Home Area Networks

Ton Koonen

COBRA, Eindhoven Univ. of Technology

Tutorial OTh1G.1

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Outline

- Convergence in home networks, home service scenarios
- Home wired network architectures, CapEx and OpEx
- Residential Gateway
- Optical fiber types
- High-capacity data transmission for wirebound delivery
- High-capacity data transmission for wireless delivery
- Converged networks
- Standards for POF transmission systems
- Advanced networking techniques (routing, MGDM, Optical wireless)
- Evolution trends and roadmap
- Concluding remarks

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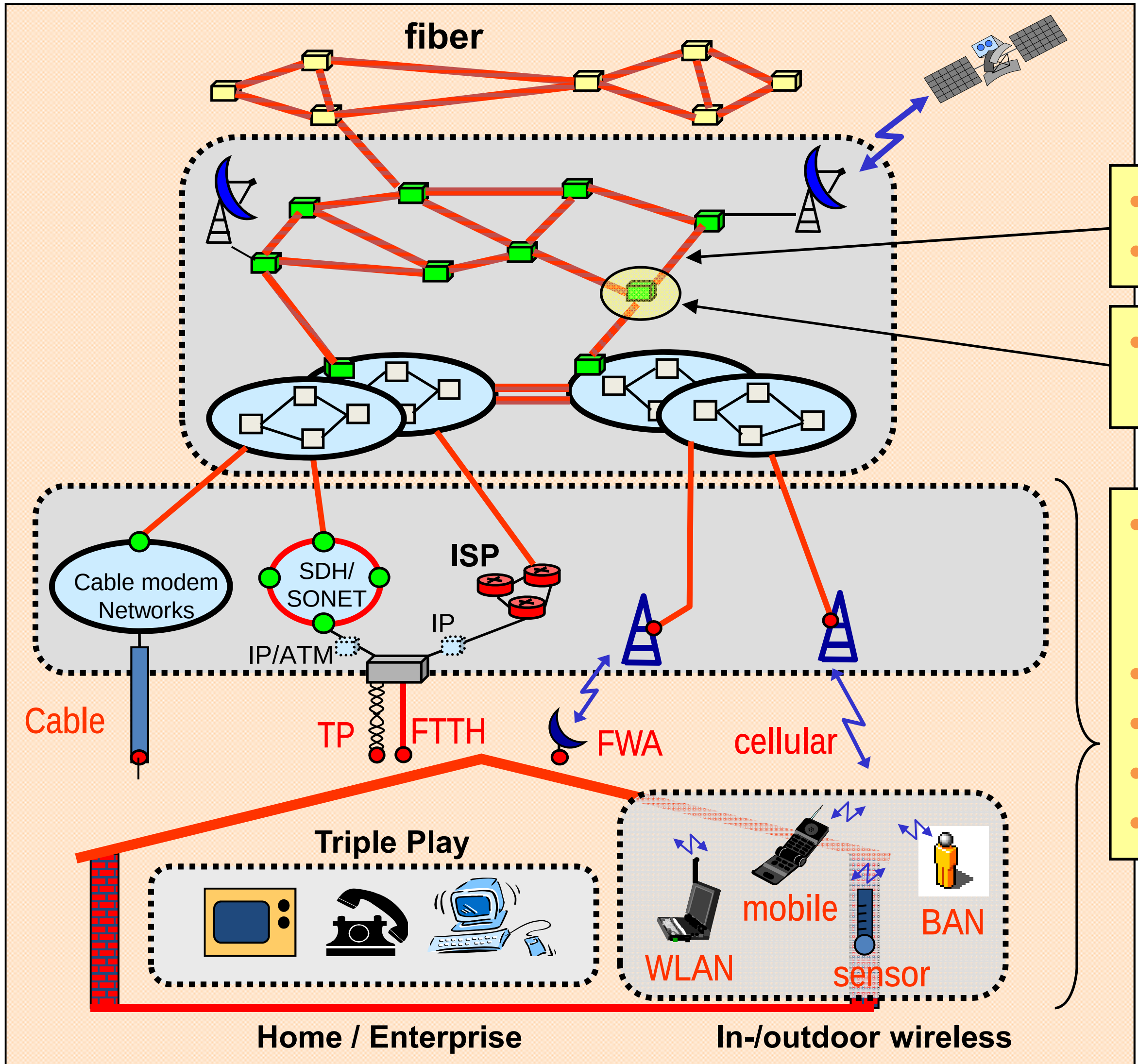
Connected World

Global Network

Metropolitan/
Regional Area
Optical Network

Client/Access
Networks

In-home and
Personal
Networks



- long reach
- high capacity

- fast packet switching

- variety of media + services
- mobility
- low power
- low cost
- personal

- end-to-end network management & control

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In-home networks vs. Access networks

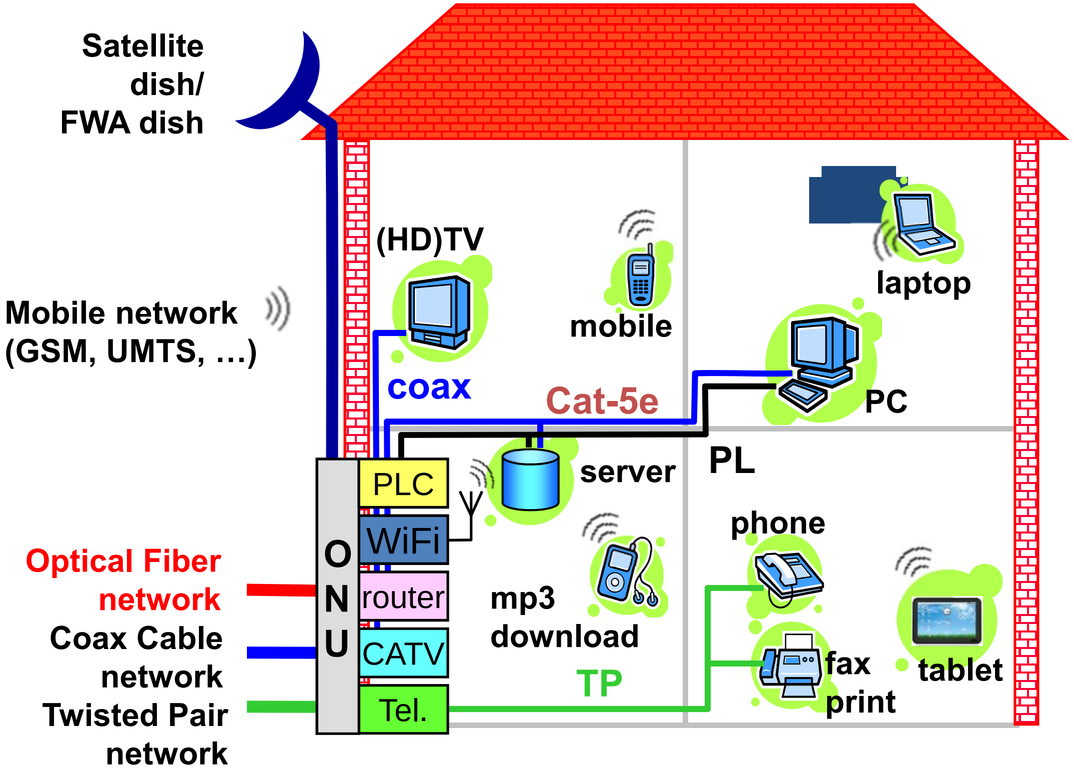
Access	In-home
Operator-owned	User-owned
Professional skills, high tech	Ease of use
Network provisioning/management	Plug-and-play
Standards	Consumer-chosen solutions
Return on investment	Consumer decides
Costs shared among many households	Single household bares the costs
Protocols (GPON, EPON, P2P Ethernet, …)	Which services to get?
Installation by professionals	Do-it-yourself?

In-home networks need a different approach!

Today's in-home networks

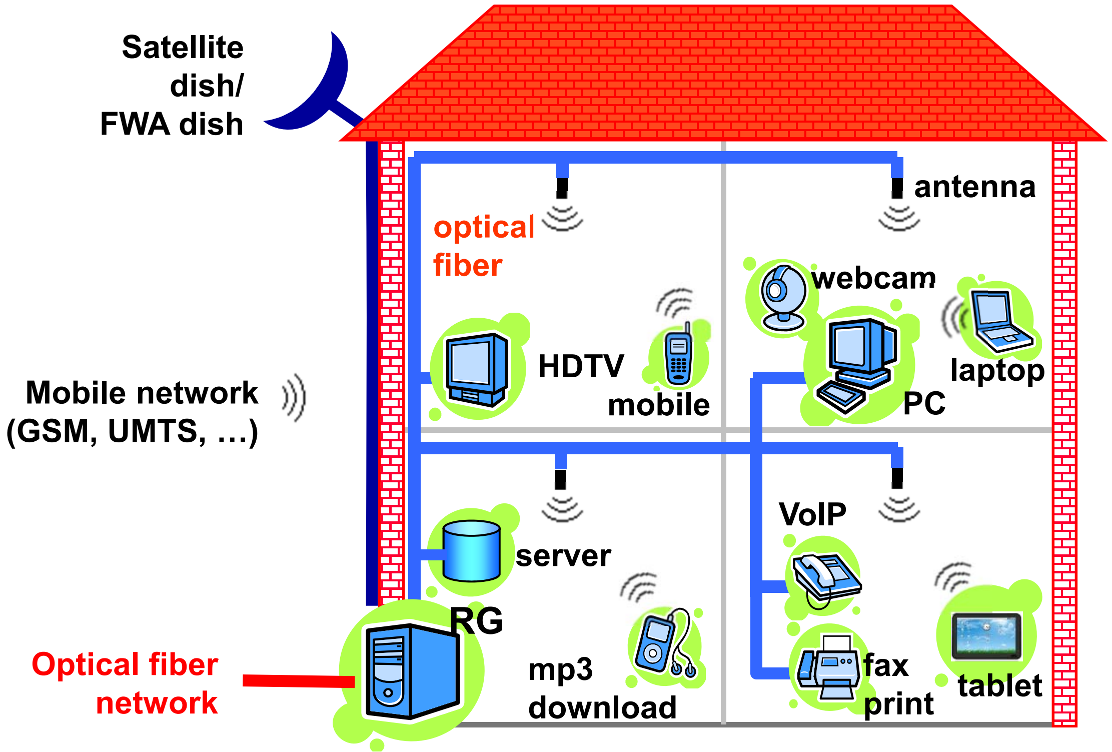
A variety of networks:

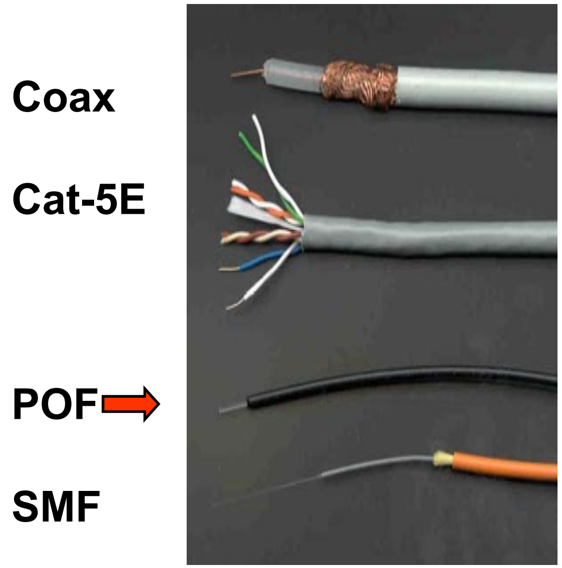
- **Twisted pair copper lines:**
  Telephone, fax, …
- **Coaxial copper lines:**
  CATV, videorec, radio, …
- **Cat-5 cables:**
  PC-s, routers, hubs, printers, servers, …
- **Wireless LAN:**
  Laptops, PDAs, …
- **Infrared:**
  remote control TV/videorec/radio/…



⇨ Complicates maintenance, upgrading, running of services on multiple platforms, interoperation of services, …

Converged in-home network: with fiber





- fiber backbone: silica SMF, MMF, or large-core POF
- integrate wired and wireless services (by e.g. WDM) in a single network
  - ⇨ reduces installation and maintenance efforts
  - ⇨ eases introduction and upgrading of services

[A.M.J. Koonen & M. Popov – ECOC 2012, Mo1G1]

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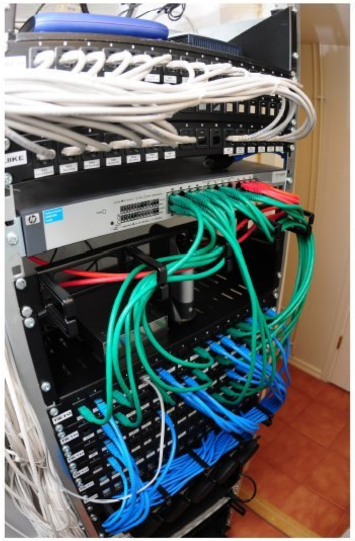
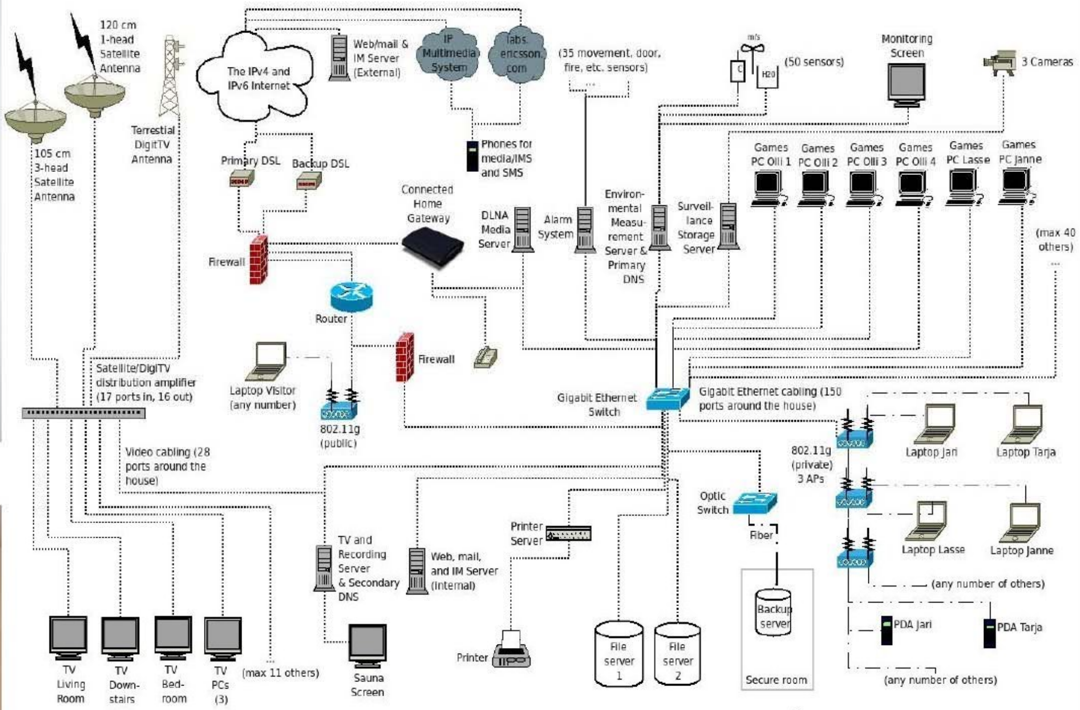
It quickly can get very complex:





- 200 Gbit/s Ethernet ports
- 4 kilometres of Cat6 cable
- IPv6
- Enables “laundry talking via Facebook”

Source: Jari Arkko, http://thingsonip.blogspot.se/2012/04/home-networks-by-magic.html

[A.M.J. Koonen & M. Popov – ECOC 2012, Mo1G1]

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Homo Zappiens

→ fast growing need for broadband capacity at home and in access; broadband internet traffic, packet-based

[Wim Veen - TU Delft]

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If we add:

- HD large-screen video (576i 4-6 Mbit/s, 1080p 10-15 Mbit/s, “4K/8K” >100 Mbit/s, …)
- Mobile backhaul and fronthaul (delay budgets in order of 10 ms, bandwidths up to Gbit/s for CPRI/OBSAI)

and

- Local backup to NAS
- Remote backup to cloud
- Web-browsing
- IP telephony
- E-mail and so on...
- All of the above from 10-20 devices (as of today)

- Plus sensors, video surveillance and other Internet of Things gadgets …

All the above does not fit neither in copper nor wireless!

<u>*Note also*</u>*:* ***the traffic load on the in-house network may go well beyond the traffic load on the access line!***

[A.M.J. Koonen & M. Popov – ECOC 2012, Mo1G1]

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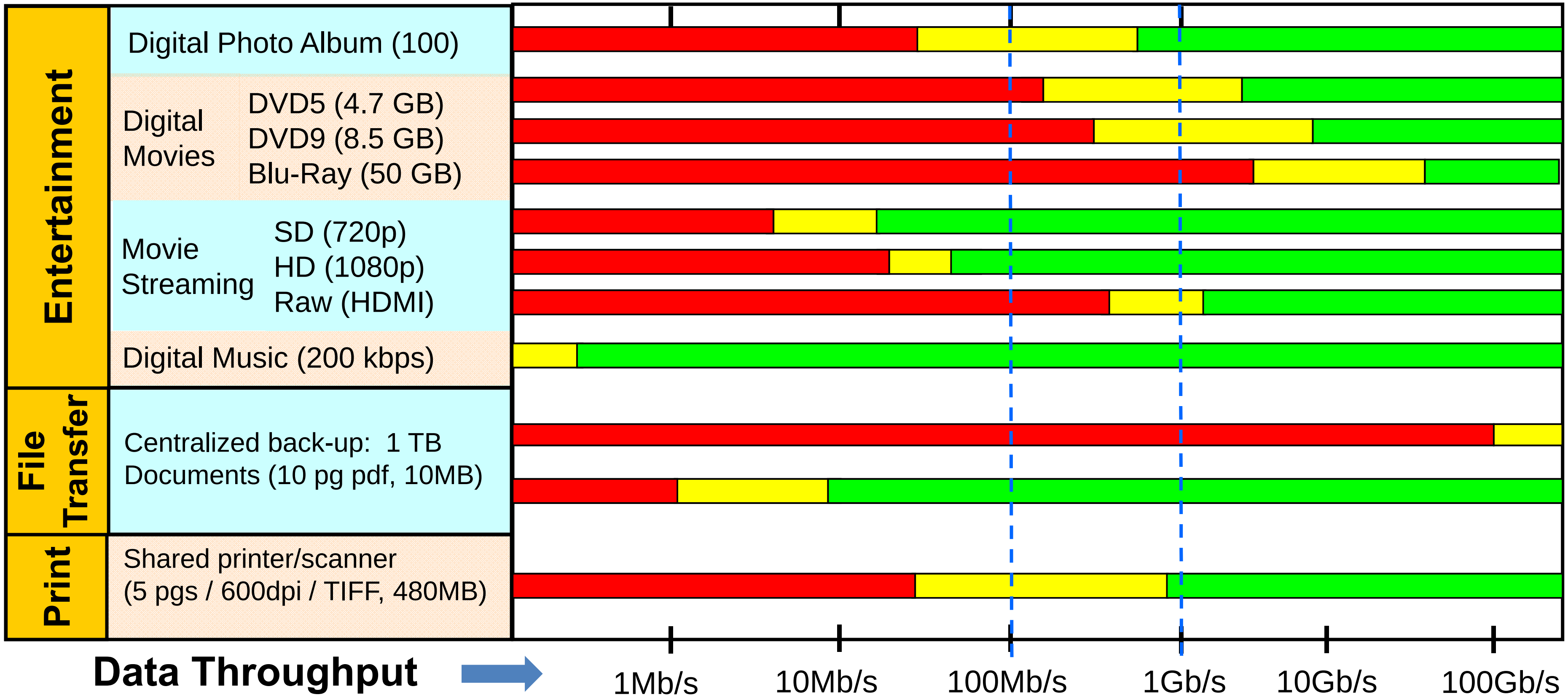
Fiber Networks in Homes

Home connectivity needs

> 1 Gb/s needed for good user experience today!

Data Transfer Time:

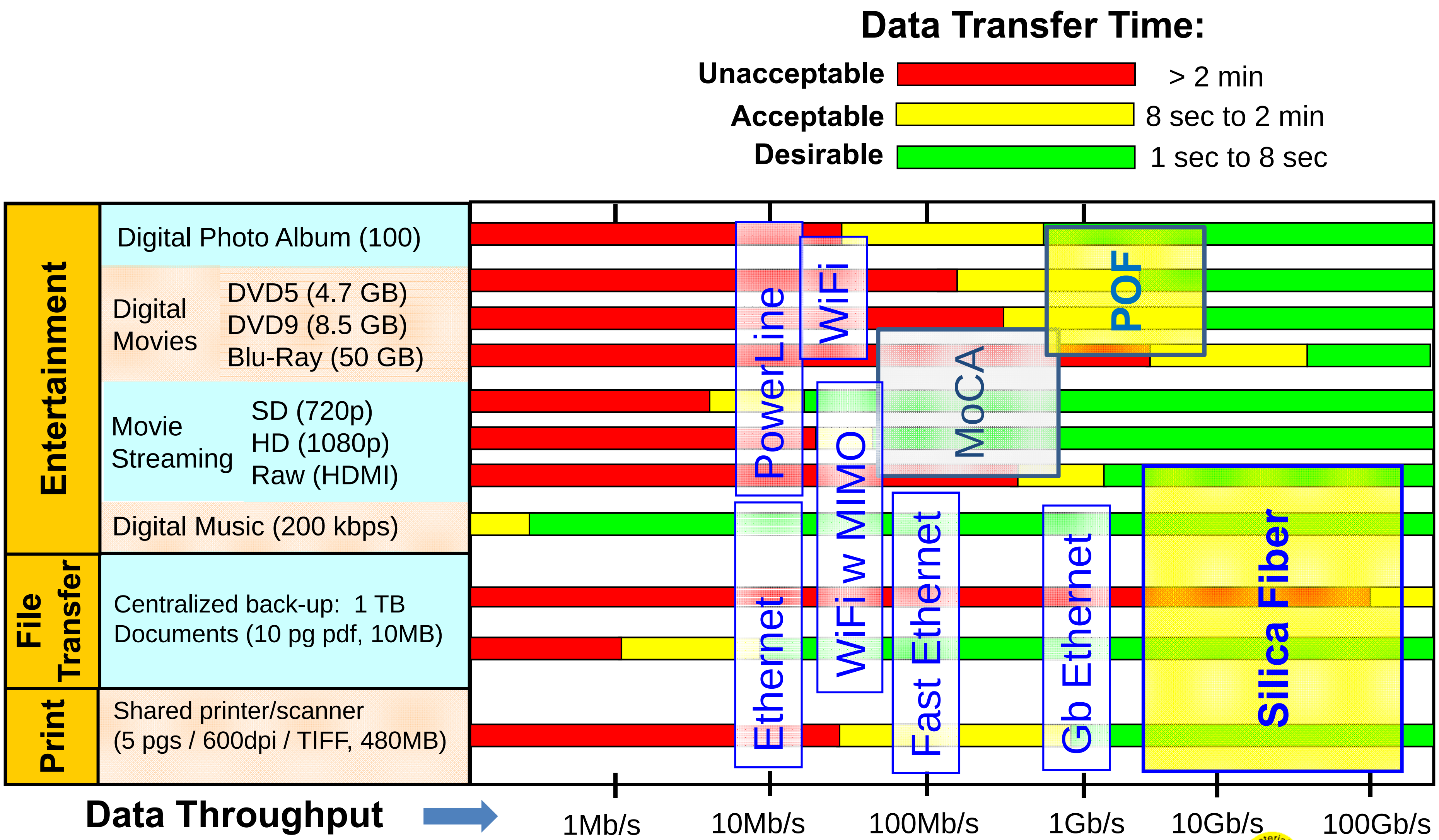
- **Unacceptable** — > 2 min
- **Acceptable** — 8 sec to 2 min
- **Desirable** — 1 sec to 8 sec



[A. Ng'oma et al., OFC 2010 Symposium on Fiber In The Home]

Fiber Networks in Homes

User needs exceed network technologies – except optical fiber



from [A. Ng'oma et al., OFC 2010 Symposium on Fiber In The Home]

