0 dBm)	500 mW (+27,0 dBm)
980 nm (MM)	7,08 mW (+8,5 dBm)	13,7 mW (+11,4 dBm)	–	–	36,3 mW (+15,6 dBm)	500 mW (+27,0 dBm)
980 nm (SM)	1,80 mW (+2,5 dBm)	2,66 mW (+4,2 dBm)	–	–	9,21 mW (+9,6 dBm)	500 mW (+27,0 dBm)
1 270 nm (MM)	140 mW (+21,4 dBm)	270 mW (+24,3 dBm)	–	–	500 mW (+27,0 dBm)	500 mW (+27,0 dBm)
1 270 nm (SM)	46,2 mW (+16,6 dBm)	76,5 mW (+18,8 dBm)	–	–	237 mW (+23,7 dBm)	500 mW (+27,0 dBm)
1 310 nm (MM)	481 mW (+26,8 dBm)	500 mW (+27,0 dBm)	–	–	500 mW (+27,0 dBm)	500 mW (+27,0 dBm)
1 310 nm (SM)	166 mW (+22,2 dBm)	277 mW (+24,4 dBm)	–	–	500 mW (+27,0 dBm)	500 mW (+27,0 dBm)
1 400 nm to 1 600 nm (MM)	13,3 mW (+11,2 dBm)	371 mW (+25,7 dBm)	–	–	See Note 1 in 4.9.3	500 mW (+27,0 dBm)
1 420 nm (SM)	10,1 mW (+10,0 dBm)	115 mW (+20,6 dBm)	–	-	See Note 1 in 4.9.3	500 mW (+27,0 dBm)
1 550 nm (SM)	10,2 mW (+10,1 dBm)	136 mW (+21,3 dBm)	–	–	See Note 1 in 4.9.3	500 mW (+27,0 dBm)