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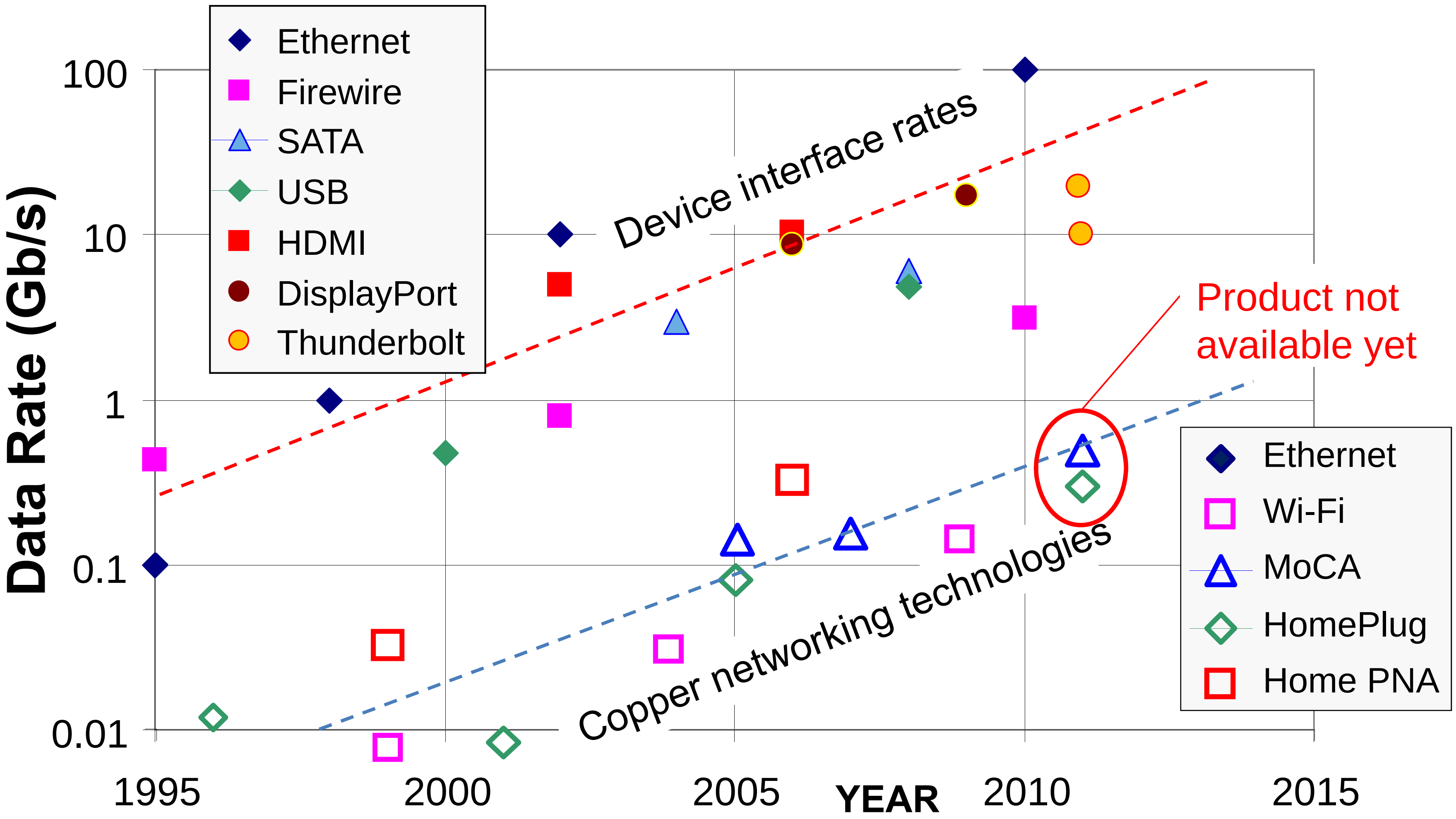
Consumer Electronic device interface rates

Existing device technologies enable up to 20 Gb/s



Copper networking technologies are lagging device interface rates and user needs

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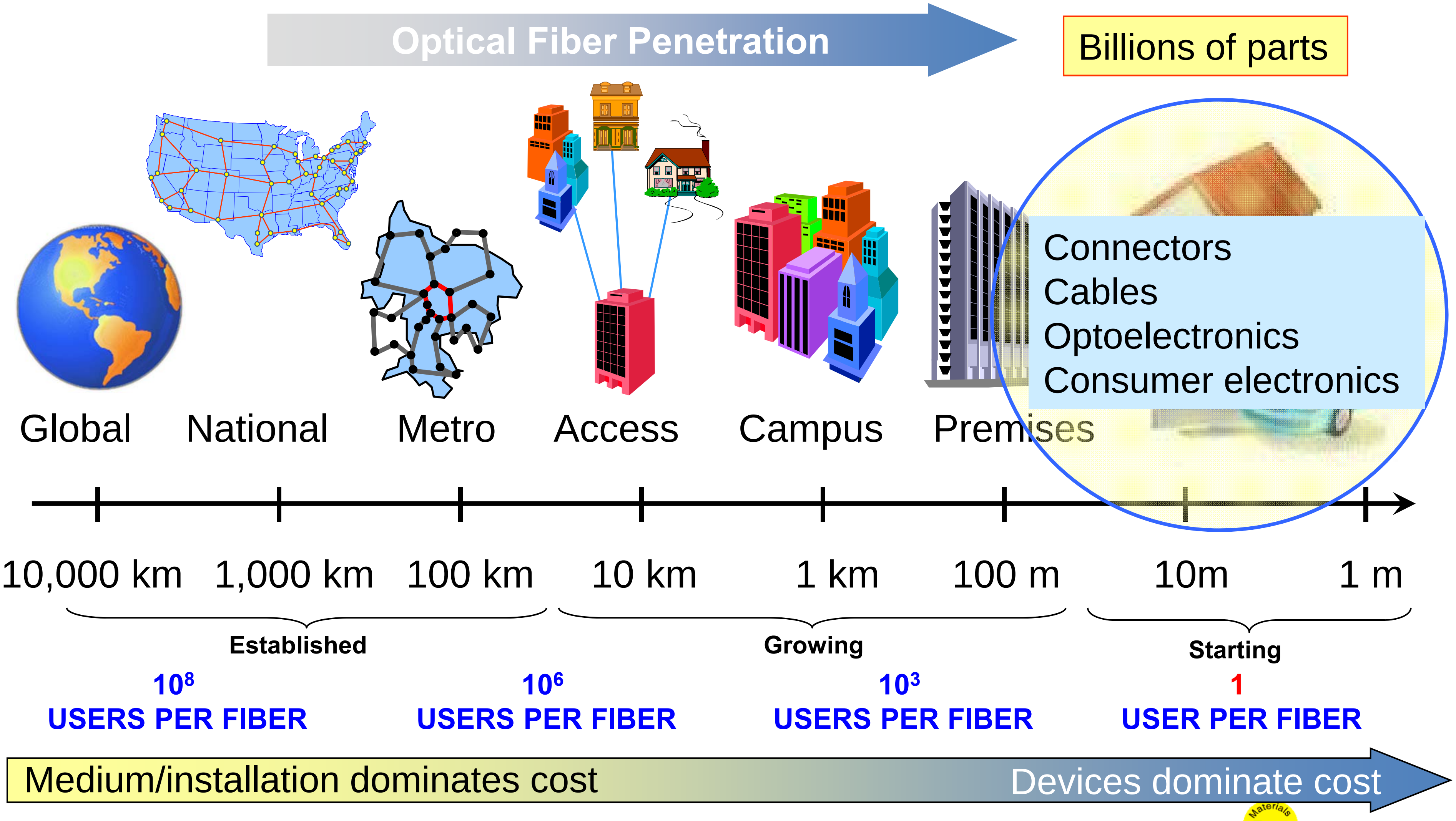
Fiber Networks in Buildings and Homes - Telecommunications trends & opportunities



[A. Ng'oma et al., ECOC2012, Mo1G4]

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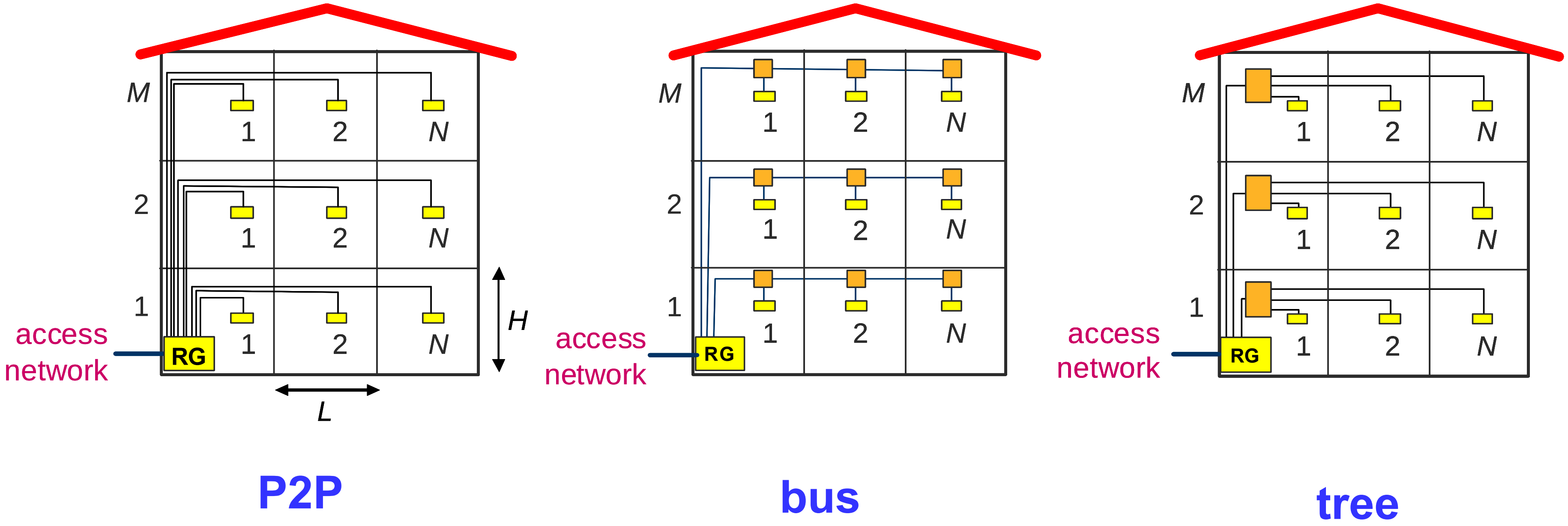
Network architectures



- + hybrid architectures
- **opaque** (with OEO conversions),
  or **all-optical** (with power splitting or λ-routing)

[A.M.J. Koonen et al., Optics Express Dec. 2011]

Building scenarios

Home

M	*N*	*H* (m)	*L* (m)
3	4	3.3	8

Office

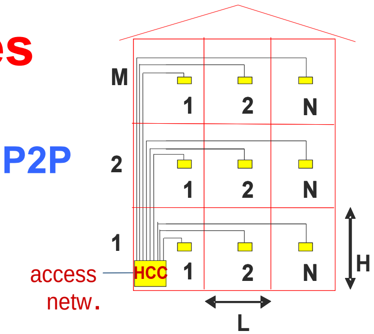
M	*N*	*H* (m)	*L* (m)
10	50	3.8	10

MDU

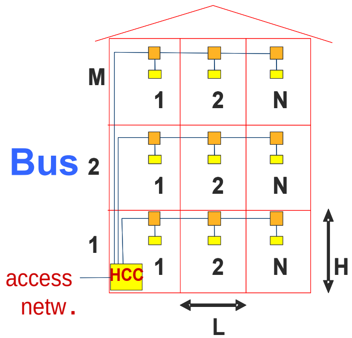
M	*N*	*H* (m)	*L* (m)
10	16	4	14

Basic topologies

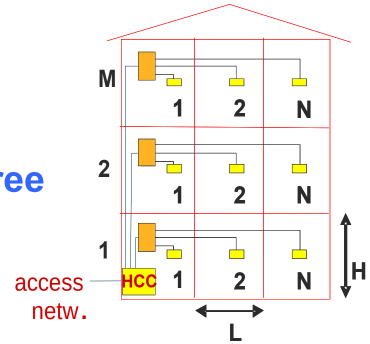
P2P



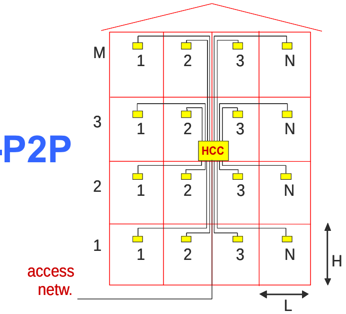
Bus



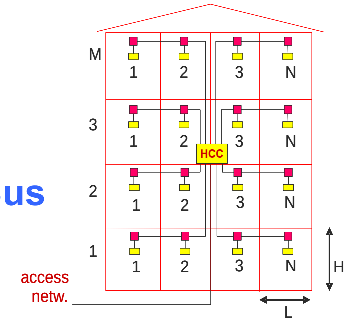
Tree



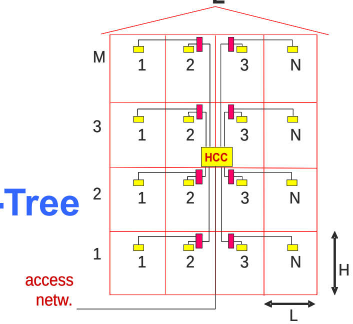
Star-P2P



Star-Bus



Star-Tree



[A.M.J. Koonen et al., Optics Express Dec. 2011]

Cost items used in the analysis

(based on 2010 market price surveys)

	Cat-5E	POF	SMF	MMF
Installed cable costs	1.8 €/m	1.7 €/m	1.74 €/m	1.95 €/m
Max. link length	100 m	70 m	1000 m	550 m
Mounted connector costs	13 €	3 €	15 € *	14 € *
Media converter costs; power consumption	(negligible); 0.65 W	30 €; 0,85 W	70 €; 1.15 W	40 €; 1.15 W
Hub/tap costs; power consumption	20 €; 0.2 W	20 €; 0.2 W	20€; 0.2 W	20€; 0.2 W
Switch costs, power consumption	10 €/port; 0.3 W/port	10€/port; 0.3 W/port	10 €/port; 0.3 W/port	10 €/port; 0.3 W/port

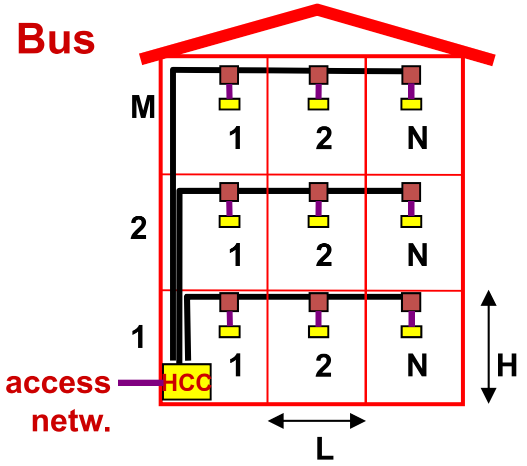
* these prices vary considerably for the various connector types and their mounting methods; we assumed SC connectors, and about 10 minutes in-field mounting time per connector (labour costs about 10€)

Duplex POF

Cat-5E

[A.M.J. Koonen et al., Optics Express Dec. 2011]

Cost modelling of architectures



Cable length

$$F = M \cdot N \cdot L + \sum_{m=1}^{M} mH = M \cdot N \cdot L + H \cdot \frac{M}{2} \cdot (M+1)$$

Duct costs

$$D = M \cdot H \cdot p(M) + M \cdot N \cdot L \cdot p(1)$$

p(*M*) = duct costs per unit length for duct containing *M* cables

Number of OEO hubs

$$T = M \cdot N$$

Number of connectors

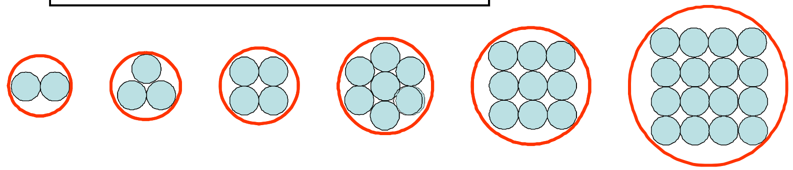
$$C = 2 \cdot M + 2 \cdot M \cdot (N-1) + M \cdot N = 3 \cdot M \cdot N$$

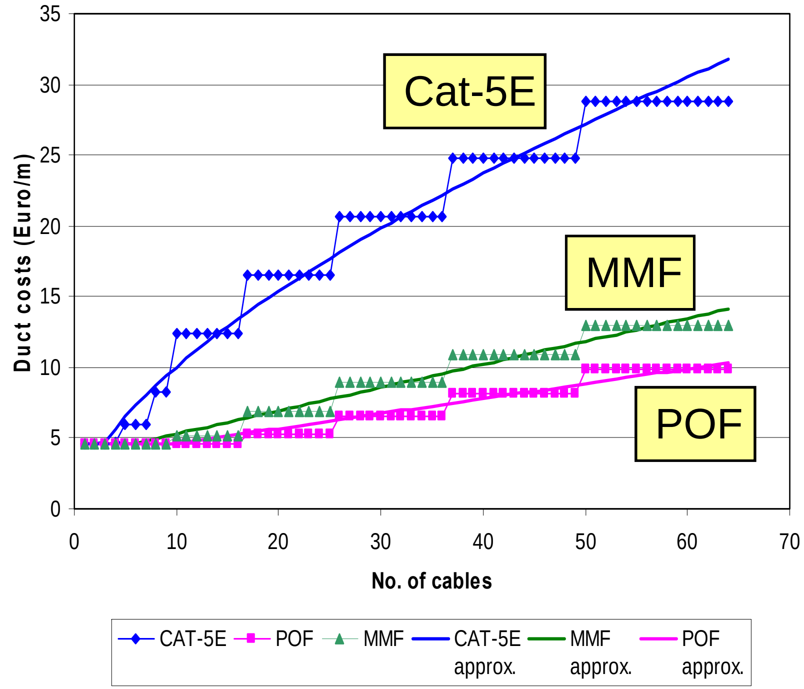
Number of media converters

$$MC = 2 \cdot M + 2 \cdot M \cdot (N-1) = 2 \cdot M \cdot N$$

Cable diameters:

- CAT-5E 5 mm
- MMF/SMF 2.5 mm
- POF 2 mm





costs of buried ducts

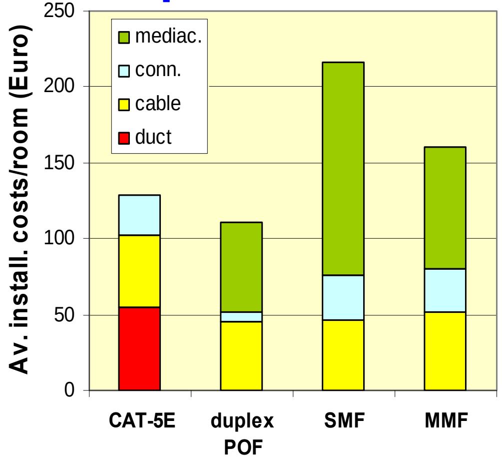
[A.M.J. Koonen et al., Optics Express Dec. 2011]

CapEx and OpEx

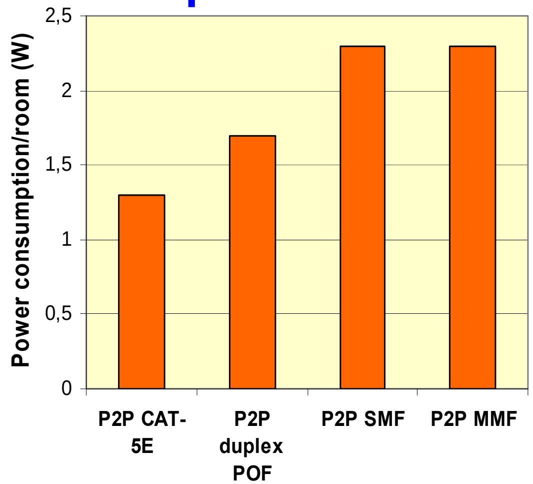
Assumptions:
- opaque network
- fiber solutions share existing duct of electricity wiring

Residential home
- 3 floors, 4 rooms/floor
- P2P network

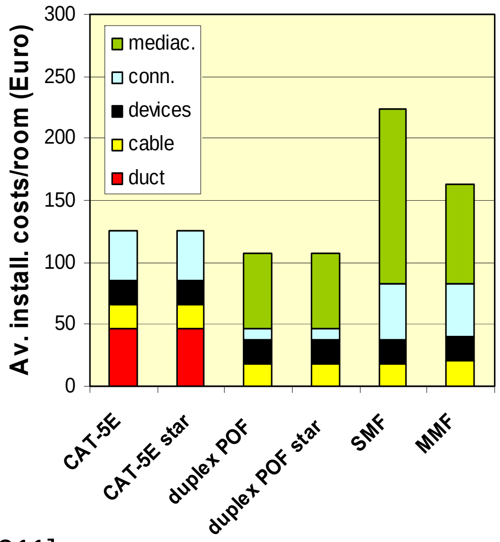
Installation costs per room

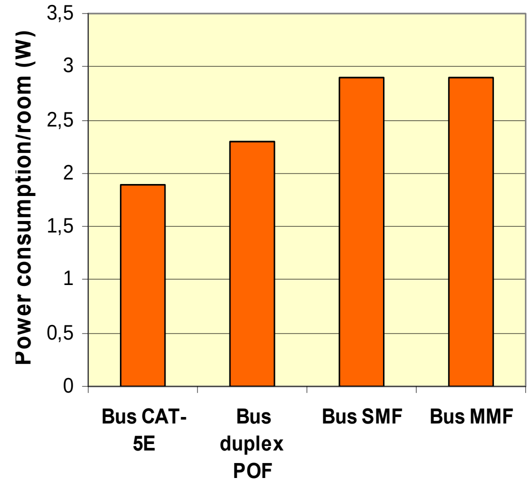


Power consumption per room



Office building
- 10 floors, 50 rooms/floor
- bus network





POF outperforms SMF and MMF, and is cost-competitive with Cat-5E

[A.M.J. Koonen et al., Optics Express Dec. 2011]

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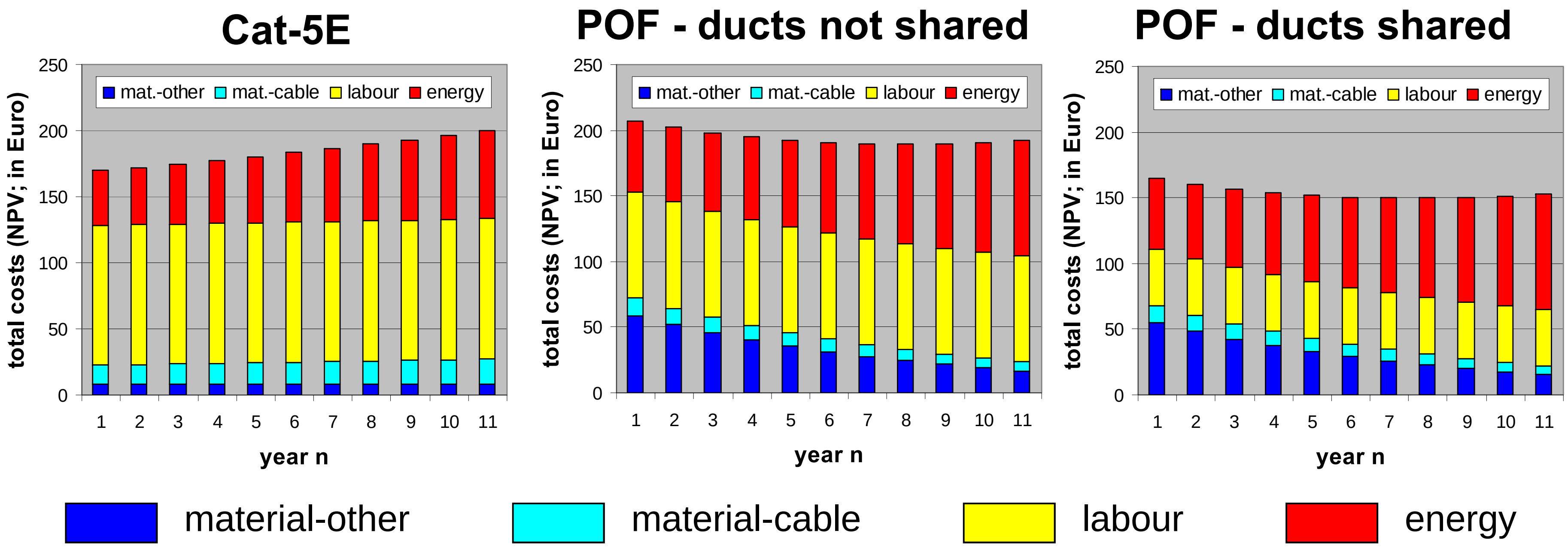
Evolution of total network costs

- CapEx + OpEx, Net Present Value
- for residential home during economic lifetime of 25 years
- when installing in year *n*

Assumptions:

- Costs of labour +2%/year, of POF products -10%/year, of Cat-5E products +2%/year, of Cat-5E cable +5%/year, of energy +5%/year
- Material/labour costs: duct 10/90%, cable 30/70%, devices 90/10%, connectors 10/90%, media conv. 90/10%



[A.M.J. Koonen et al., Optics Express Dec. 2011]

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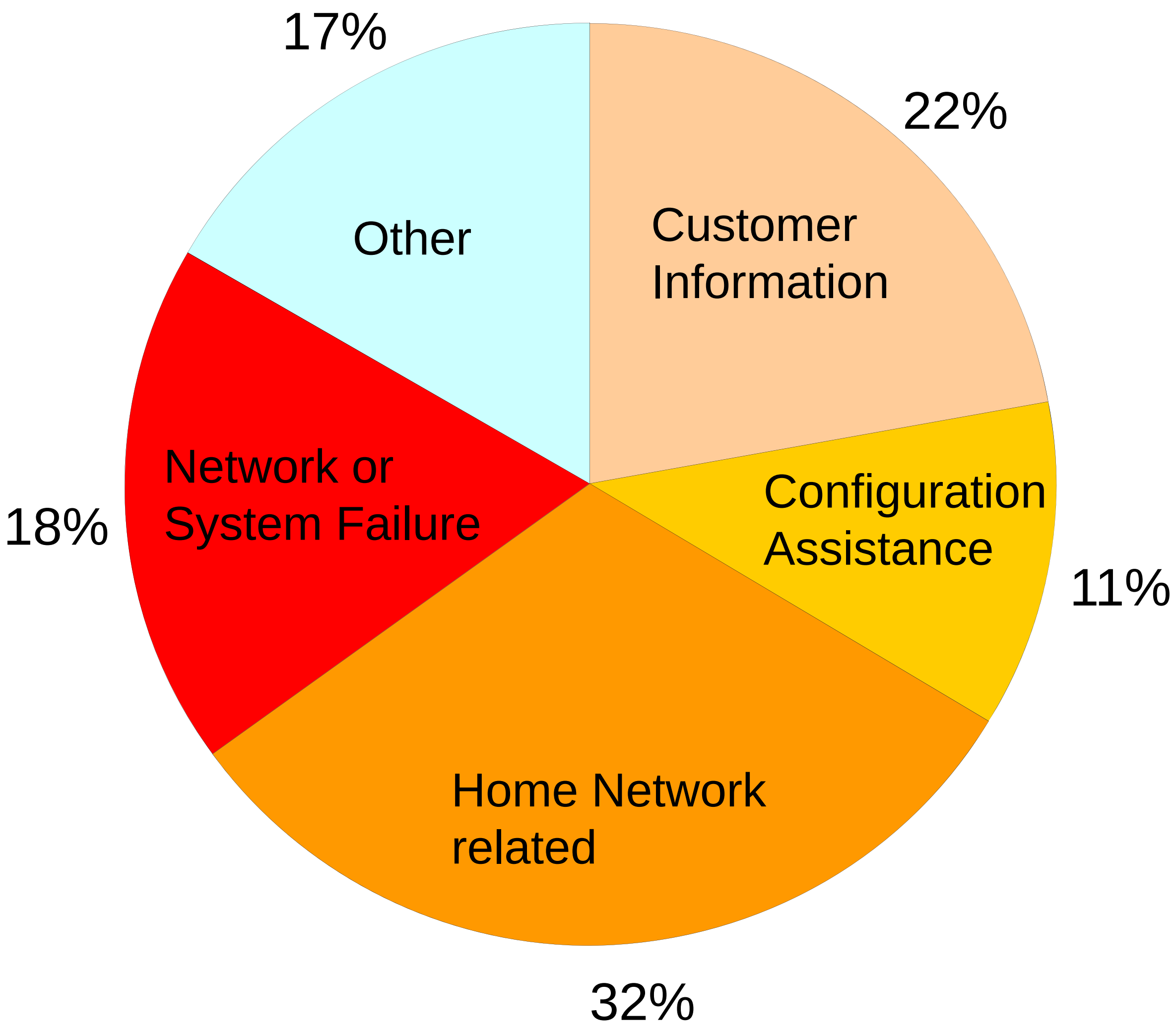
Managerial complexity for the service provider….

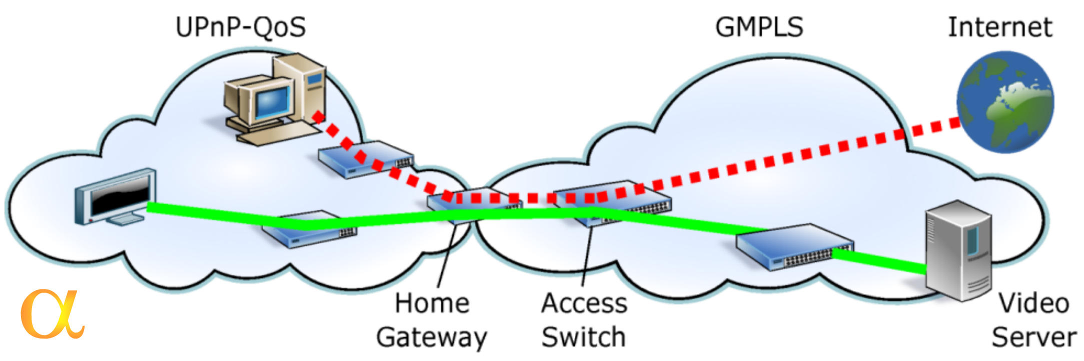
43% of service provider help desk calls is home network related



[F. Den Hartog, TNO – ECOC 2012]

Home Gateway

- Bridges between public access network and in-home network
- Allows (remote) diagnostics of in-home network (BW probing, device discovery, topology discovery, fault detection, performance measurements, …)
- Translate IP addresses and modulation formats
- Assures security and privacy
- Provides access to third parties for maintenance and upgrading
- Provides QoS control for indoor terminals
- May host home-internal functions (local data storage, interoperation of devices…)



"Home Gateway can communicate QoS data between access and home domains"

[A.M.J. Koonen & M. Popov – ECOC 2012 Mo1G1]

Home Network standardization is complex

Broadband	TCP/IP	**Tele- communications**	SIP
	Microsoft P&P		Femtocell
	Apple P&P		IMS
	Google Platforms		DECT
	W3C		ETSI HF
	PUCC		Bluetooth
	G.hn		ETSI TISPAN
	OSGi		
	TR-069	**Multimedia and**	ISO/IEC 15018
	ITU-T H610	**Entertainment**	UPnP
	Wi-Fi		DLNA
	Ethernet		DVB
	HGI		IEC 62045
	HomePNA		MoCA
	IEEE 1901		OpenIPTV
			IEC Home Server
Home	KNX		ETSI NGN HAN
management of	EN 50173		
appliances,	Zigbee	**Energy**	LON
comfort services,	6LowPAN	**managment**	HES
safety&security	IEC 61850	**services and**	CIM
	OpenTherm	**health care**	IEC 61334
	Insteon		DLMS/COSEM
	Z-wave		M-bus
	EN 61508		U-SNAP
	EN 60335		Continua
	ISO 18012-1		
	EN 50523		
Peripheral	USB	HDMI	
Networks	UWB	WHDI	
	NFC	Wireless HD	
	RFID	FireWire	

[F. den Hartog et al, *CENELEC SmartHouse Roadmap*]

Home Gateway Initiative: Connecting Homes, Enabling Services

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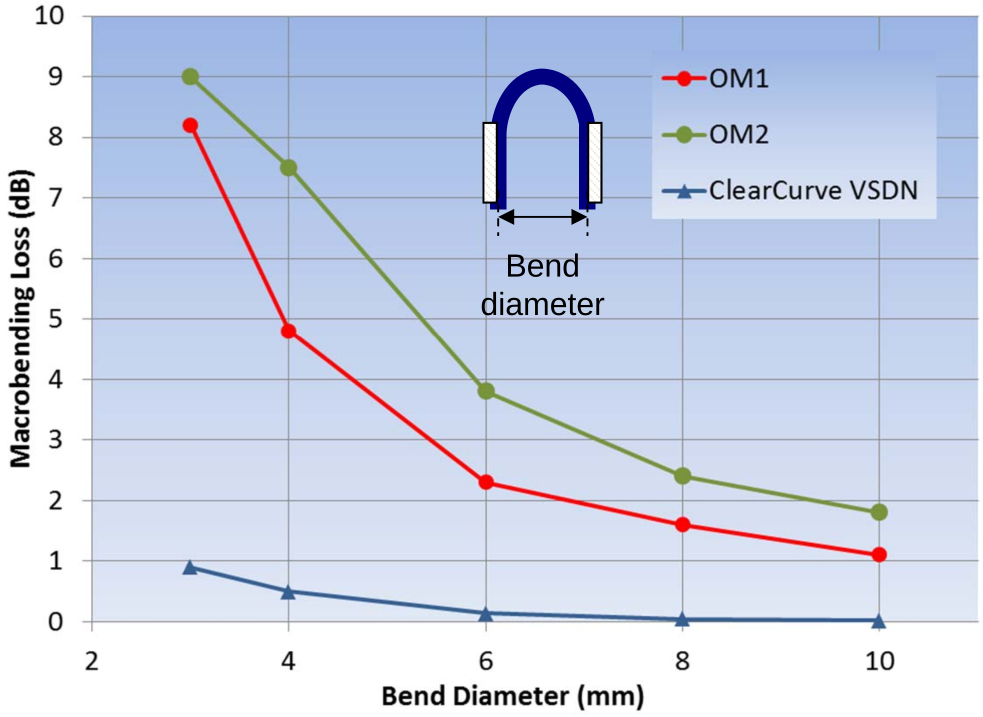
Optical Fiber Requirements for In-Home Networking

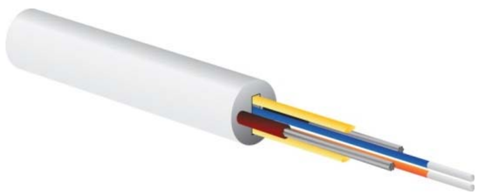
- Throughput of at least 1 Gb/s
- Bend-insensitive performance
- Small diameter, flexible, yet robust cable
- Small form-factor connector
- Low power consumption and immunity to EMI
- Fiber characteristics optimized for low-cost links
- Support for multiple consumer-electronics protocols
- Future-proof for upgrade to >10 Gb/s

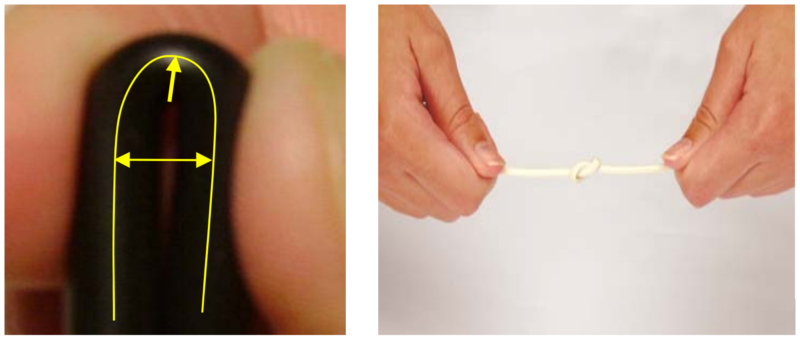
Bend-insensitive Fiber Cable



ClearCurve® VSDN® :

- silica GI-MMF, ∅ 80μm core
- NA=0.29
- enables ∅ 3mm cable design that maintains link robustness in case of temporary cable pinch and knot
- >7dB lower loss at 3mm bend diameter
- >75% tighter bends for 1dB loss



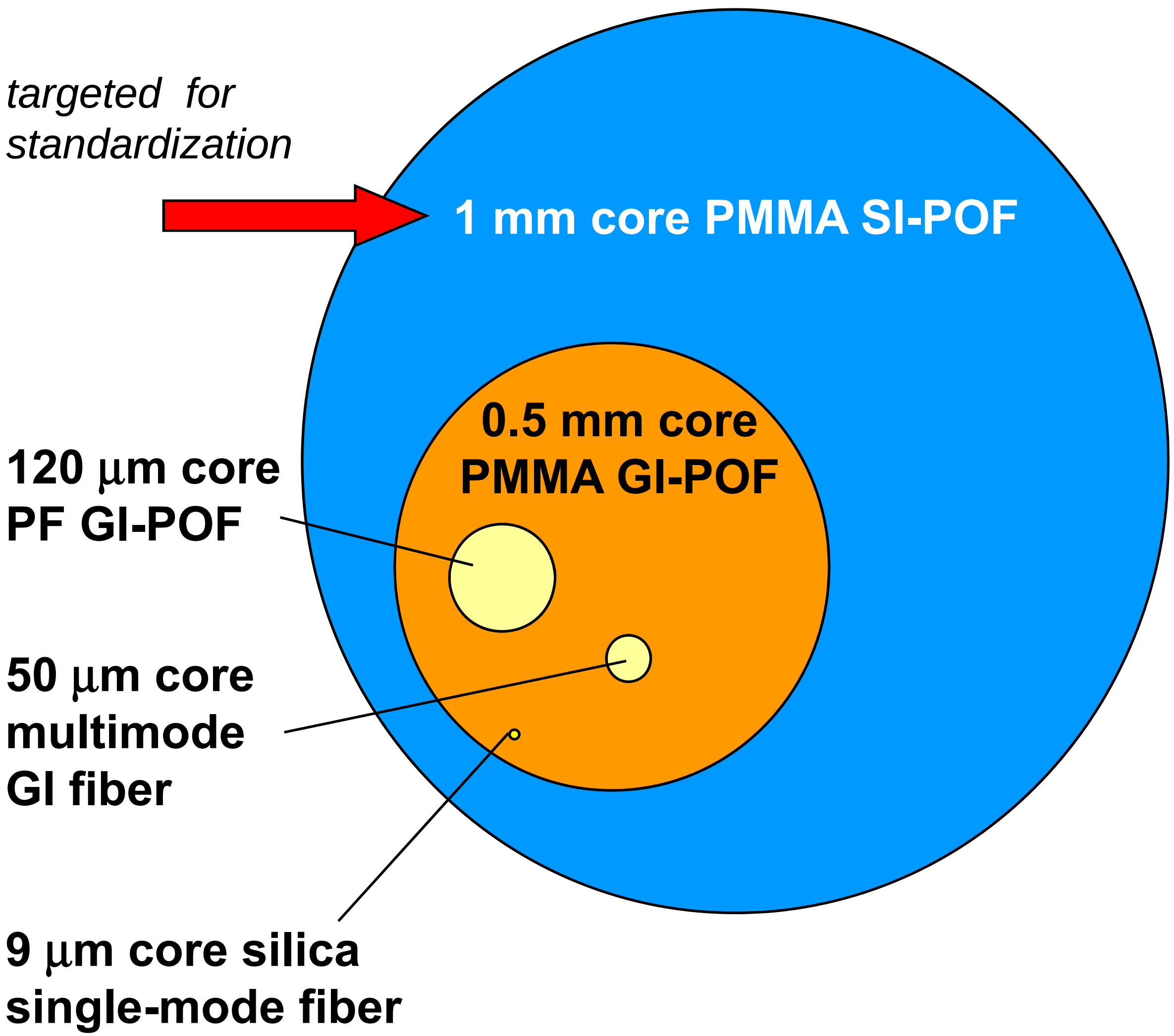


Knots in cables induce < 3 dB

CORNING

[A. Ngoma et al,, ECOC 2012, Mo1G4]

Silica and Plastic Optical Fiber

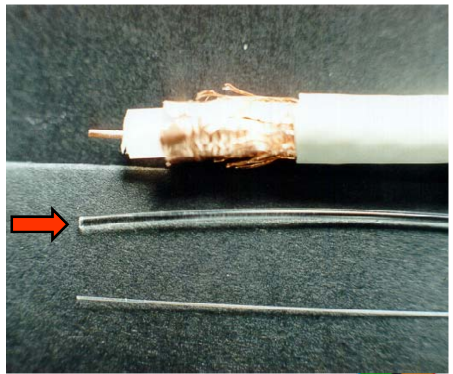


POF's Advantages:

- ☺ Ductile
- ☺ Not conductive
- ☺ Easy to splice
- ☺ Easy to connectorise

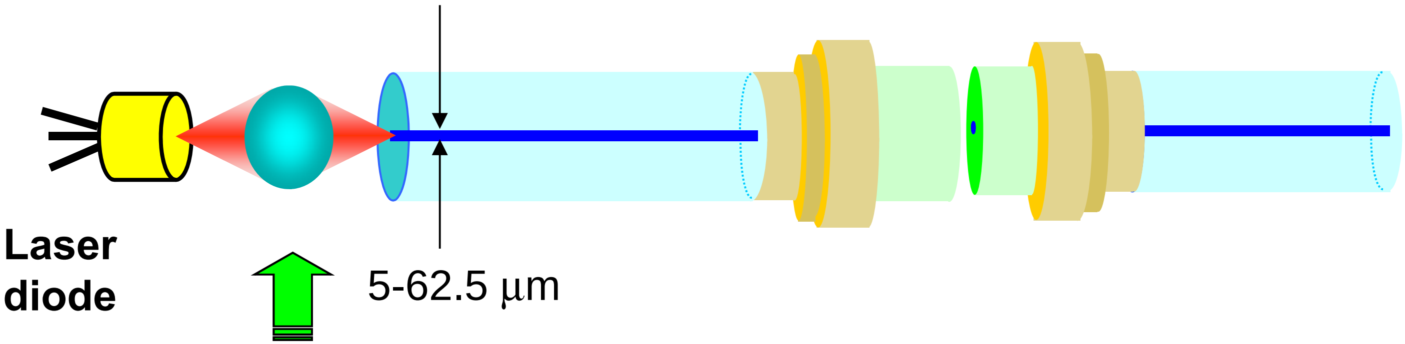
Disadvantages:

- ☹ Higher loss
- ☹ Lower bandwidth



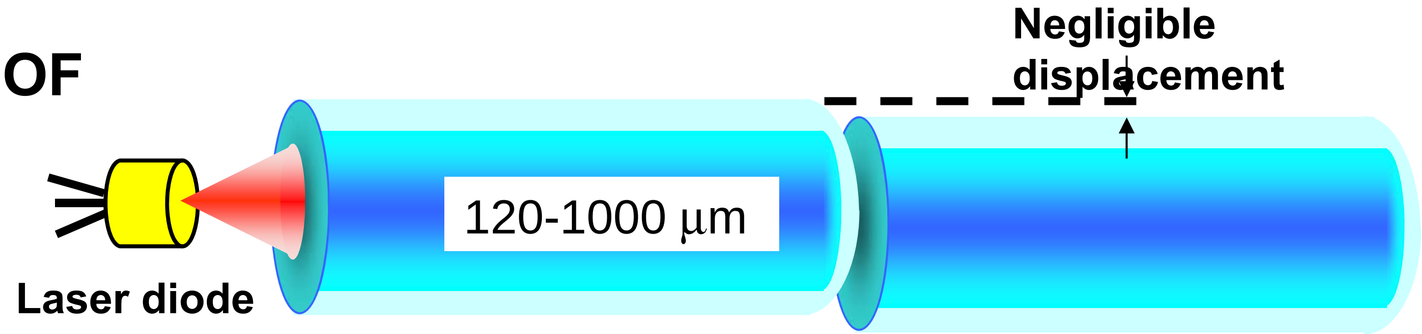
Handling POF

Silica based optical fiber



Lens system or expensive ceramic connector with very high accuracy is required for high coupling efficiency.

POF

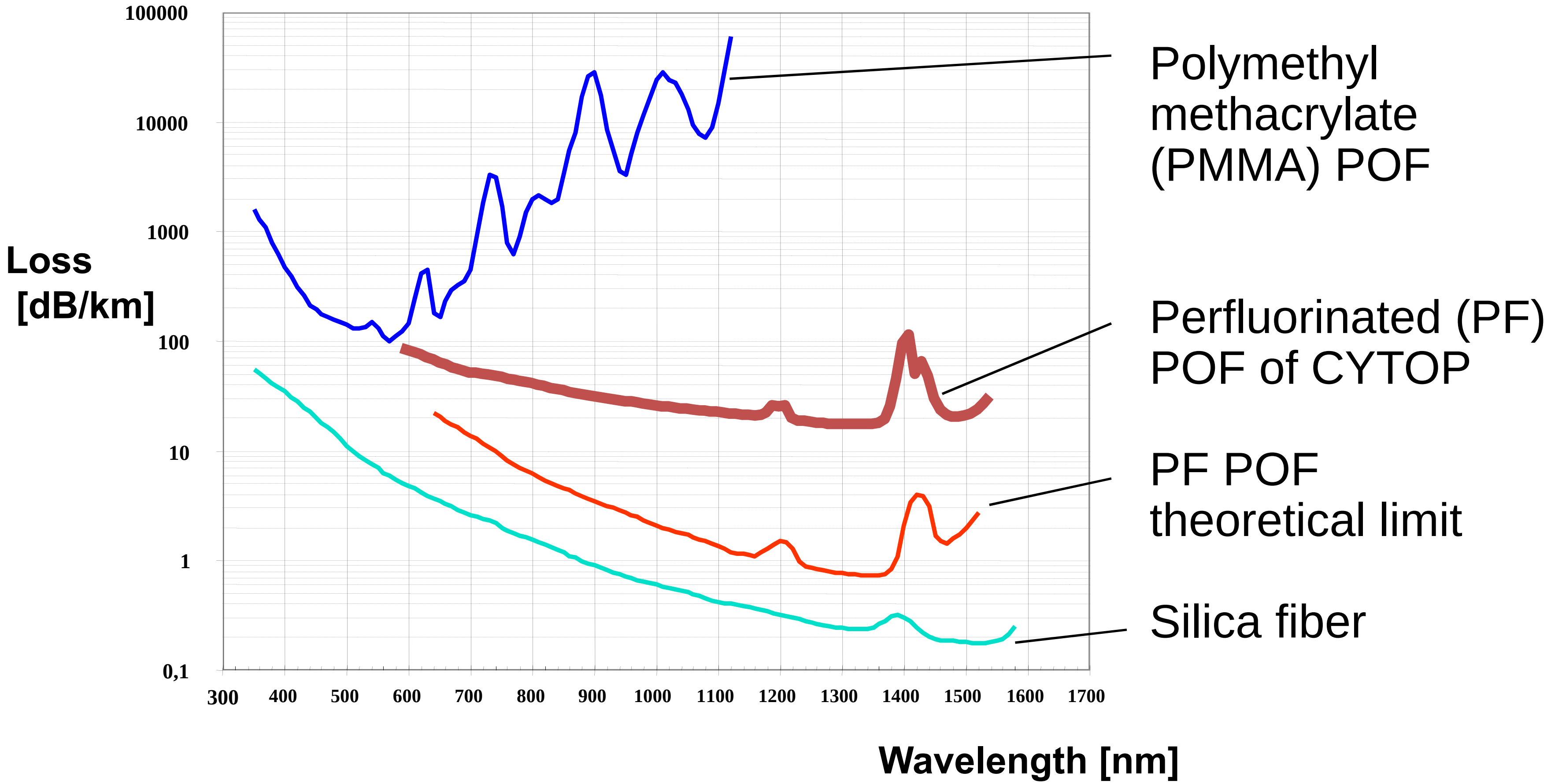


Easy alignment

Small modal noise because of large mode number

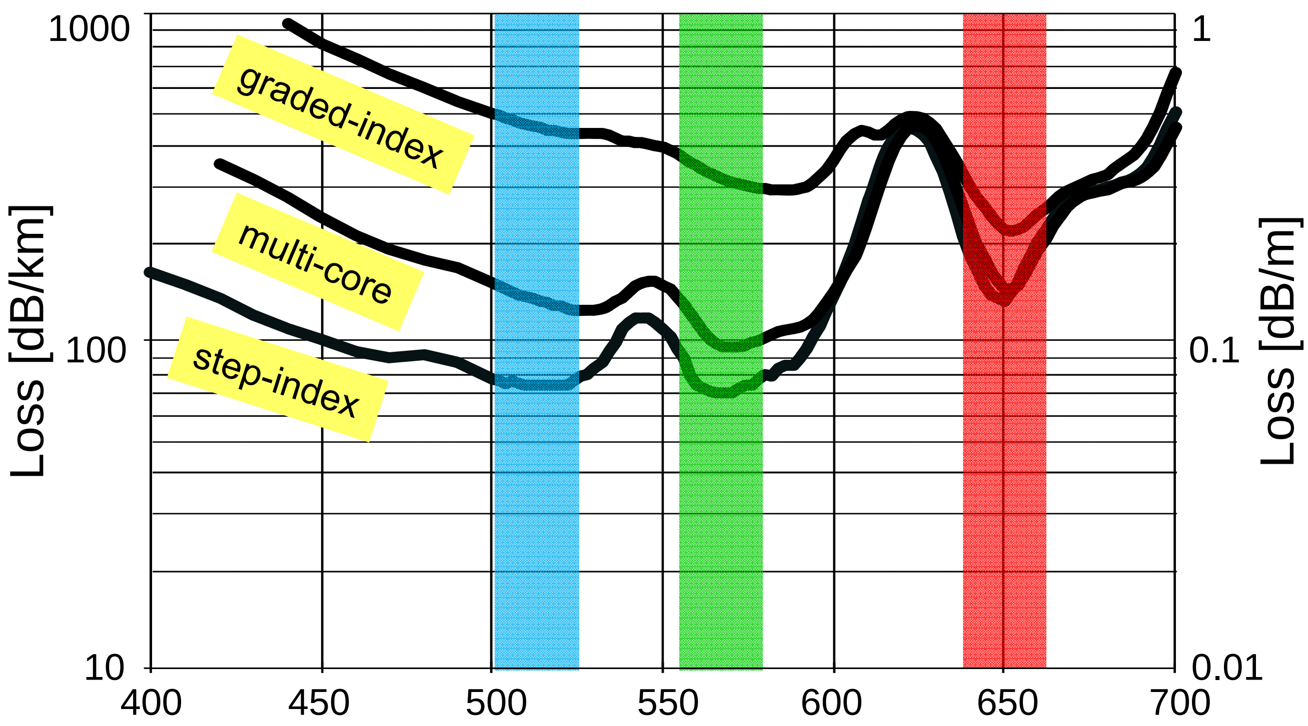
[Source: Keio University]

Attenuation of POF



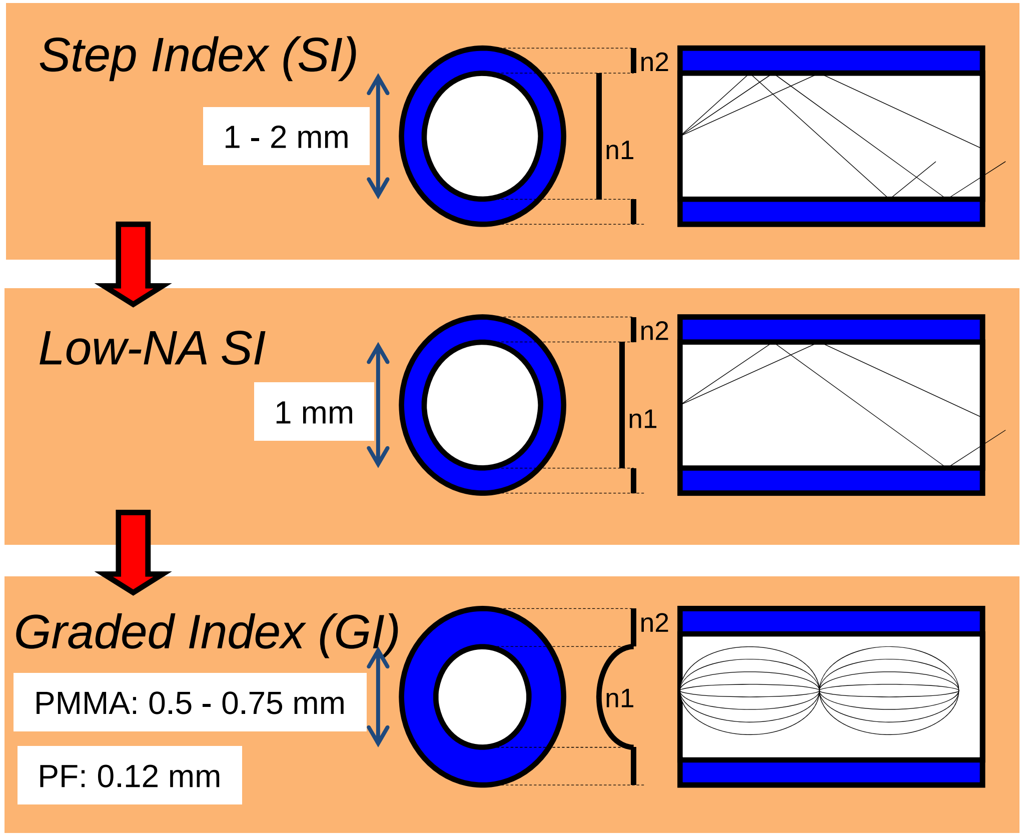
PMMA: for use from 450 to 650 nm (visible light)
PF: for use from 600 to 1350 nm

Optical losses in PMMA POF



- Three spectral windows of interest:
  red 650 nm, green 570 nm, and blue 520 nm
- Fiber lengths ≥ 50 meters (classified by ETSI)
- Visible light: eases network diagnostics

POF bandwidth



Fibre @ wavelength		BW at 100 m
PMMA SI @ 650 nm		**0.04** GHz
PMMA low-NA SI @ 650 nm		**0.1 – 0.2** GHz
PMMA GI @ 650 nm		**2.2 – 3** GHz
PF GI @ 650 nm		**2 – 4.5** GHz
PF GI @ 850 nm		**2.3 – 2.7** GHz
PF GI @ 1300 nm		**2.4 - 7** GHz

- Material dispersion of PF-POF is lower than that of silica fiber over a broad λ range

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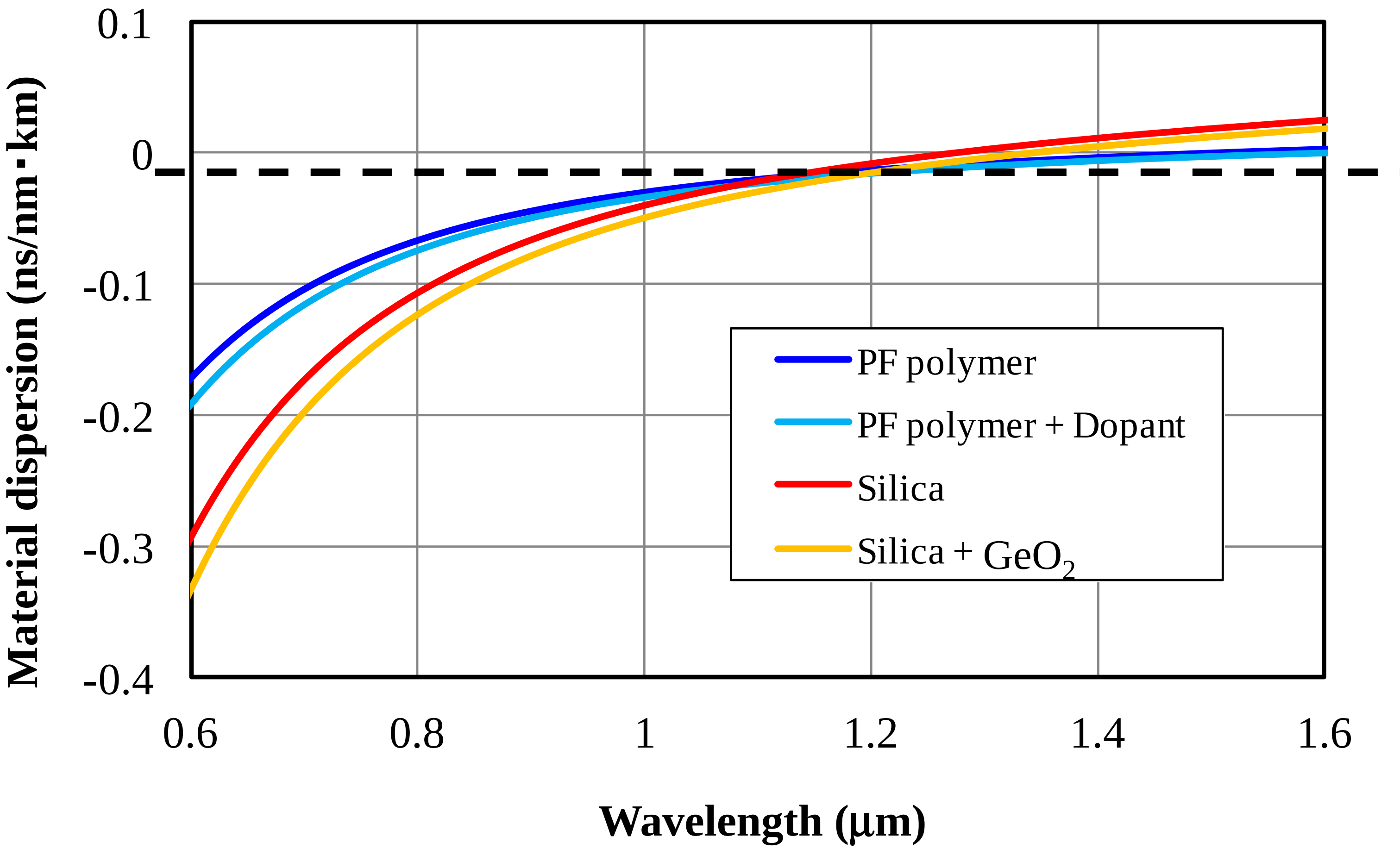
Advantage of Perfluorinated (PF) polymer



PF polymer has low material dispersion in a wide wavelength range from visible to near infrared region.

[Y. Koike, ECOC2012, Mo1G6]

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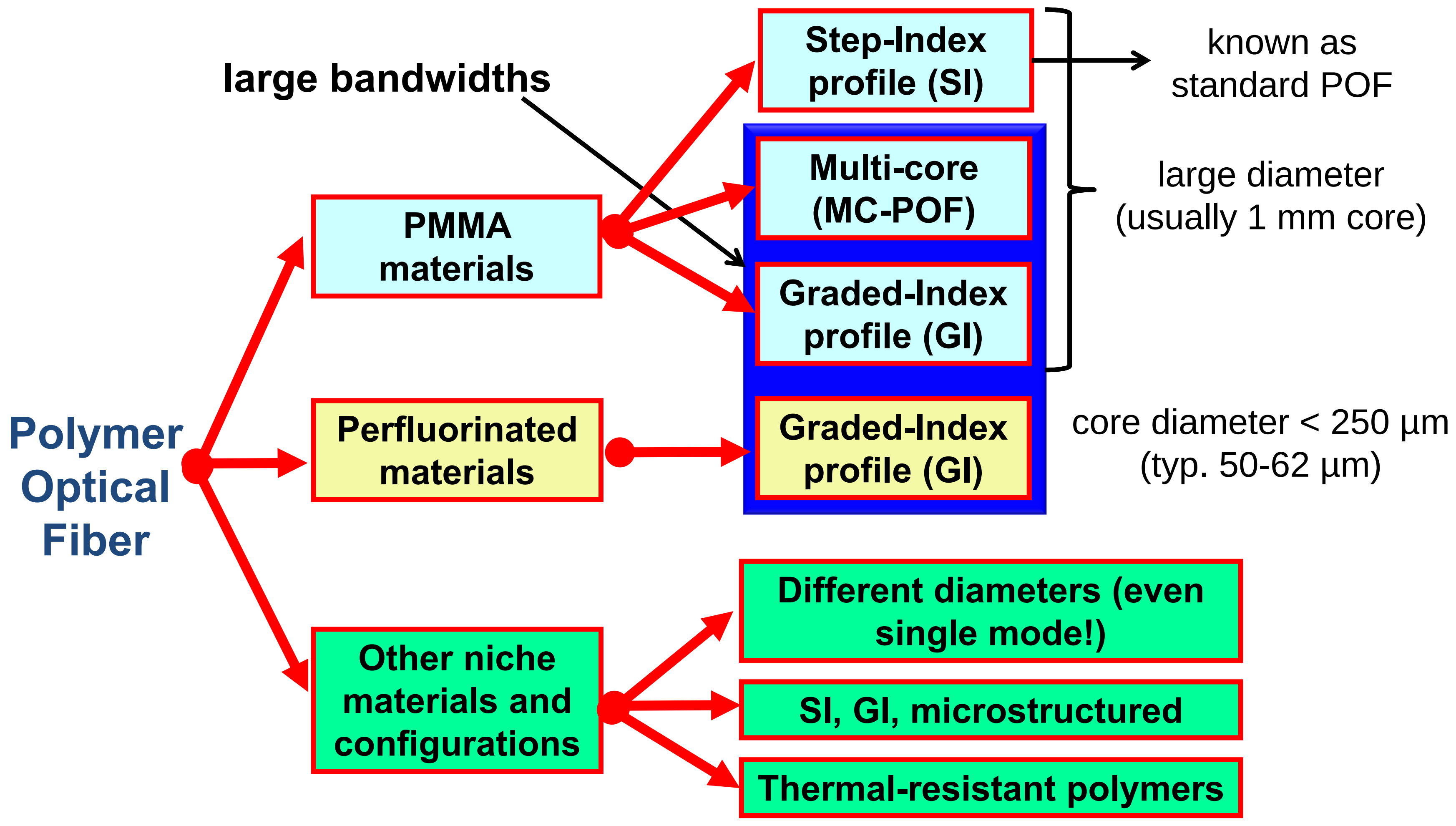
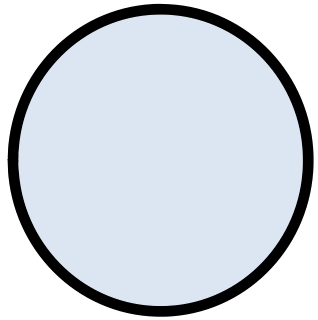
Plastic (/Polymer) Optical Fiber options

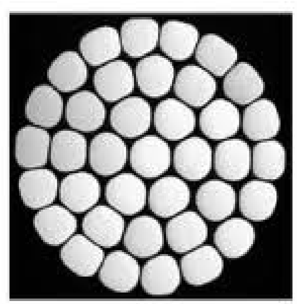


Choice of POF

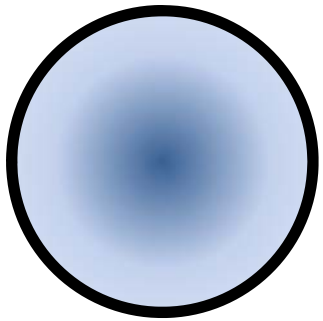
- **Up to 1 Gbit/s:**
  exploit the only standardized, mass produced POF, i.e., PMMA step-index POF with 1-mm core diameter (IEC A4a.2)



- **Beyond 1 Gbit/s:**
  very good results on PMMA multi-core POF (MC-POF)
  - Much better bending resilience
  - Slightly better bandwidth



- **If >10 Gbit/s is required**
  Graded-index POF
  - Large-core preferred
  - For very high capacity → soft plastic (Perfluorinated)
  - Not yet standardized
  - Issue: bending losses

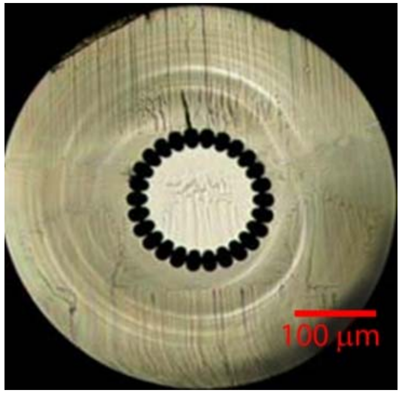


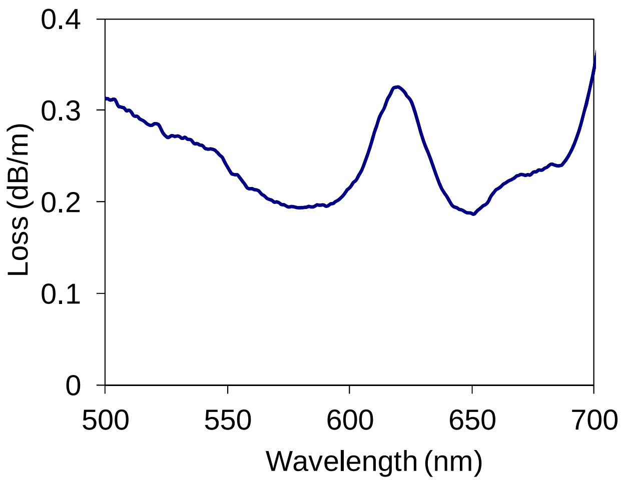
COBRA

Microstructure POF (mPOF)

Potential for:

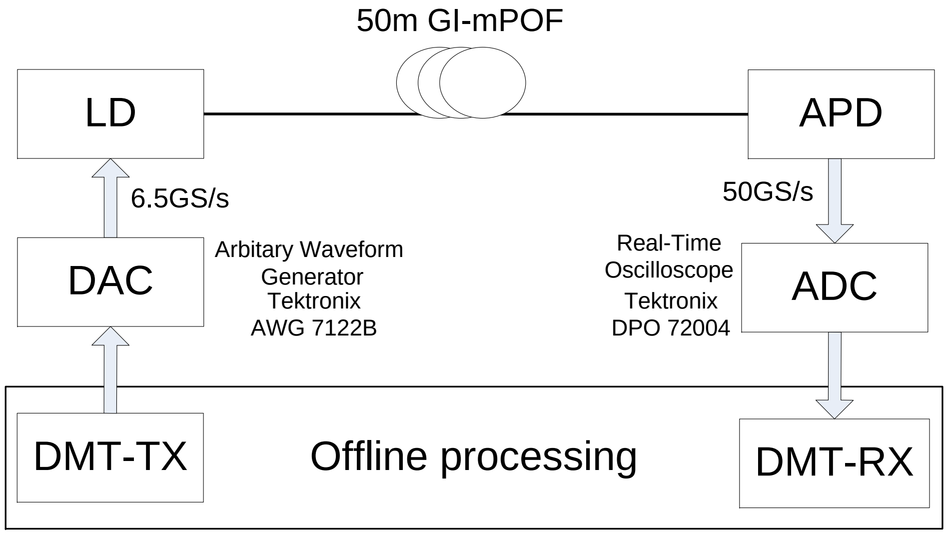
- Flexible core sizes
- Low bend losses
- Broad bandwidth





7.3 Gbit/s transmission over mPOF

- 650 nm transceiver
- DMT technology with bit-loading
- 50 m long ∅140/500µm mPOF



[Y. Shi et al., PTL July 2012]

COBRA

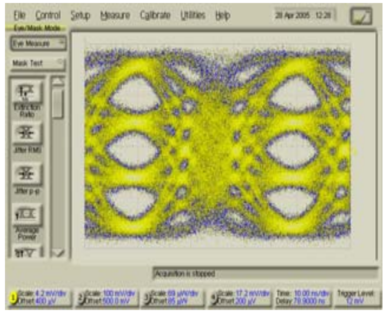
Outline

- Convergence in home networks, home service scenarios
- Home wired network architectures, CapEx and OpEx
- Residential Gateway
- Optical fiber types
- High-capacity data transmission for wirebound delivery
- High-capacity data transmission for wireless delivery
- Converged networks
- Standards for POF transmission systems
- Advanced networking techniques (routing, MGDM, Optical wireless)
- Evolution trends and roadmap
- Concluding remarks

Overcoming the limited BW of POF

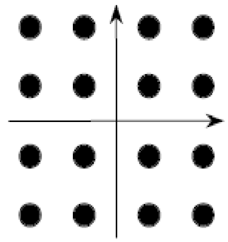
Baseband modulation formats

- NRZ + strong equalization
- 4-PAM, 8-PAM and beyond



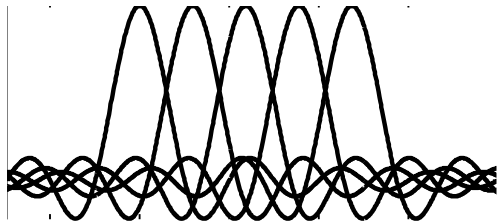
Quadrature-like modulation formats

- QPSK, QAM-x
- improved spectral efficiency



Multitone Transmission (OFDM, DMT)

- dispersion-robust
- benefit from high market-volume for wireless LAN, xDSL, DVB-C, and DOCSIS cable modems
- Gh.n standard (DMT)



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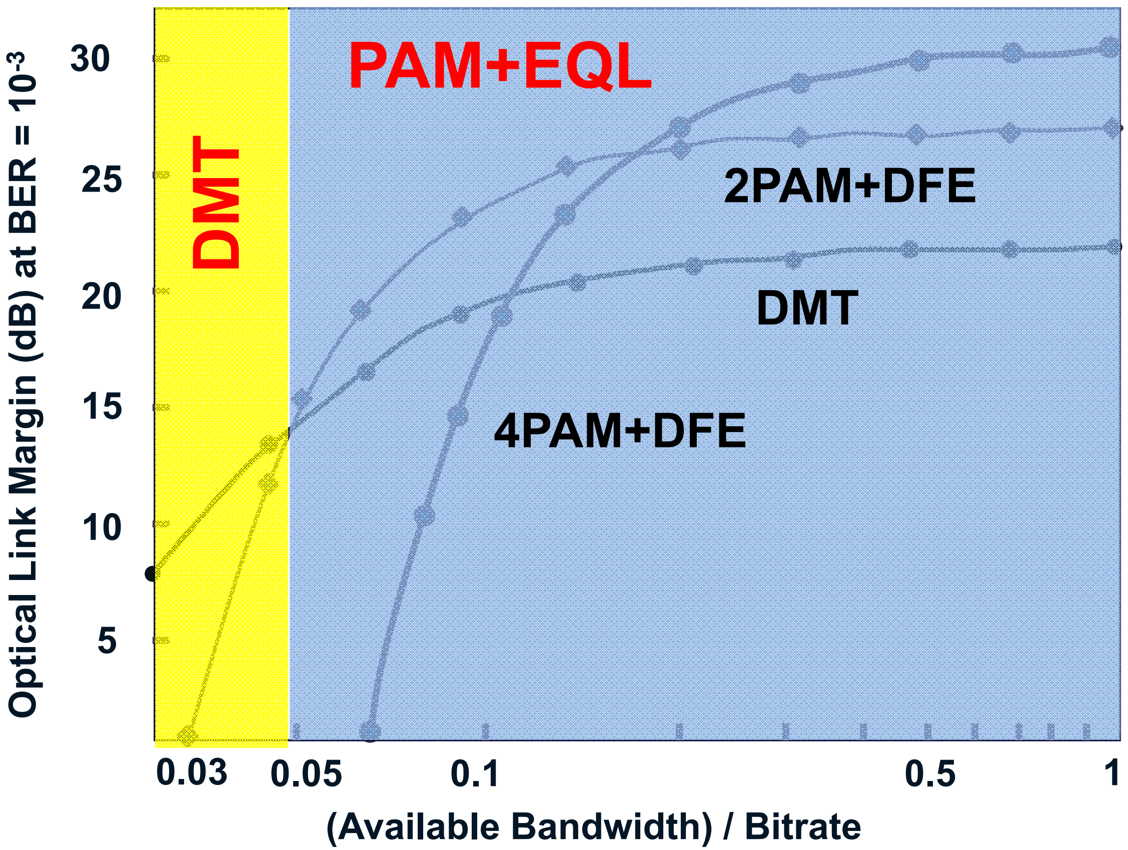
Modulation Formats



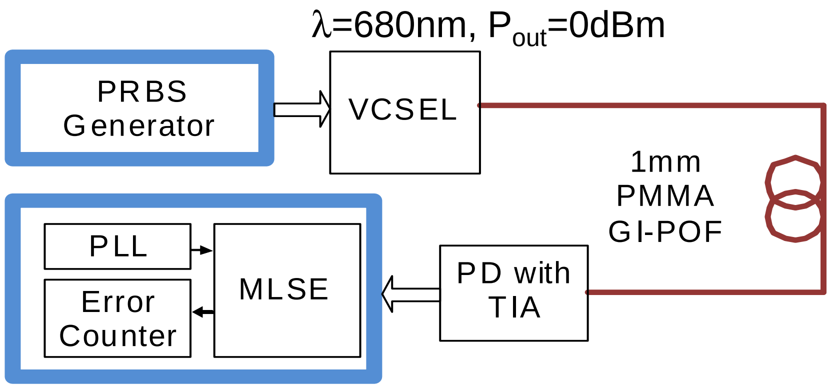
DMT=Discrete Multi-Tone
PAM=Pulse Amplitude Modulation
DFE=Decision Feedback Equalizer

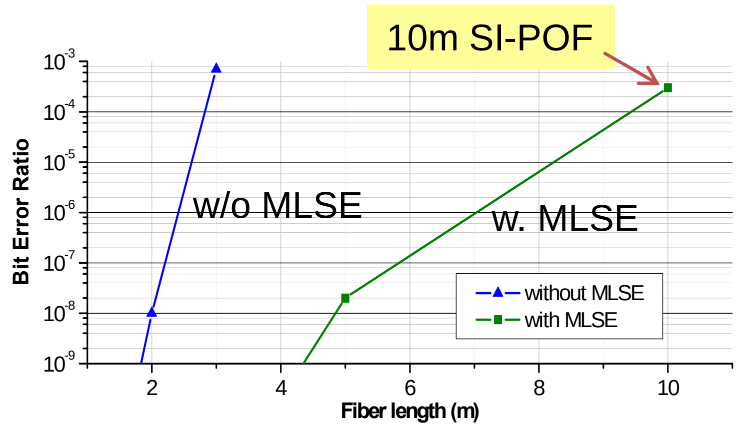
- Moderate bandwidth → PAM+EQL
- Narrow bandwidth → DMT (incl. bit loading)

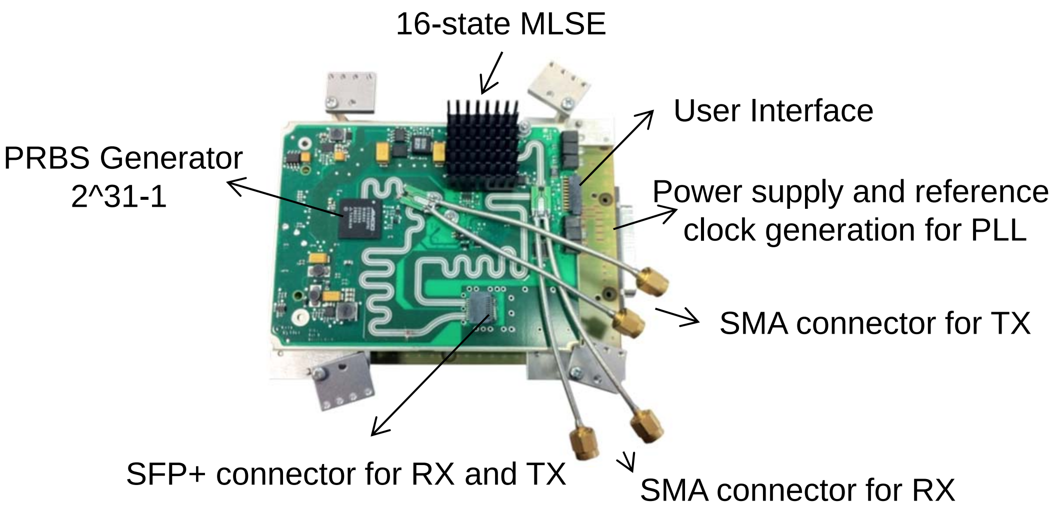
[S. Randel et al., IEEE JSTQE (16), 5, p. 1280-1289, Oct. 2010]

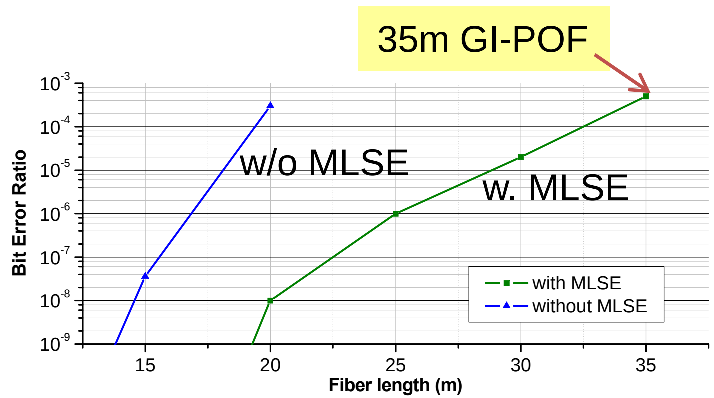
COBRA

Real-time 10.7Gbit/s 2-PAM (OOK) over POF using MLSE





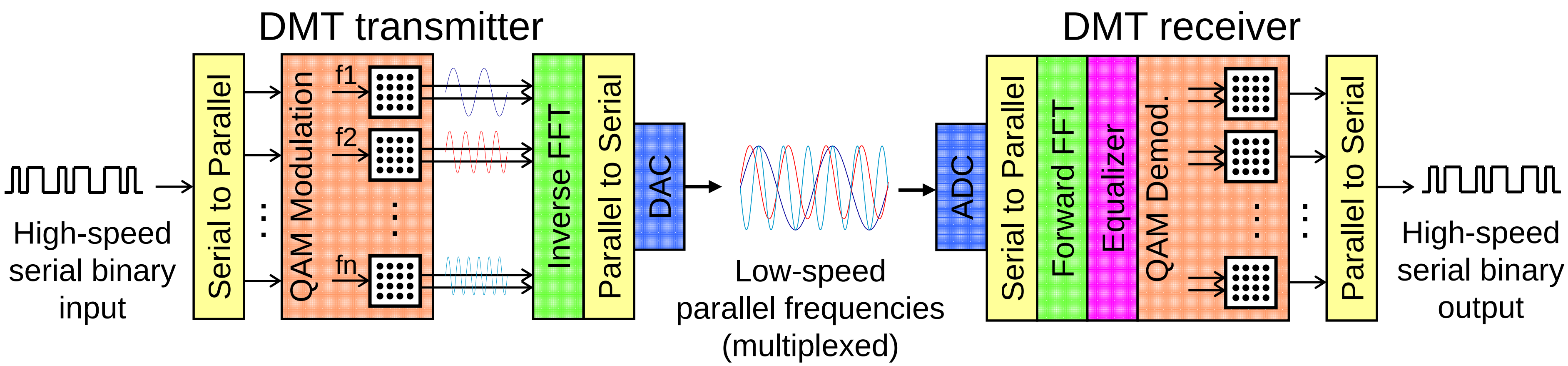




[S. Loquai et al., PTL Dec. 2012]

COBRA

High data rates over dispersive POF links using DMT



- *Discrete Multitone (DMT) modulation:* high-speed serial data transmitted parallel at low-speed using different frequencies
- *high spectral efficiency* with multi-level QAM, not only "on-off"
- especially suitable for *multipath dispersive channels* such as MMF and POF
- 51.8Gbit/s over 100m Ø50mm core PF GI-POF [1]
- 4.7Gbit/s over 50m 19-cores Ø1mm PMMA SI-POF [2]
- 5.3Gbit/s over 50m Ø1mm core PMMA GI-POF [3]

SIEMENS

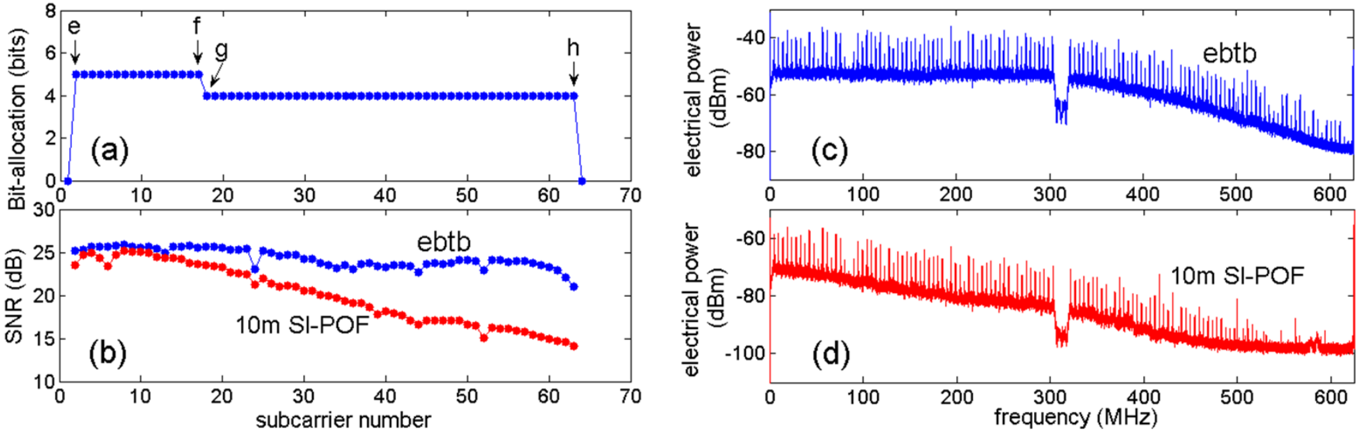
[1] H. Yang et al., OFC2009, Postdeadline paper PDP8
[2] H. Yang et al., OFC2010, paper OWA4
[3] D. Visani et al., OFC2010, Postdeadline paper PDPA3

COBRA

Real-time 1.25 Gbit/s DMT over ∅ 1mm core SI-POF

GbE real-time DMT including adaptive bit loading and power loading

- 1.25 Gbit/s DMT
- over 10m ∅1mm core step-index PMMA POF
- FPGA: Xilinx Virtex4 FX100
- ADC1: 8 bit, 3 GS/s
- ADC2: 12 bit, 500 MS/s



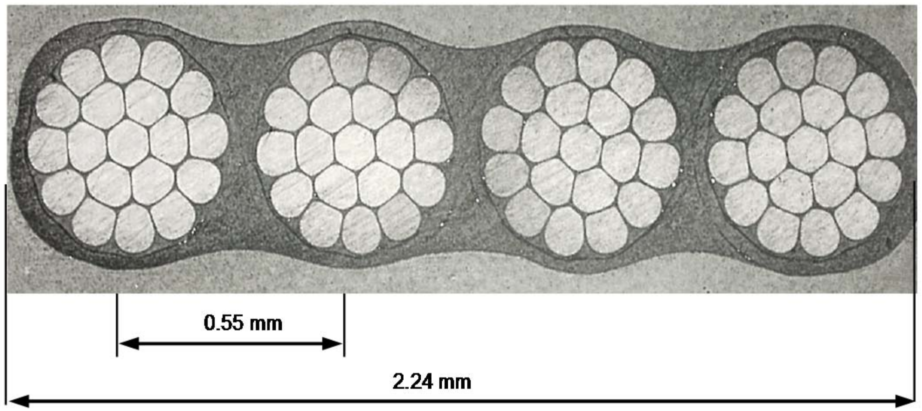
SIEMENS

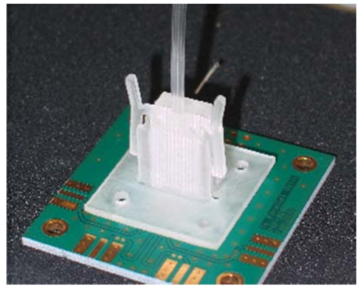
[S.C.J. Lee et al., *Elect. Lett.*, 45(25), 1342-1343]

COBRA

10 Gbit/s and more using POF

- Using <u>parallel</u> POFs, viz. a ribbon structure of multi-core





POF ribbon is attached to PCB
10 Gbit/s (4×2.5 Gbit/s) on a thin cable

- Using a different type of POF, viz. perfluorinated (λ=1302nm, core $\varnothing$50μm)

352 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 28, NO. 4, FEBRUARY 15, 2010

47.4 Gb/s Transmission Over 100 m Graded-Index Plastic Optical Fiber Based on Rate-Adaptive Discrete Multitone Modulation

Hejie Yang, *Student Member, IEEE*, S. C. Jeffrey Lee, *Student Member, IEEE*, Eduward Tangdiongga, Chigo Okonkwo, *Student Member, IEEE*, Henrie P. A. van den Boom, Florian Breyer, *Student Member, IEEE*, Sebastian Randel, *Member, IEEE*, and A. M. J. Koonen, *Fellow, IEEE*

POF+

eurofos
a photonics network

COBRA

Some recent POF transmission system experiments

- using ∅1mm core PMMA POF (unless otherwise indicated)

Data rate	POF type	Core ∅	Tx	Wavelength	Rx	Format	Lengt h	Year
1.25 Gb/s (real time)	SI-POF	1 mm	Eye-safe RCLED	650 nm	Large area receiver	OOK	50 m	2010
2.2Gb/s (wired) +480Mb/s (wireless)	GIPOF-PON (1×4)	1 mm	High power laser	650 nm	APD	DMT/OFDM	50 m	2012
3Gb/s (wired) +480Mb/s (wireless)	GI-POF	1 mm	VCSEL	665 nm	APD	DMT/OFDM	50 m	2011
4.7Gb/s	MC-POF	1 mm	Eye-safe VCSEL	665 nm	APD	DMT	50 m	2010
5.3Gb/s	GI-POF	1 mm	Eye-safe VCSEL	665 nm	PIN+TIA	DMT	50 m	2010
5.8 Gb/s	GI-POF	1 mm	High power laser	650 nm	PIN+TIA	PAM2+DFE	75 m	2011
7.3 Gb/s	mPOF	**140 μm**	High power laser	650 nm	APD	DMT	50 m	2012
4×2.5Gb/s	Ribbon		VCSEL array	665 nm	PIN Diode array	OOK	25 m	2011
10 Gb/s	MC-POF	1 mm	High power laser	650 nm	PIN+TIA	DMT	25m	2011
10 Gb/s	GI-POF	1 mm	High power laser	650 nm	PIN+TIA	DMT	35 m	2011
10.7Gb/s	SI-POF	1 mm	WDM high power lasers	405, 515, and 650 nm	PIN+TIA	DMT	50m	2012
10.7 Gb/s	GI-POF	1 mm	VCSEL	665 nm	MSM PD+TIA	NRZ+MLSE+PLL	35m	2012
47.4 Gb/s	**PF** GI-POF	**50 μm**	DFB	1302 nm	∅25μm PD	DMT	100 m	2010

[Y. Shi et al., accepted for JLT]

COBRA

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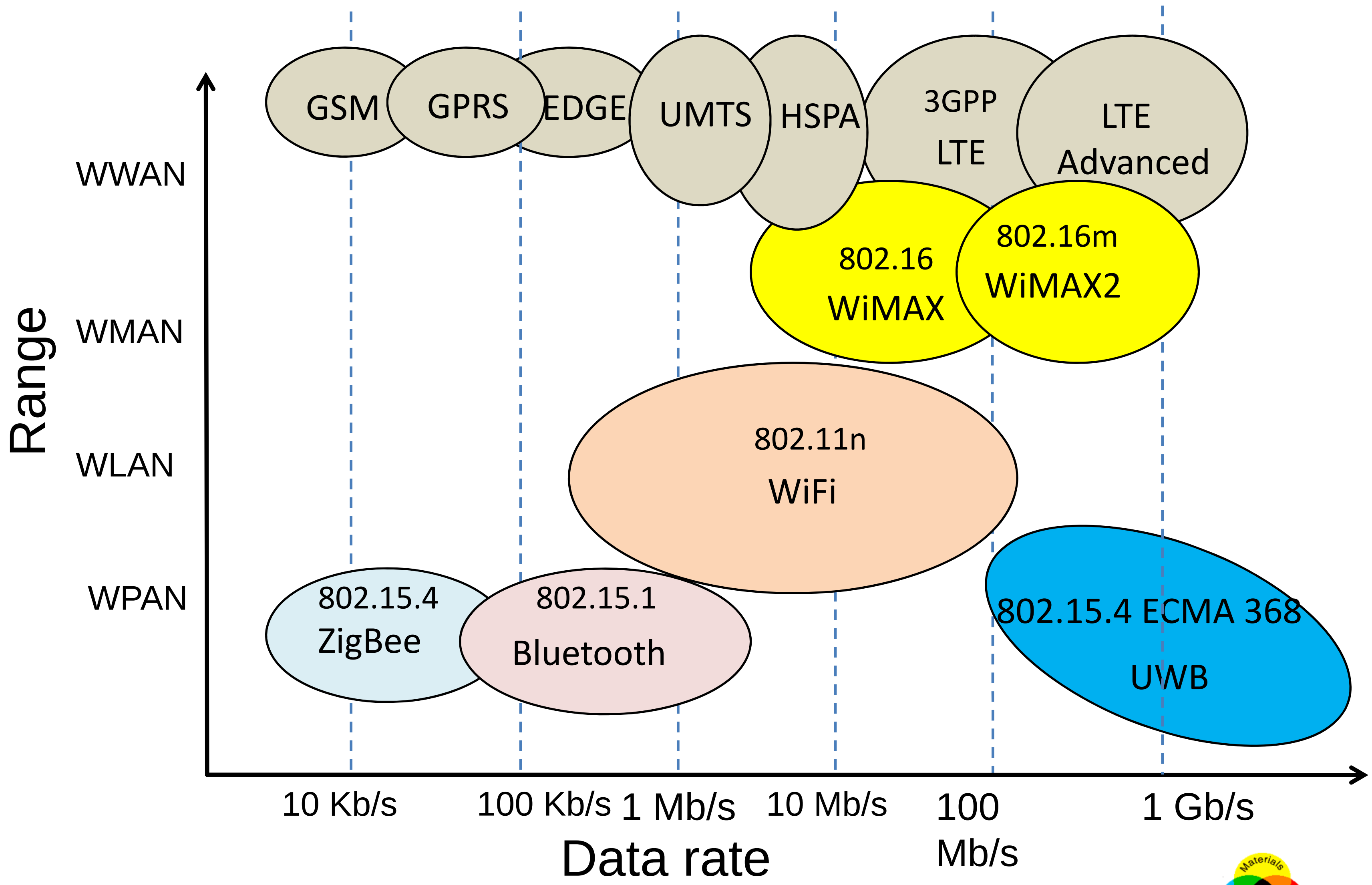
COBRA

Wireless technology standards



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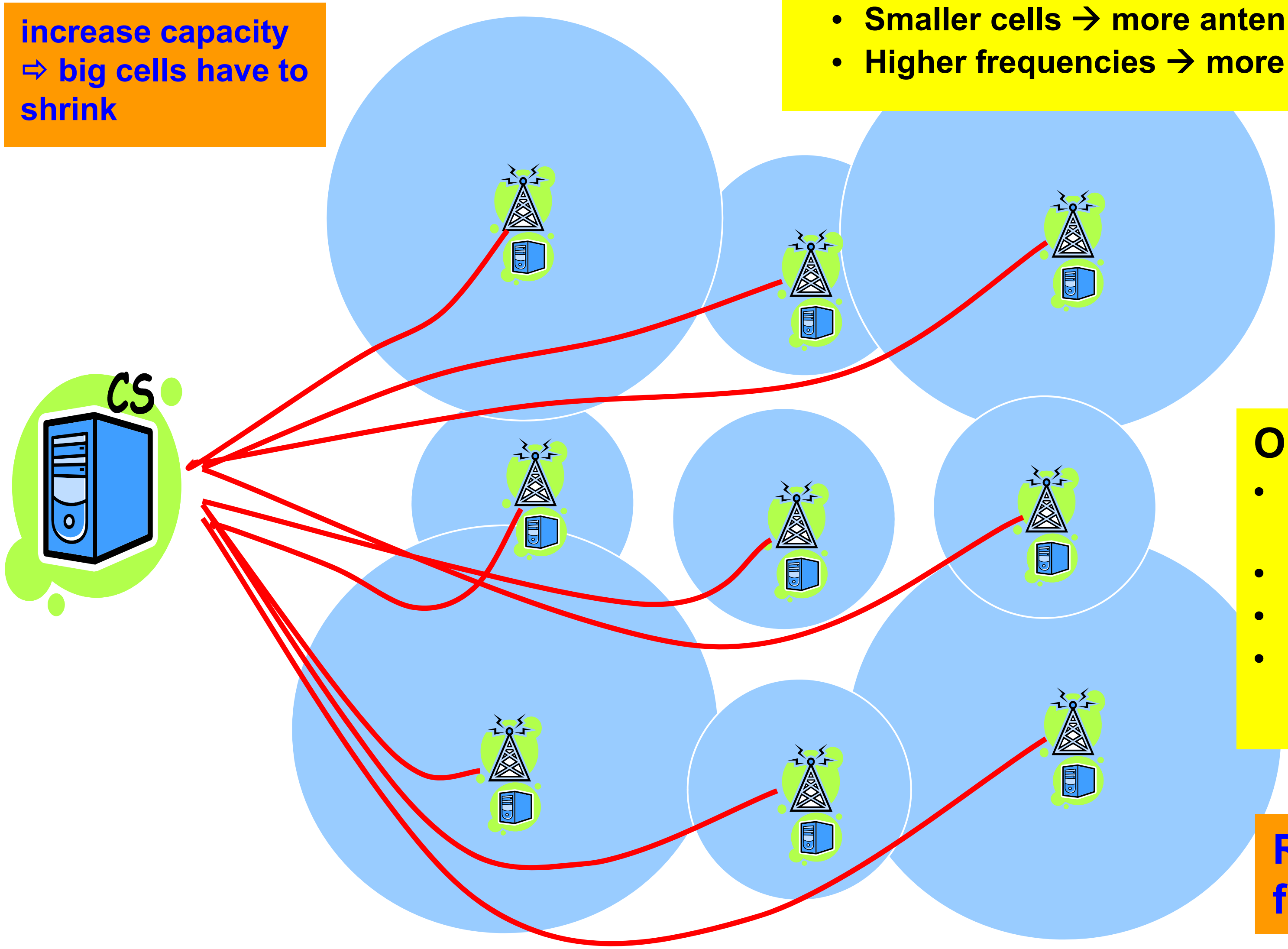
Wireless technology standards - characteristics

Technology	Standards	Coverage	Frequency bands	Modulation	Data rates (peak downlink)	Bandwidth
LTE	3GPP	Up to 100 km	700/900, 170/1900MHz, etc.	OFDMA / SC-FDMA	345.6Mb/s(4*4 MIMO, in 20 MHz FDD)	1.4, 3, 5, 10, 15, 20 MHz
WiMax	802.16m	3 km,5-30 km,30-100 km	2.3, 2.5 and 3.5 ,5.8 GHz	SOFDMA	365Mb/s(4*4 MIMO, 2x20 MHz FDD)	5,10,20 MHz
WiFi	802.11ac	Up to 70 m (indoor)	2.4, 3.65, 5 GHz	OFDM	600 Mb/s (4*4 MIMO, in 40 MHz channel)	20 ,40 , 80 MHz
Bluetooth	802.15.1	10 m (class1)	2.4 GHz	GFSK, π/4-DQPSK and 8DPSK with FHSS	3 Mb/s	1 MHz (79 bands in total)
Zigbee	802.15.4	70 m	868, 915 MHz and 2.4 GHz	OQPSK with DSSS	250 kb/s	5 MHz (16 bands in total)
UWB	802.15.3/ ECMA368	10 m	3.1-10.6 GHz	QPSK/OFDM (MB-OFDM)	480 Mb/s (MB-OFDM)	528MHz for each sub-band (MB-OFDM)
				BPAM(DS-UWB)	1 Gb/s(DS-UWB)	<7.5 GHz(DS-UWB)

Radio over fiber



To increase capacity:

- Smaller cells → more antenna sites
- Higher frequencies → more complexity

Optical fiber

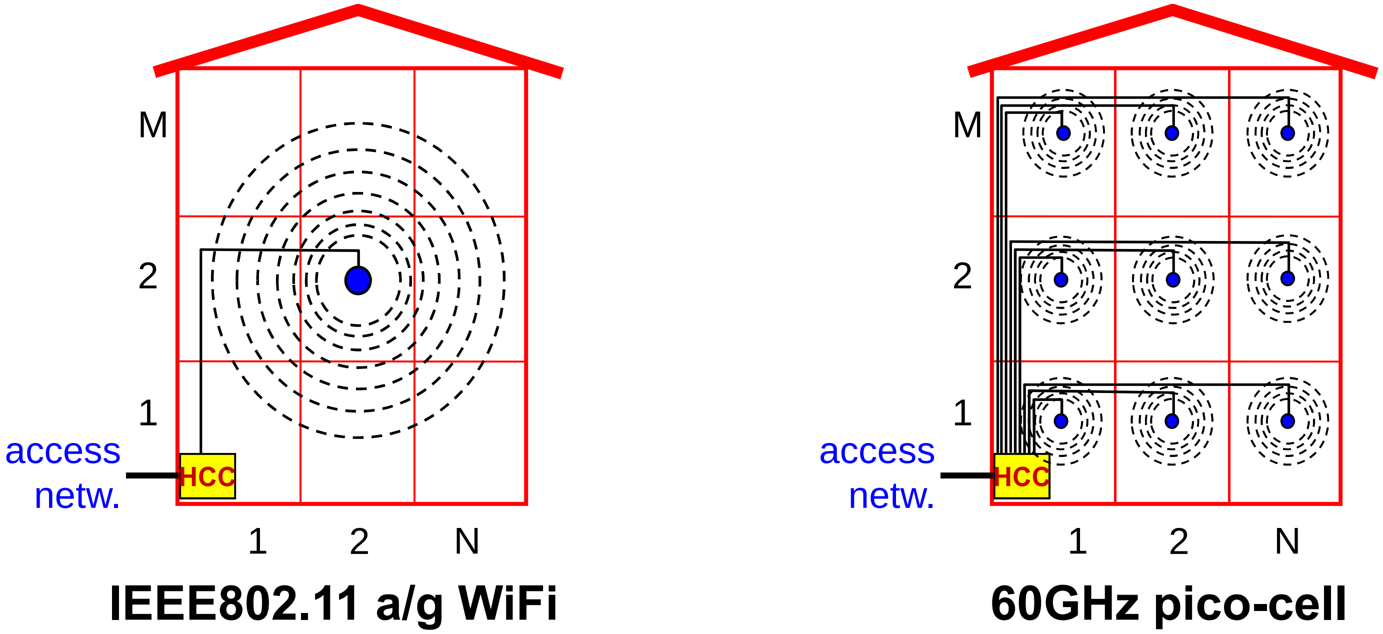
- Unlimited bandwidth
- Low loss
- Light weight
- EM immunity

⇩

Radio over fiber

[courtesy of Maria Garcia Larrode]

Moving to wireless pico-cells



- **Radio emission power per antenna ~ (radius of cell)²**

  $P_{\text{WiFi}} \cong c \cdot R^2 \cdot$ (losses in walls)

  $P_{\text{pico}} \cong K \cdot c \cdot (R/\sqrt{K})^2 = c \cdot R^2$

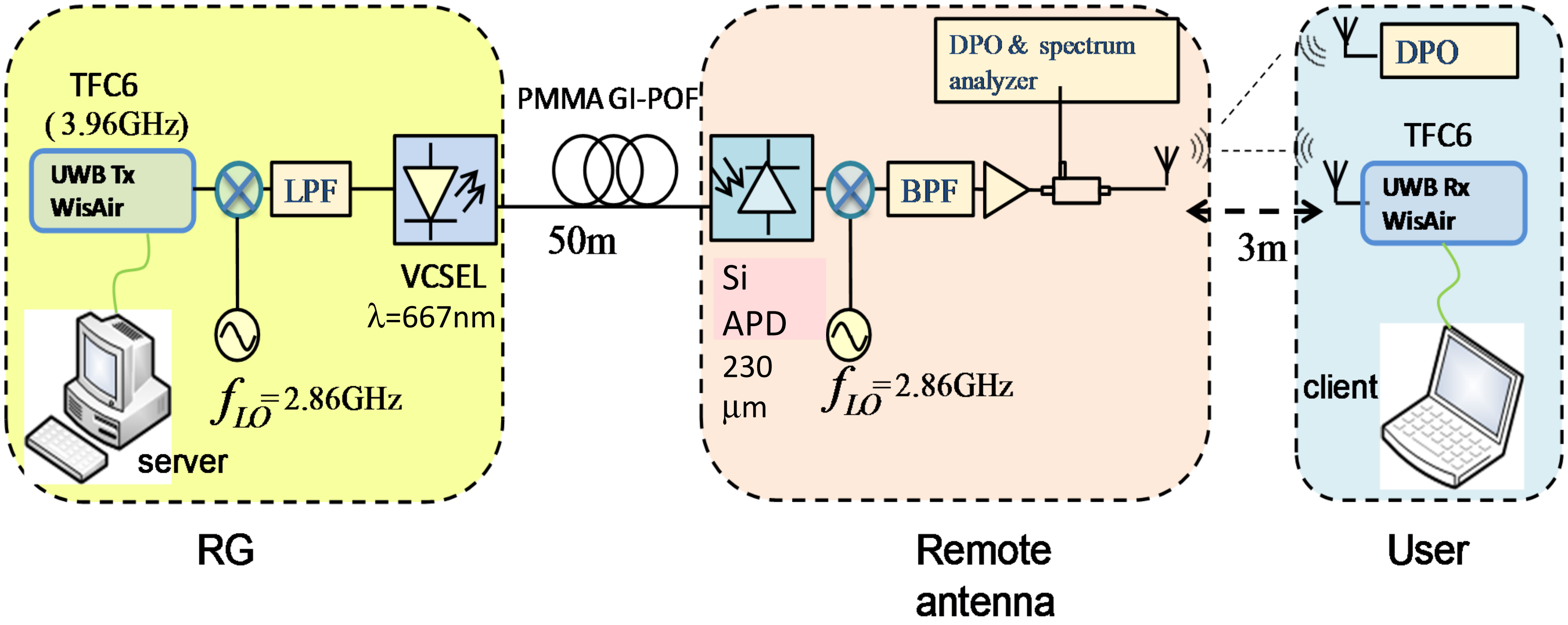
- **Further energy savings by capacity-on-demand signal routing** (e.g. by optical routing using radio-over-fiber)

⇨ pico-cell approach + radio signal routing save energy

COBRA

UWB radio over ∅ 1mm core GI-POF

- Real-time HD video over 50m ∅1 mm core GI-POF + 3m wireless
- 528MHz UWB (TFC6, 3.696-4.224GHz)
- Downconversion to 0.836-1.364GHz band
- EVM B2B 9.7%, after 50m GI-POF <15.5%

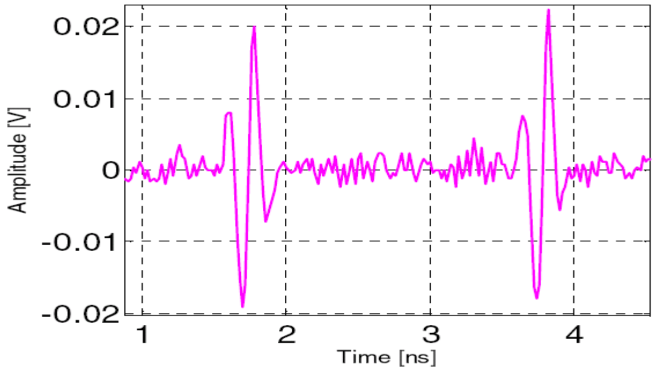


Highly spectrum-efficient reach extension of UWB over GI-POF

[Y. Shi et al., OFC 2011]

2 Gbit/s Impulse Radio UWB over ∅ 50μm core GI-POF

- IR pulses of type Gaussian monocycle and doublets
- Fully-compliant to FCC regulations
- Linear combination of low-order Gaussian derivatives



Temporal response

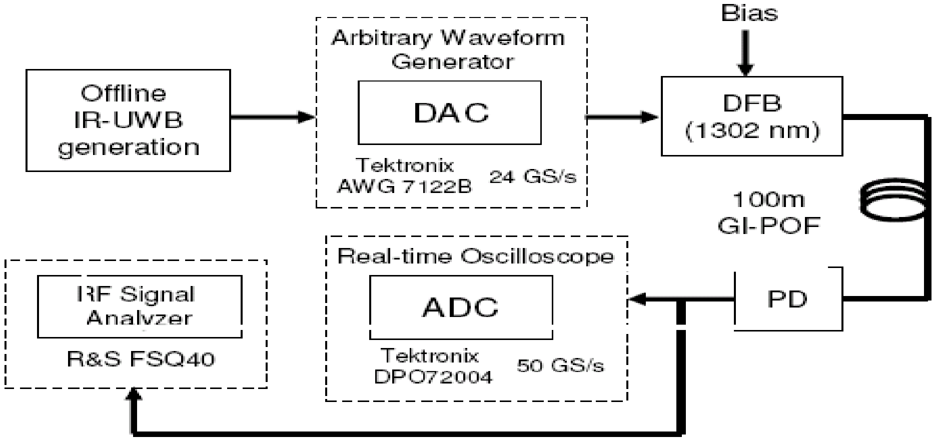
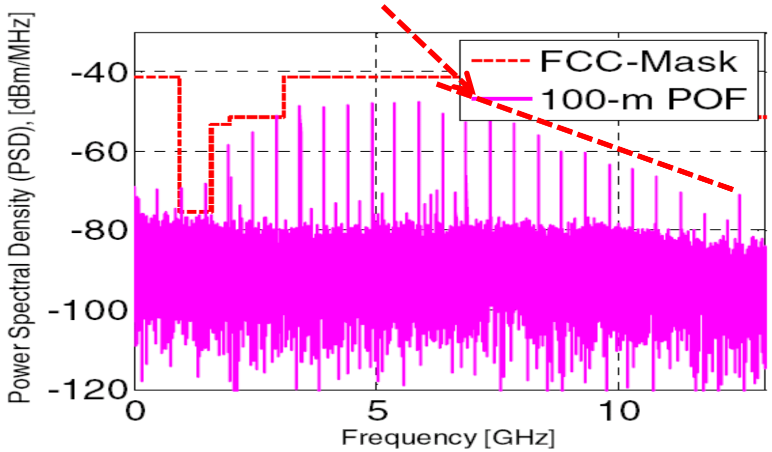


Fig. 1: Transmission experiment setup

Bandwidth limitation of POF

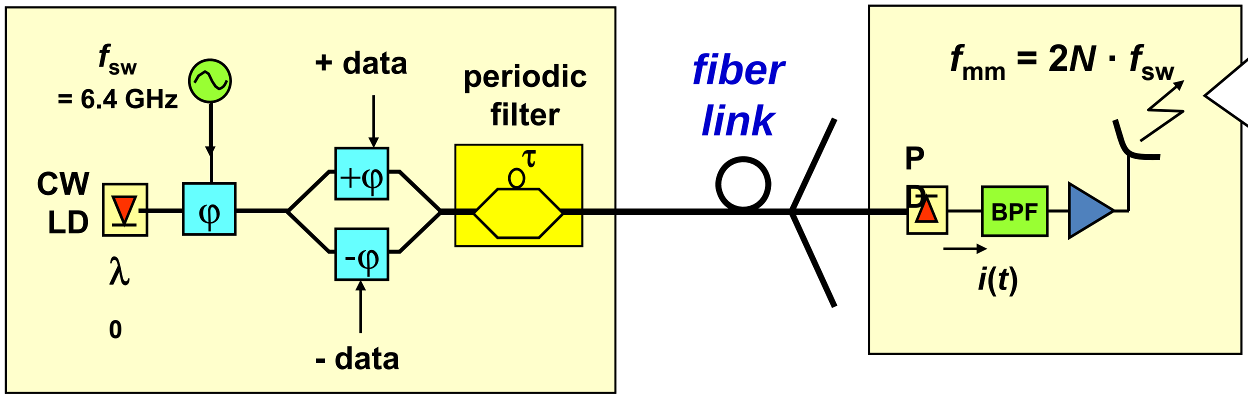


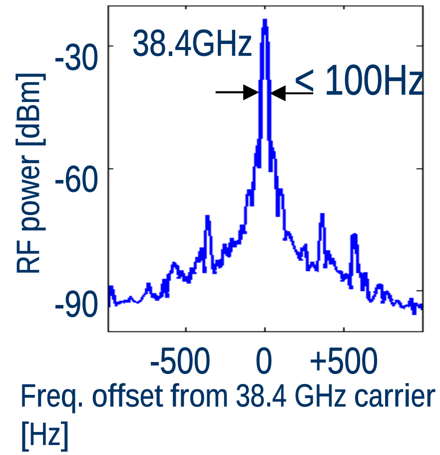
>2 Gbit/s reach extension of IR-UWB over short-link 100m 50μm PF GI-POF

[S.T. Abraha et al., OFC 2010]

COBRA

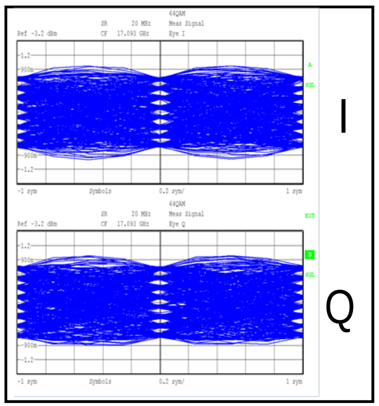
Optical Frequency Multiplying





- low-frequency CS technology (generating harmonics of the sweep freq. by FM-IM conversion in periodic filter)
- simple antenna stations (selecting the desired harmonic)
- very pure microwave → high wireless capacity achievable by comprehensive modulation formats (such as x-QAM)
- dispersion-tolerant → for SMF and MMF

120 Mbit/s
64 QAM
@ 17.2 GHz
after 4.4 km
silica MMF



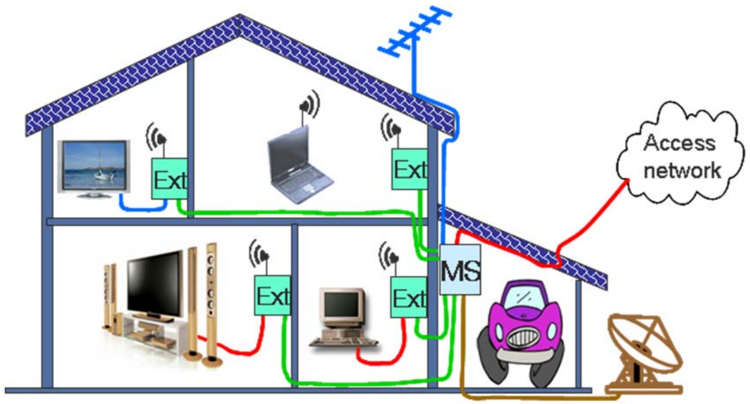
[A.M.J. Koonen, Patent NL 1019047]
[A.M.J. Koonen and M. Garcia Larrode, JLT/MTT 2008]

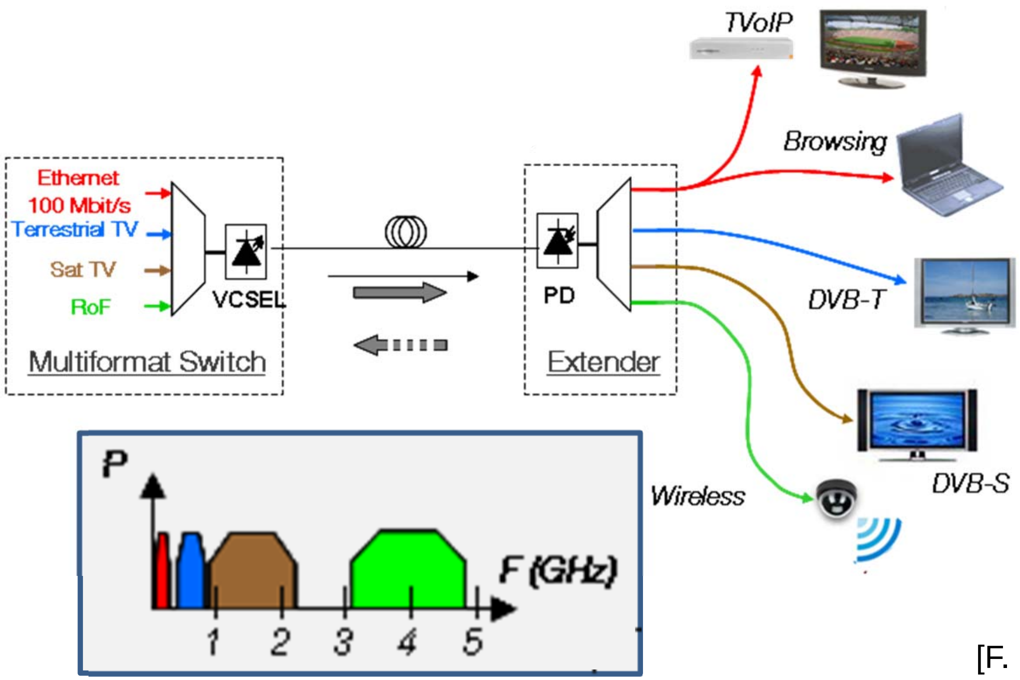
MuSe IOP COBRA

Outline

COBRA

Multiformat Home Network - static routing by electrical B&S in multi-format active star



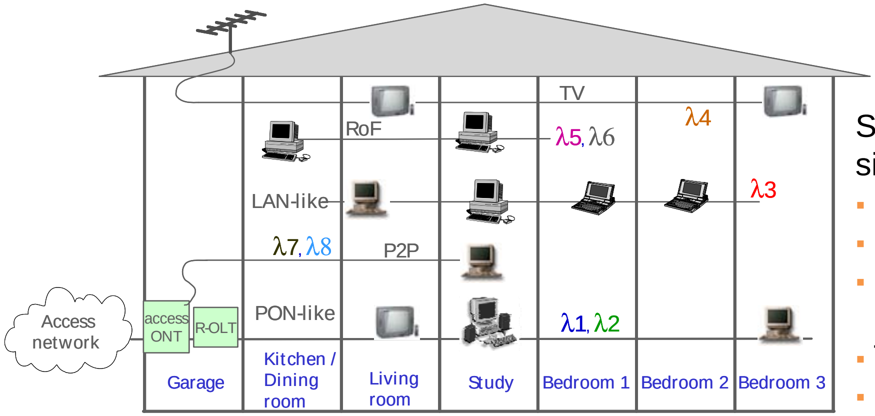


- Electrical broadcast-and-select in star network architecture
- Multipoint-to-multipoint
- Various signal types are electrically multiplexed on FDM basis
- Multi-format Switch (MS) is interconnected with remote Extenders (Ext) through fiber (SMF/MMF) backbone
- Ext selects frequency bands
- Medium-term solution for smaller buildings

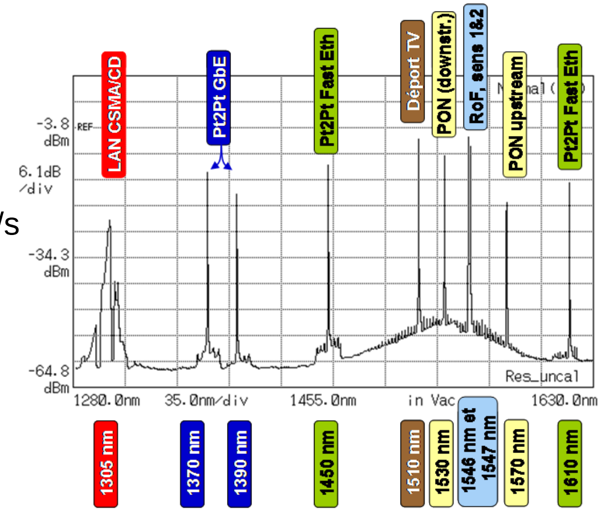
[F. Richard et al., OFC 2011]

Multiformat Home Network – routing by optical B&S in passive SMF star network

- Applications with 16x16 splitter

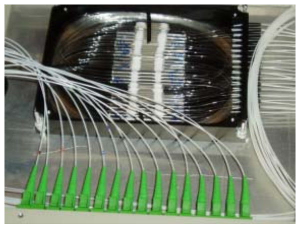


Several applications running simultaneously:
- PON TDMA 2.5 / 1.25 Gbit/s
- LAN CSMA/CD 100 Mbit/s
- P2P 1 Gbit/s Eth, P2P 100Mbit/s Eth
- Terrestrial TV
- RoF (UWB)



- Each application validated in CWDM environment
- All active and passive components available with SMF technology

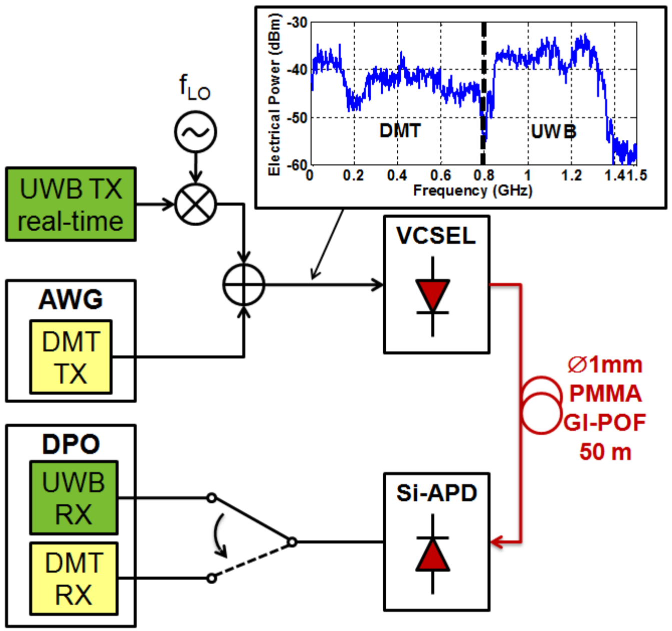
Demonstration for ALPHA european project

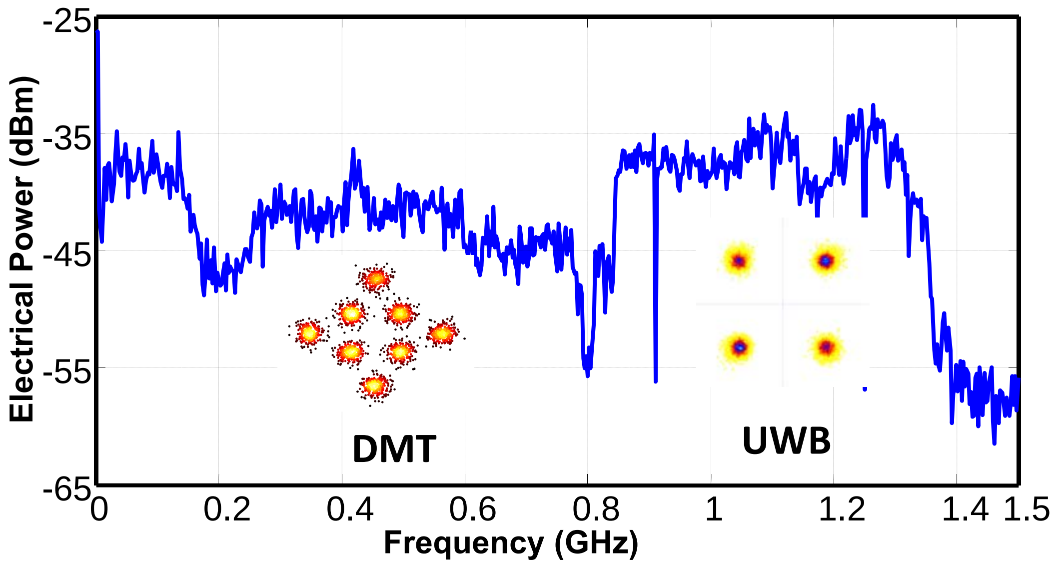


16x16 optical splitter

Cascaded Add & Drop filters

Wirebound + wireless services over POF



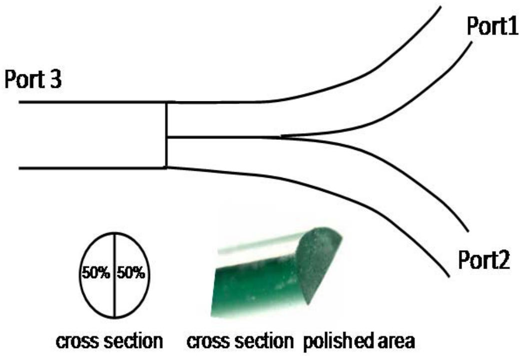


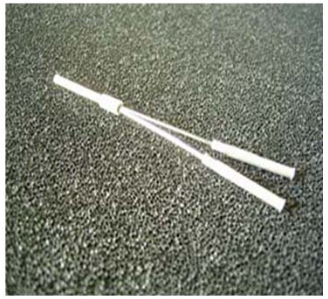
- Wired signals DMT and wireless UWB
- Bandwidth split to DMT (0–0.8 GHz) and UWB (0.85–1.4 GHz)
- UWB bitrate 480 Mbit/s (max) and DMT rate adaptive
- Transmitter VCSEL -1 dBm λ=667nm
- Detector Si-APD with ∅230-μm active area
- 50-m ∅1-mm core graded-index POF

Converged transport of high capacity wirebound and wireless signals

[E. Tangdiongga et al., OFC 2011]

P2MP topologies with POF splitters

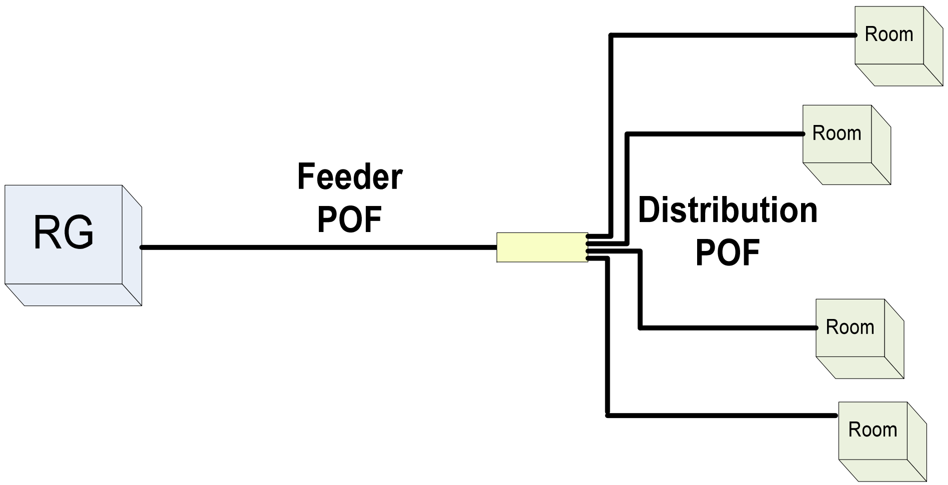




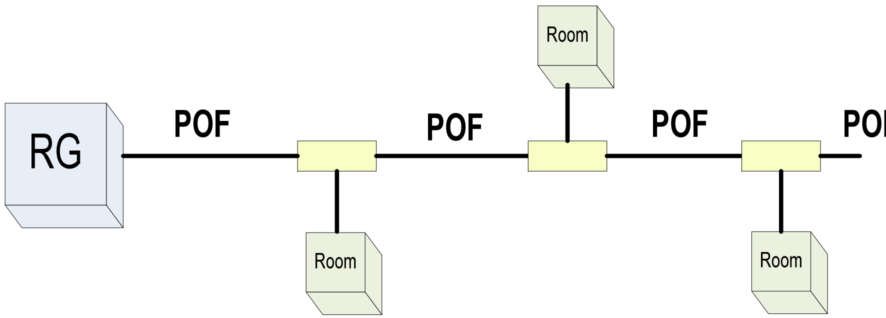
Main characteristics

Splitting ratio	Excess loss	Isolation between two ports (without fiber)
~50:50	2.5~3.1	>30 dB

1×2 GI-POF splitter
[Samples provided by DieMount GmbH]



Tree topology

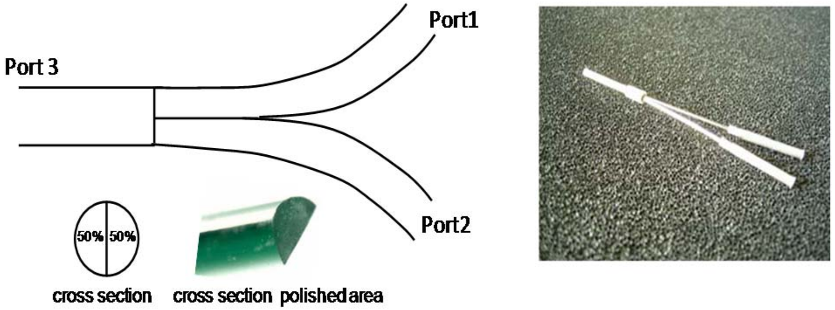


Bus topology

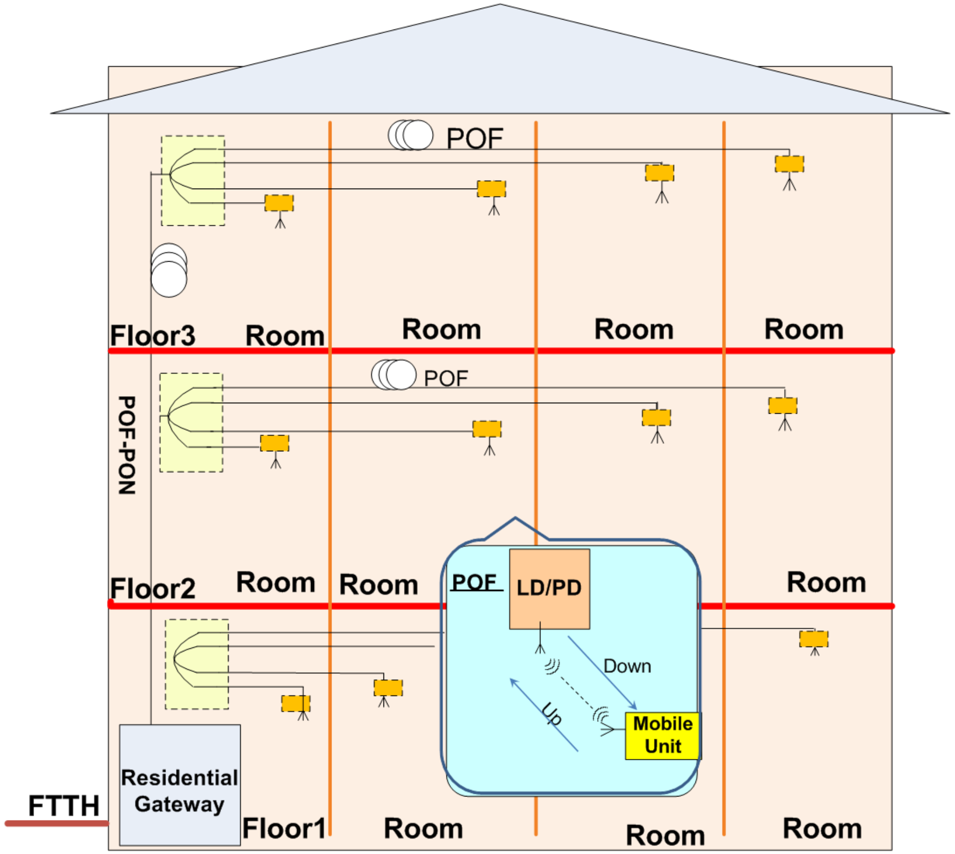
[Y. Shi et al., OFC 2012, OTh3G5]

COBRA

POF-PON based Home Networks



1×2 GI-POF splitter

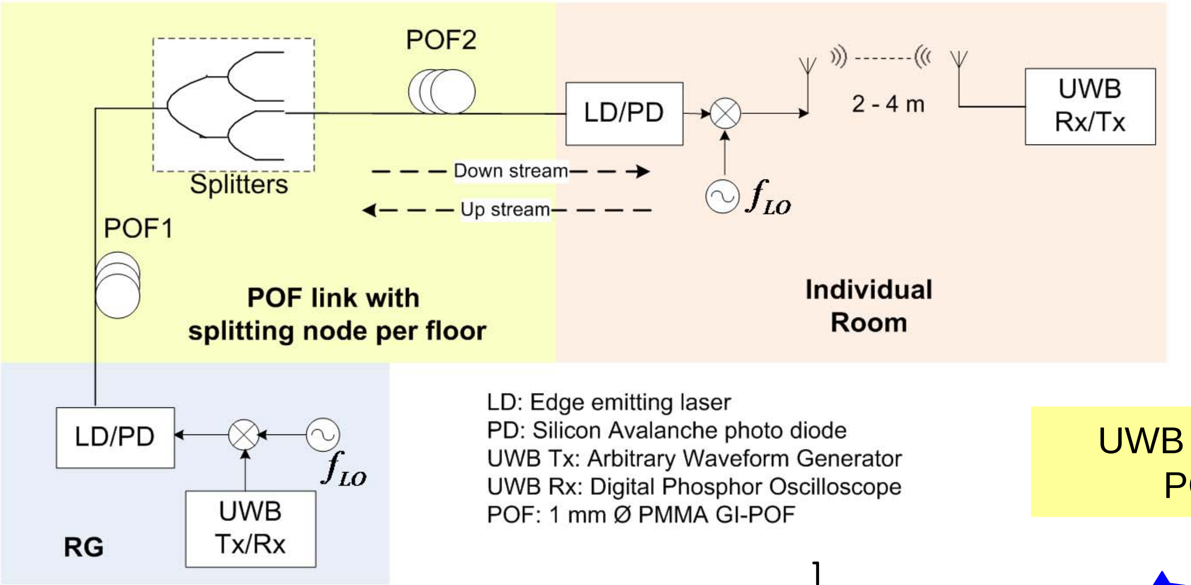


Features:

- Employing passive POF splitters
- All-optical point-to-multipoint architecture
- Both bus and tree topologies valid
- Supporting converged services
- Bi-directional transmission

[Y. Shi et al., OFC/NFOEC 2013, NTu3J.4]

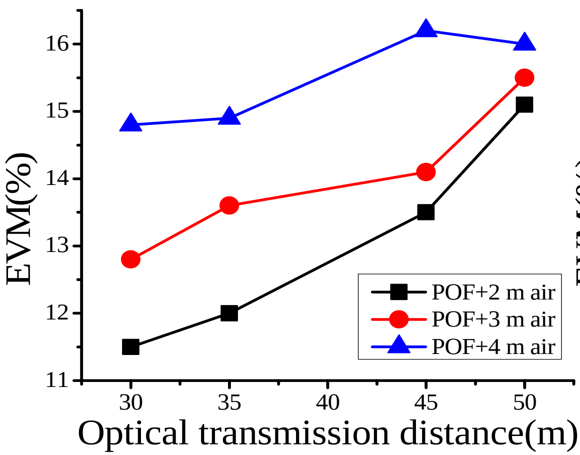
Bi-directional UWB over POF-PON



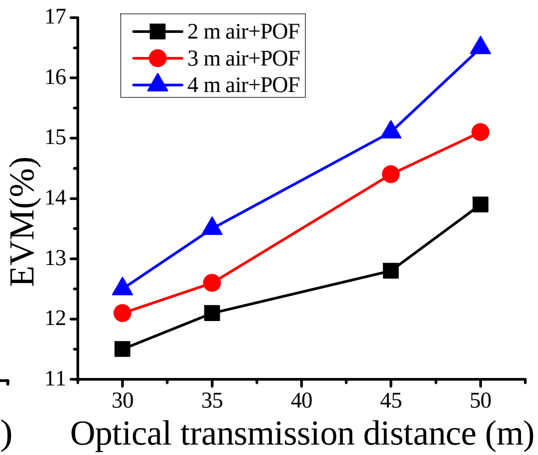
LD: Edge emitting laser
PD: Silicon Avalanche photo diode
UWB Tx: Arbitrary Waveform Generator
UWB Rx: Digital Phosphor Oscilloscope
POF: 1 mm Ø PMMA GI-POF

UWB transmission performance over POF-PON +wireless channel

POF1 (m)	POF2 (m)	Optical total(m)	Wireless (m)
25	5	30	2, 3, 4
25	10	35	2, 3, 4
35	10	45	2, 3, 4
35	15	50	2, 3, 4



(a)downstream

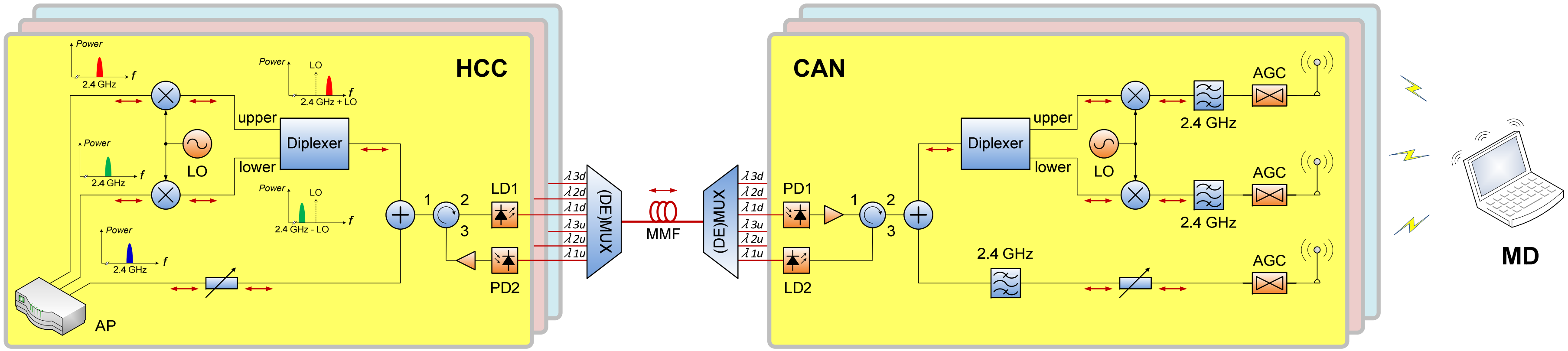


(b) upstream

[Y. Shi et al., OFC/NFOEC 2013, NTu3J.4]

COBRA

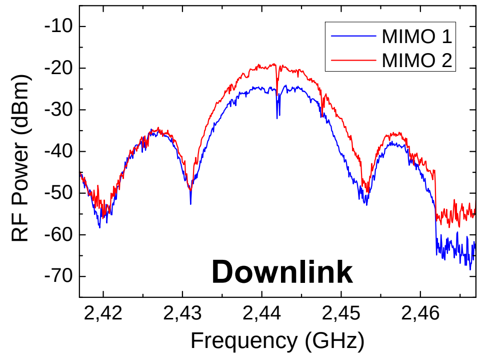
3x3 MIMO over fiber using SCM

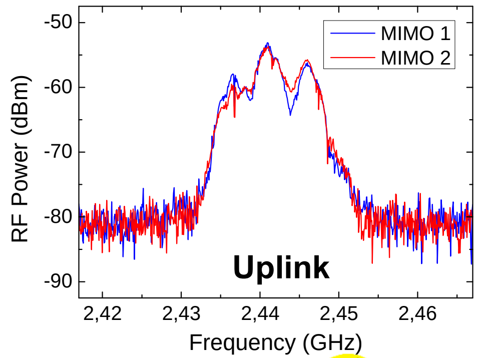


Experimental setup:

- Bidirectional transmission with 2x2 MIMO channels, WLAN IEEE 802.11n
- MIMO channels frequency-shifted and multi-/demultiplexed
- DS DFB λ=1.31μm, US VCSEL λ=850nm, over 100m GI-MMF

RF spectra of 802.11n MIMO signals at the receiving point





[S. Zou et al., OFC/NFOEC 2013, JTh2A.08]

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Outline

- Convergence in home networks, home service scenarios
- Home wired network architectures, CapEx and OpEx
- Residential Gateway
- Optical fiber types
- High-capacity data transmission for wirebound delivery
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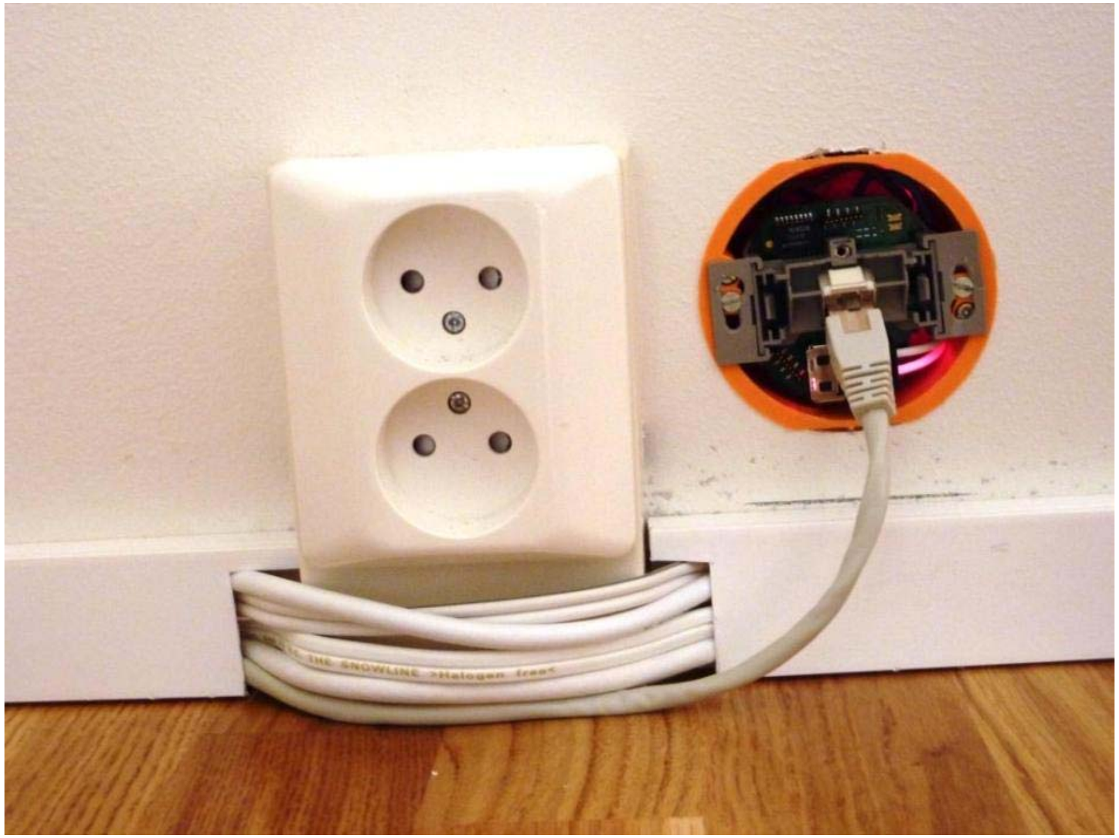
COBRA

How real are POF networks?



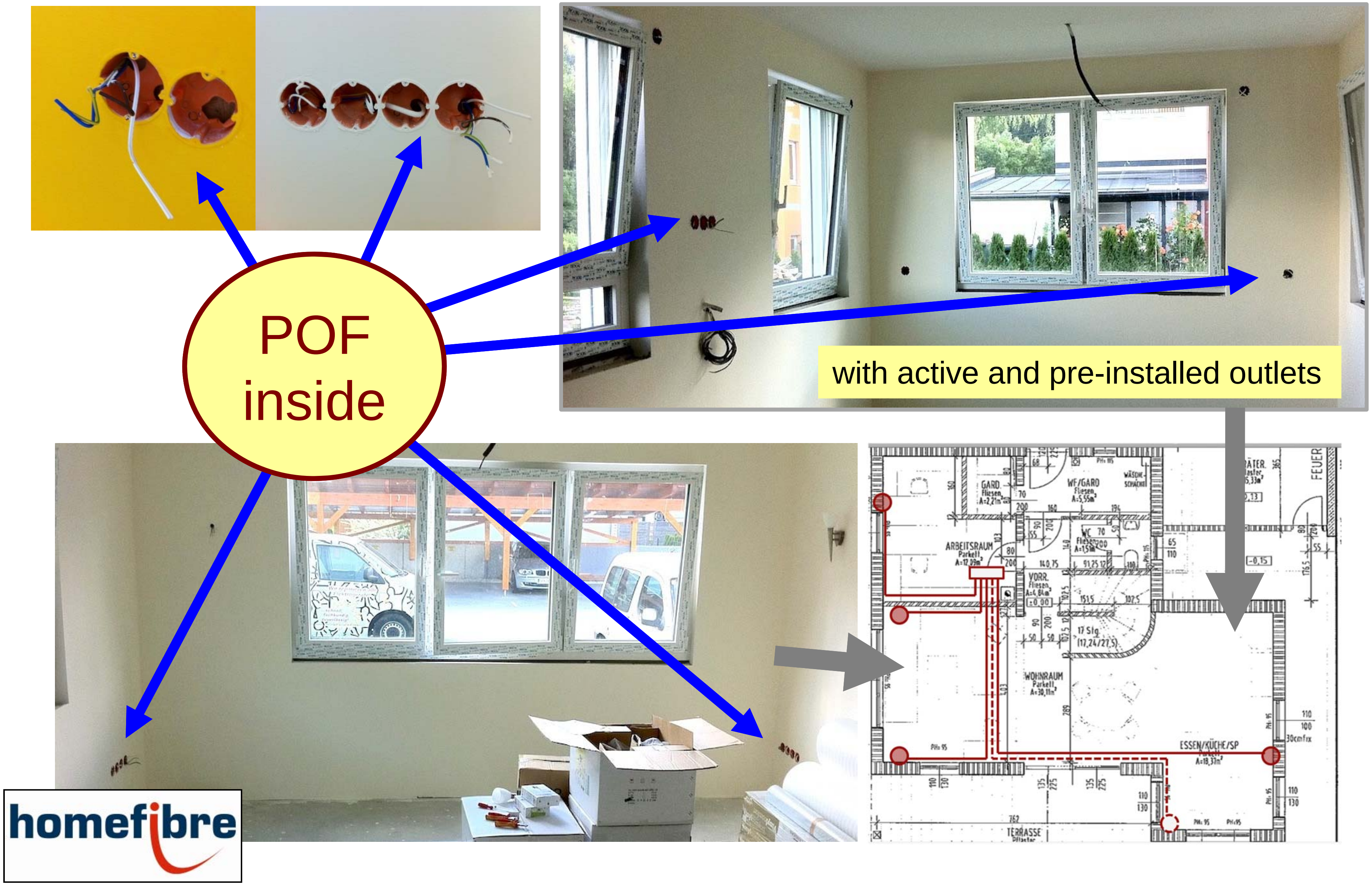
First DIY Swedish POF installation in a house, summer 2010

Source: ALPHA Del. 0.5

[A.M.J. Koonen & M. Popov – ECOC 2012]

COBRA

One Network for All - IP



Presently discussed standardization options for 1 Gbit/s POF links

Proposal available:
THP + PAM16 + MLCC

Product announced:
DMT

prefers reuse of G.hn technology: *DMT*

IC prototype:
NRZ + equalizer

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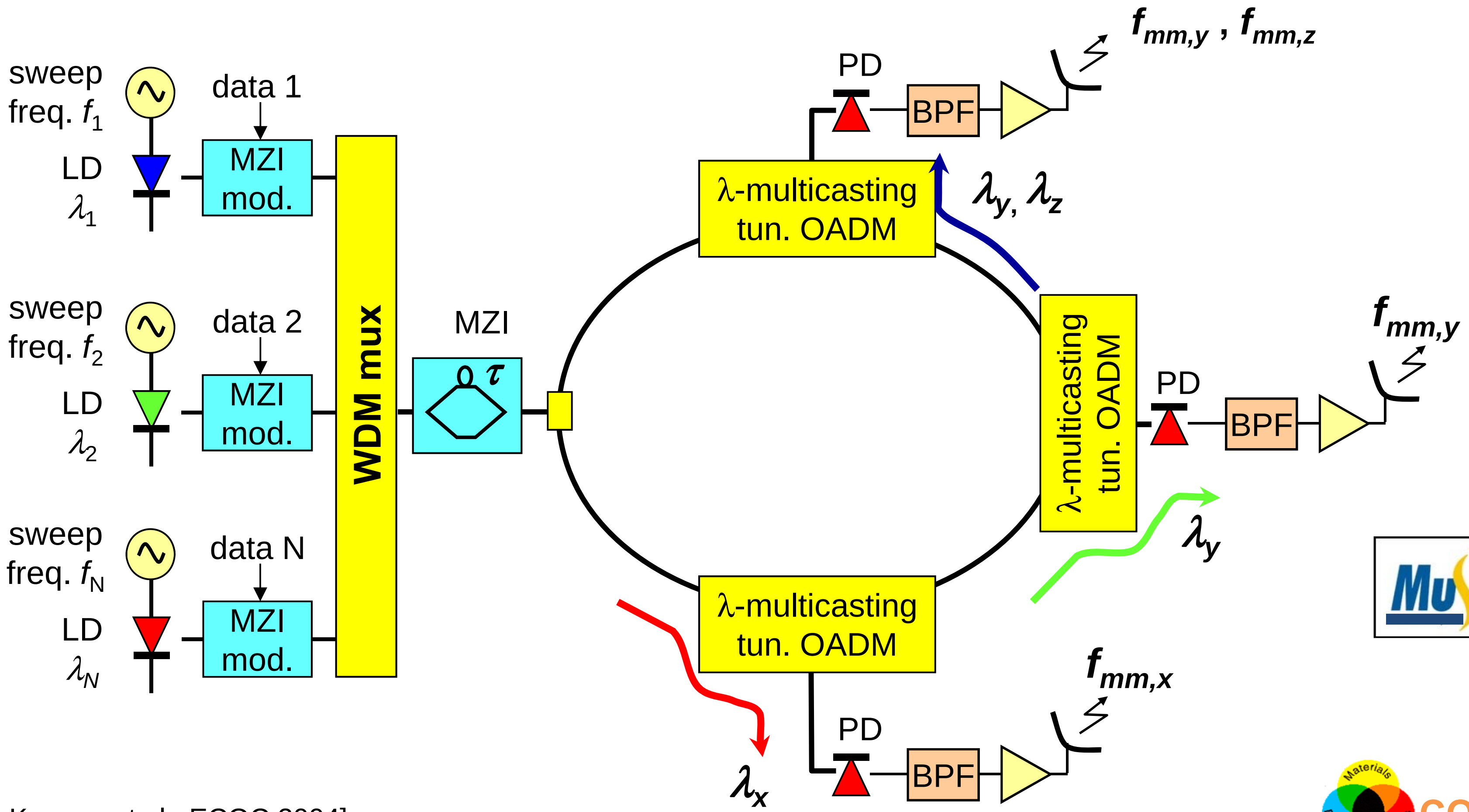
Dynamic capacity allocation

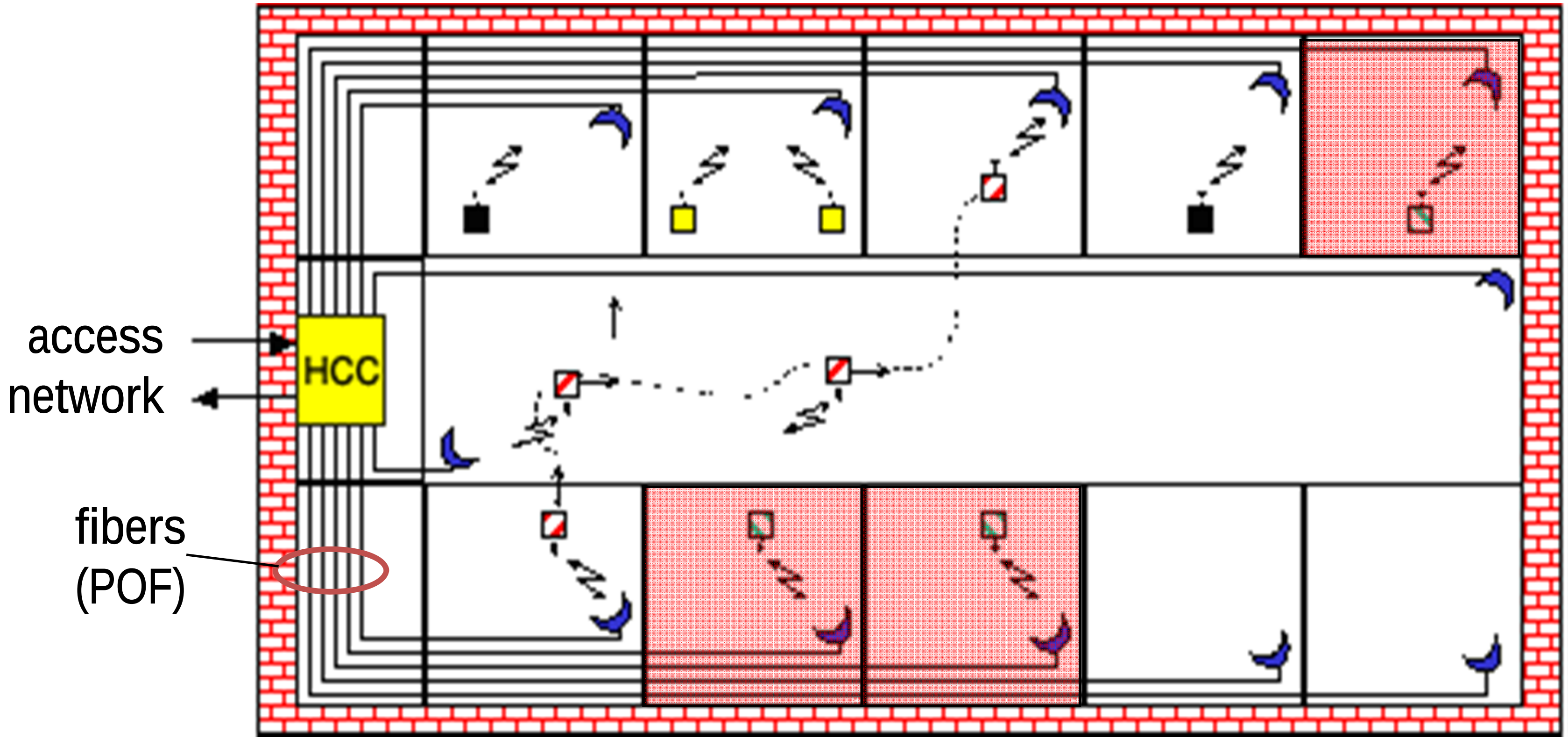
- By flexible wavelength routing
- Multi-standard operation
- RAP is λ-agnostic, may handle multiple RF signals
- Link switching requires dispersion-robustness, e.g. by using OFM



[T. Koonen et al., ECOC 2004]

COBRA

Inter-room μ-wave wireless communication



HCC: Home Communication Controller

- transparent for any wireless signal format
- any-to-any room communication
- multi-casting

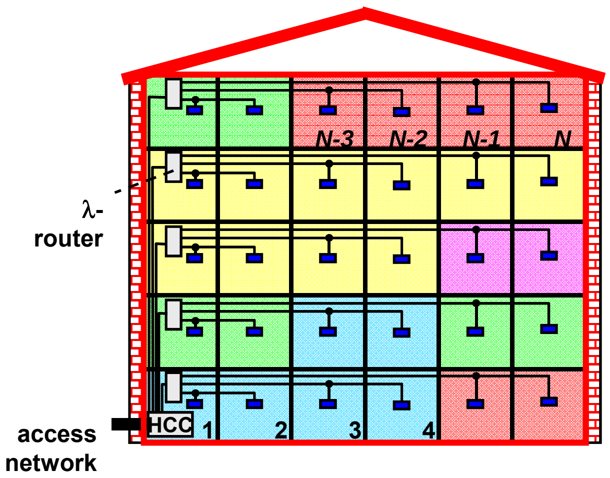
[T. Koonen et al., ECOC 2004]

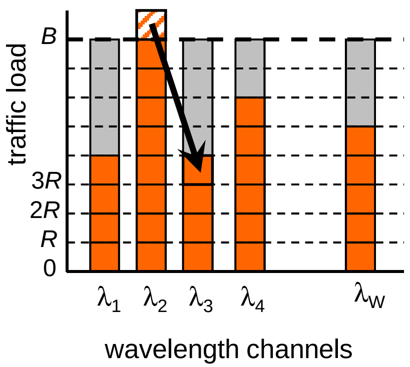
IOP

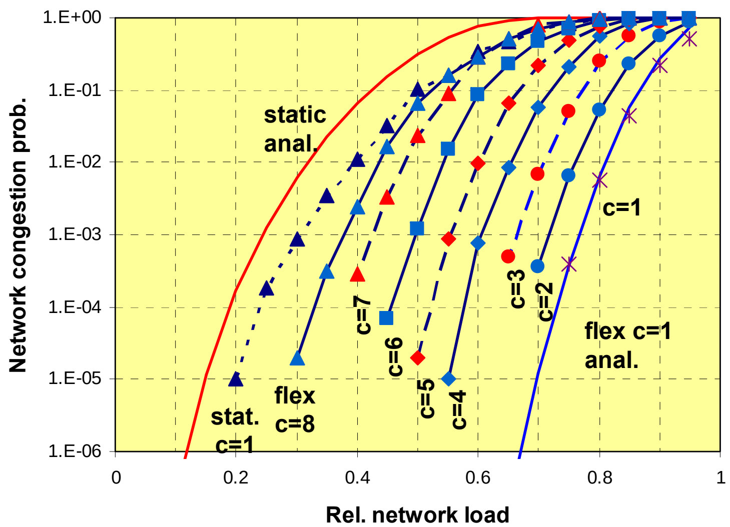
COBRA

P2MP dynamic traffic allocation - by tunable wavelength routing

- Network reconfiguration using wavelength routing for dynamically allocating wavelength channels to clusters of rooms
- λ-routing: e.g. by tunable microring resonators, AWG + SOA gates, tunable FBG-s
- Analysis for WDM-TDM case (160 living units MDU building, 10 λ-s, 1GbE per λ, active LU requesting 100MbE):







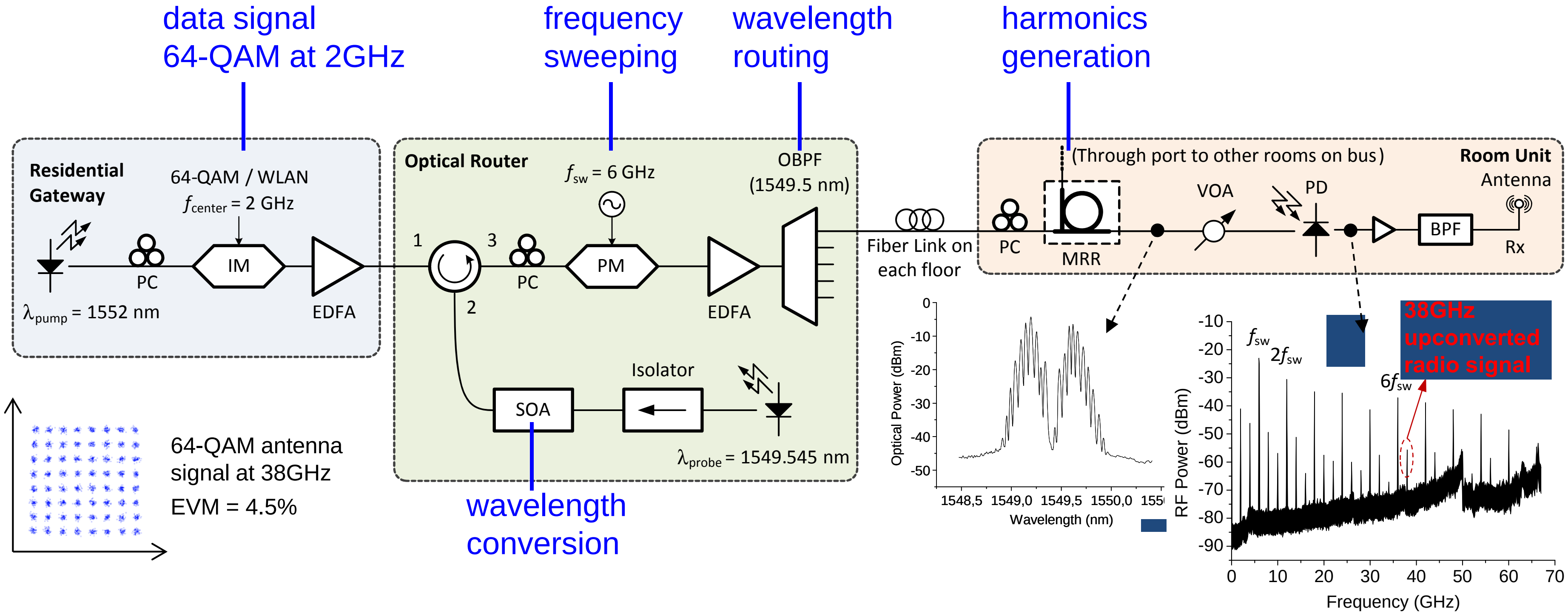
⇨ Dynamic wavelength routing with larger cluster size can improve network performance while restricting system complexity.

[A.M.J. Koonen et al., OFC 2011]

COBRA

Generation + routing of mm-wave radio-over-fiber signals

- signal transfer to 38GHz carrier by applying the **Optical Frequency Multiplying** technique (freq. sweeping source light, FM-to-IM conversion, select higher-order harmonic)
- FM-to-IM conversion by thermally-tunable microring resonator (MRR)
- wavelength conversion by cross-gain modulation in SOA
- shown for 150Mbit/s 64-QAM and 54 Mbit/s 802.11a 64-QAM WLAN



Dynamic routing of 150Mbit/s 64-QAM and 54Mbit/s 802.11a 64-QAM at 38GHz (EVM<5%)

[A.M.J. Koonen, M. Garcia Larrode, JLT Aug. 2008;
C. Okonkwo et al., ECOC 2010; S. Zou et al. , OFC2012, OTh3G6]

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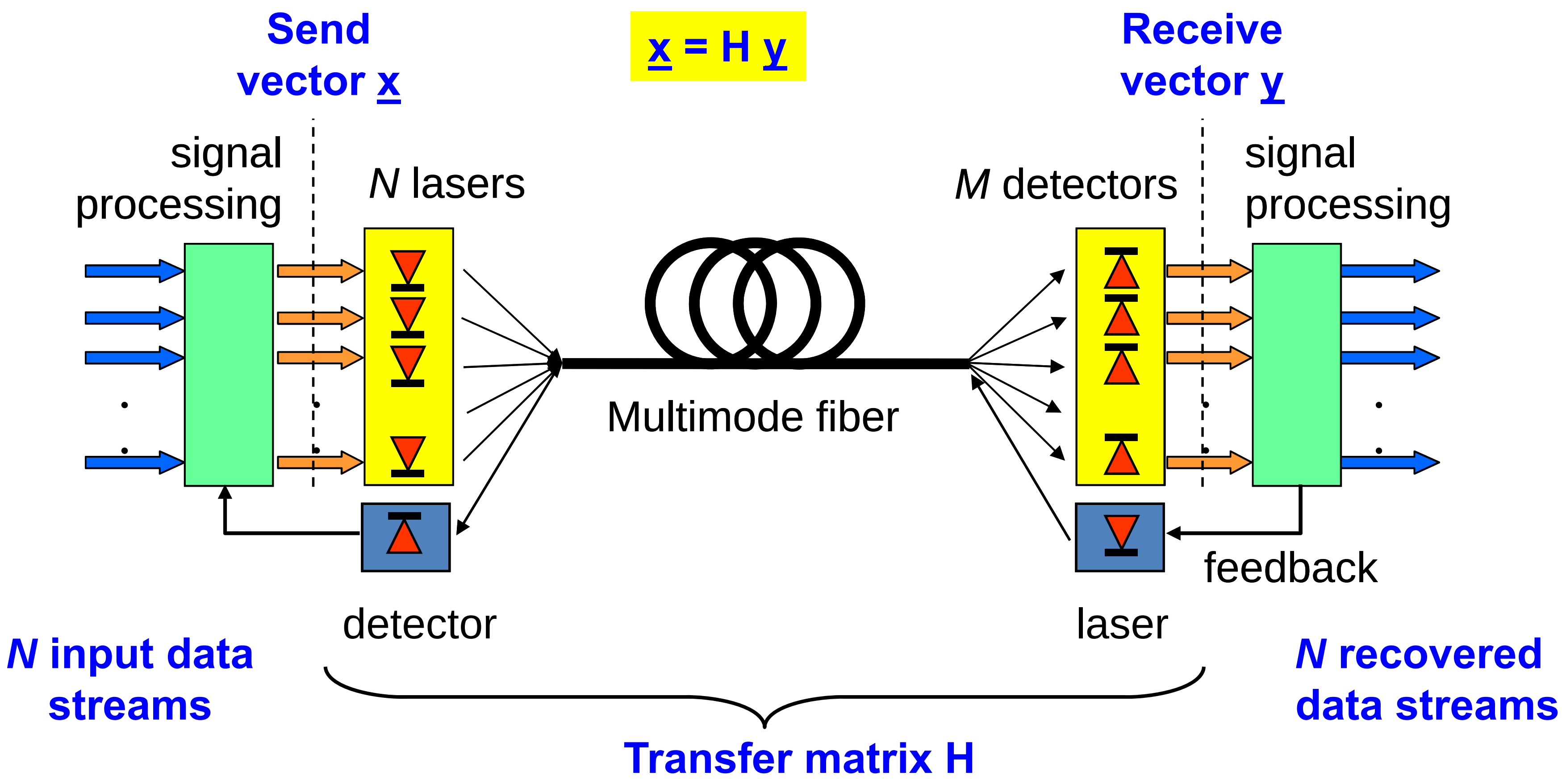
Mode Group Diversity Multiplexing



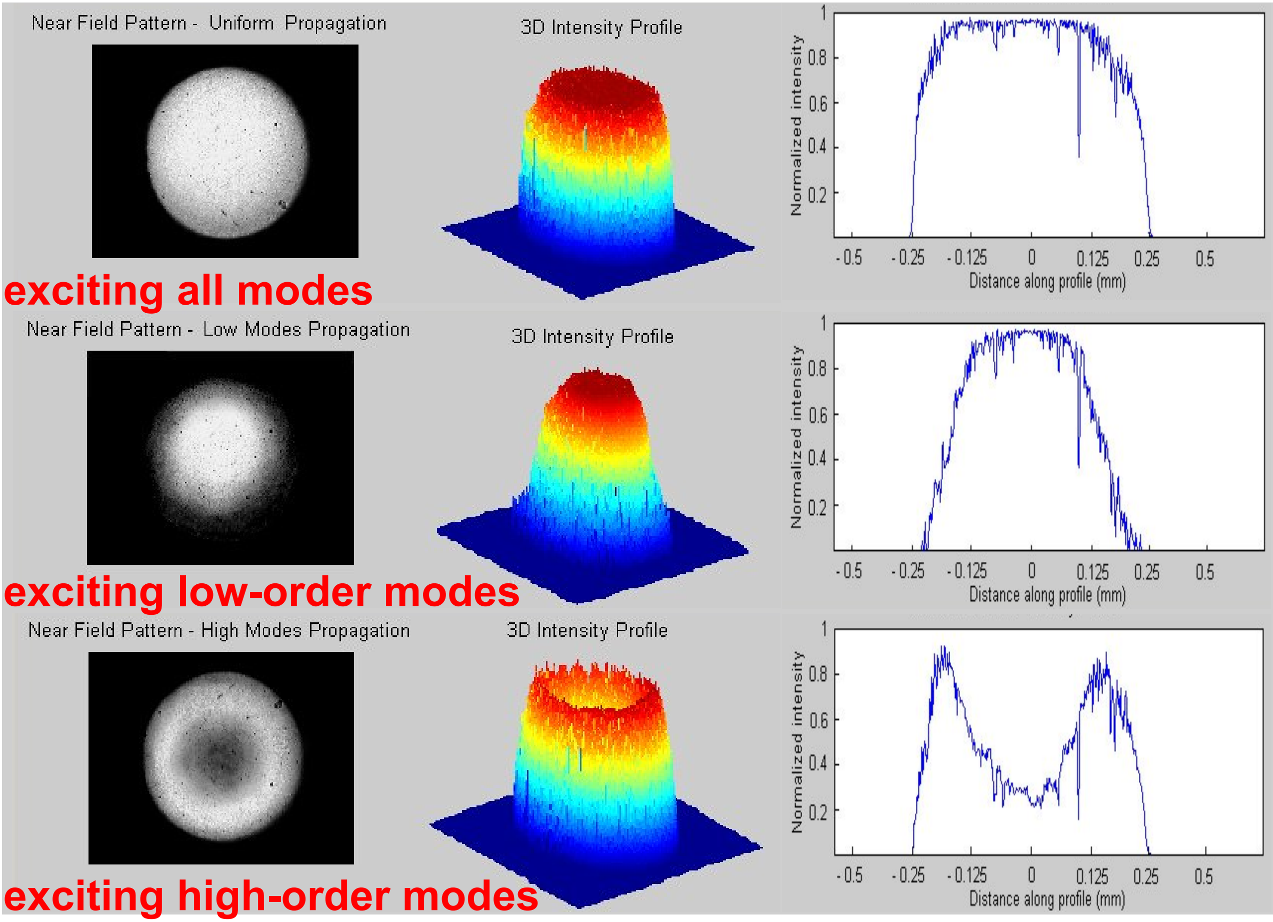
- selective mode group launching
- experiments with $N=M=2$ at 1 Mbit/s per channel
  over 1 km 62.5 µm MM fiber [Stuart, Lucent Technologies Bell Labs, OFC 2000]
- scalable to Gbit/s with high-speed processing
- transfer matrix: incl. crosstalk, mode mixing; to be inverted by signal processing

[T. Koonen et al., POF 2002, ECOC 2003, OFC 2004, ISSLS 2004, NOC 2004]

FREEBAND

COBRA

Near-Field Patterns at POF output



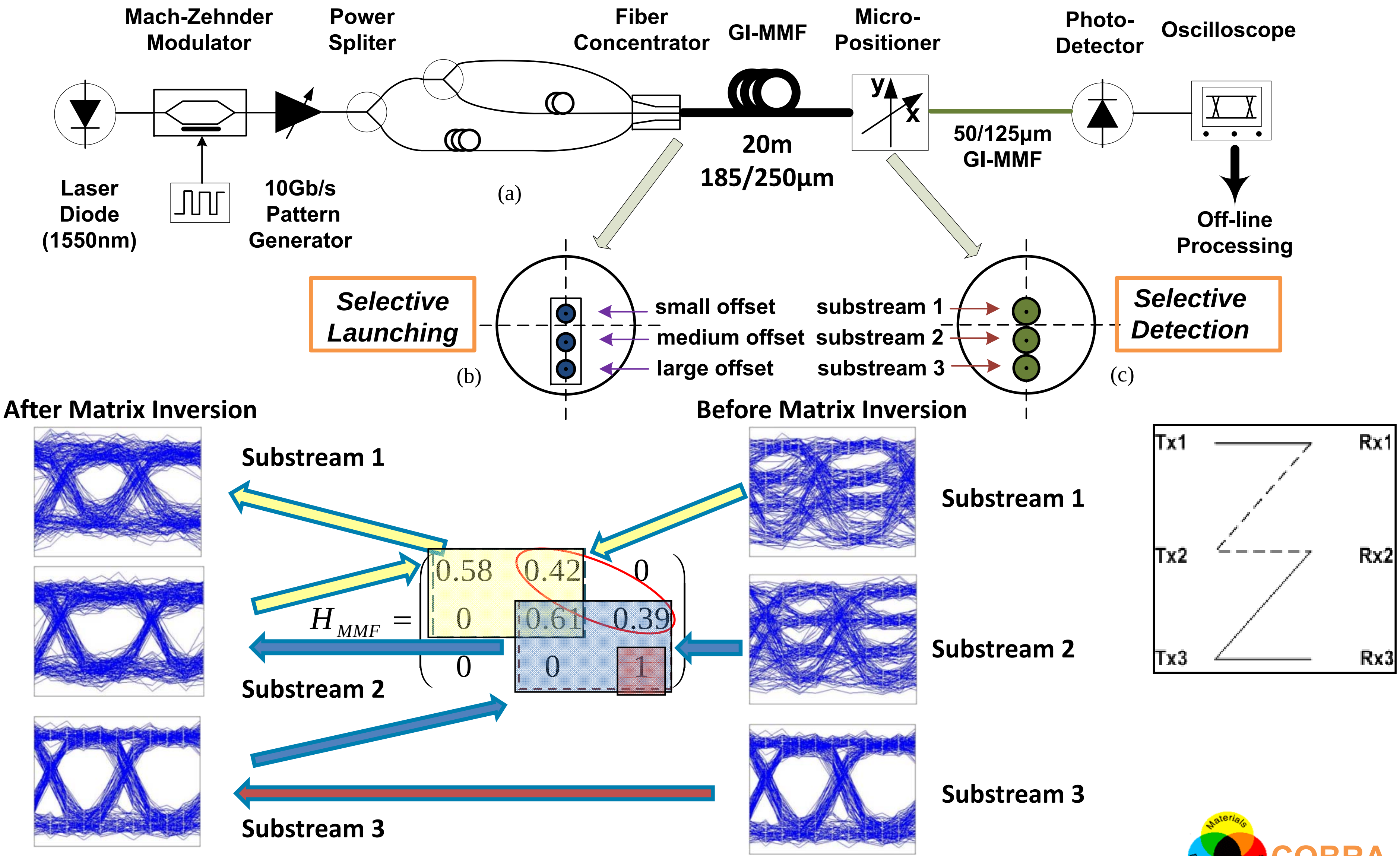
- 100 m PMMA GI-POF, ∅500 μm core
- Example: low-order modes and high-order modes form 2 complementary NFPs

➔ Complementary NFPs for MGDM feasible

FREEBAND

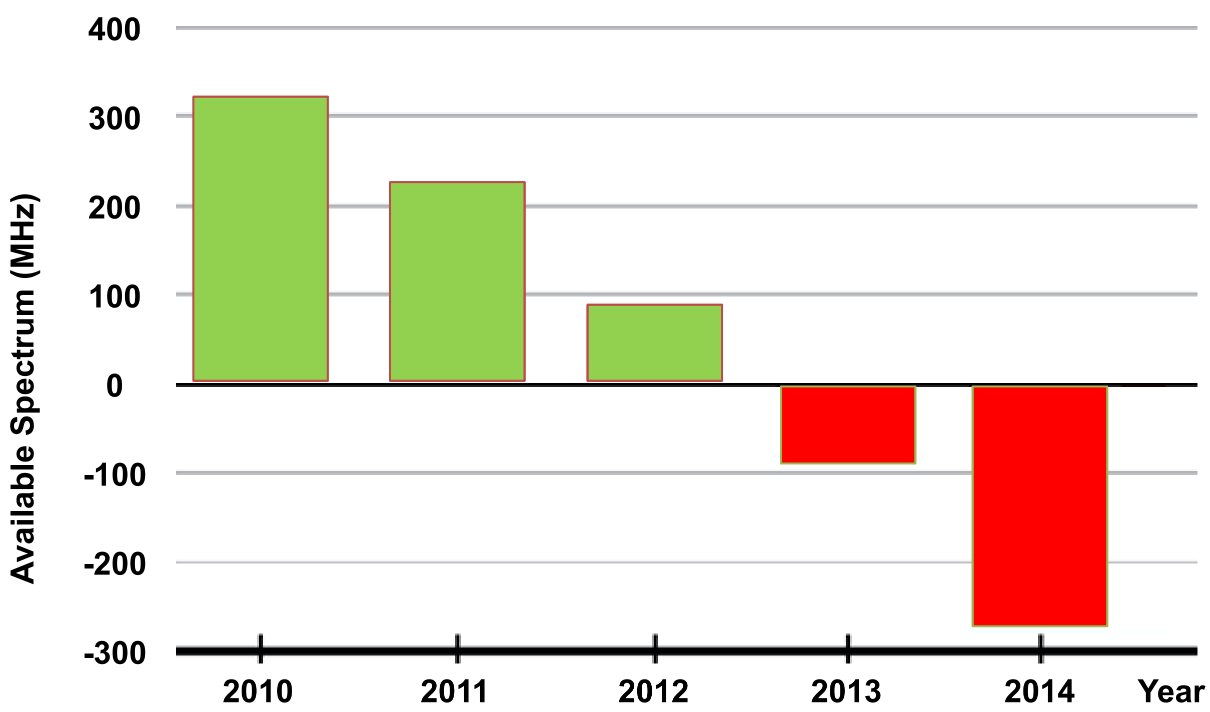
COBRA

3x10Gbit/s Optical 3 × 3 MGDM in GI-MMF



[H.-S. Chen et al., PTL Sep. 2011]

The Point of Wireless Disconnect



The FCC projects a spectrum deficit for wireless communications by 2013

Source: GIIC Point of View: Wireless Point of Disconnect, San Diego, Oct. 2011

Approaches to solutions

- Cognitive radio
- Use of microwave & lower THz-spectrum
- Use of unregulated bandwidth in the upper portion of the EM spectrum

→ **Optical wireless communication (OWC)**

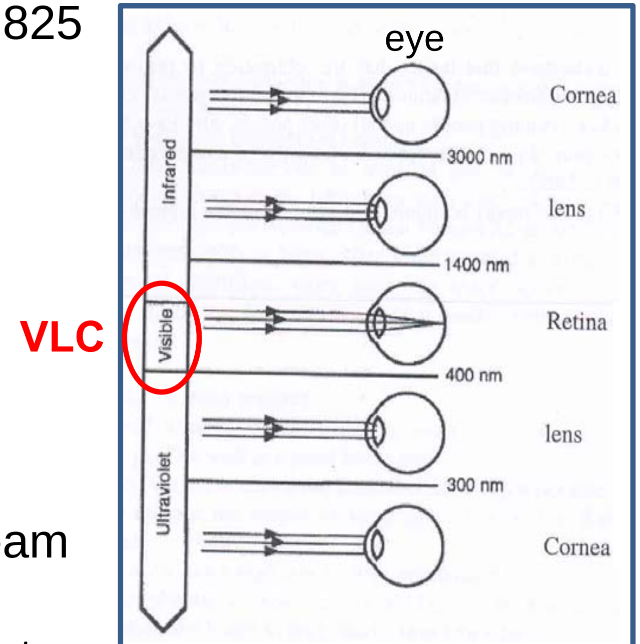
→ **Infrared, visible and ultraviolet light**

[K.-D. Langer - FHG-HHI, ECOC2012, Mo2G5]

Optical wireless communication

- **eye safety**: regulated by ANSI Z-136 series and IEC 825 series

IEC draft for FSO	Max. power @ λ = 880 nm	Max. power @ λ = 1550 nm
Class 1	< 0.5 mW	< 10 mW
Class 1M	< 2.5 mW	< 150 mW
Class 3R	< 500 mW	< 500 mW

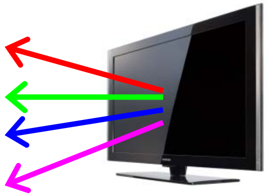
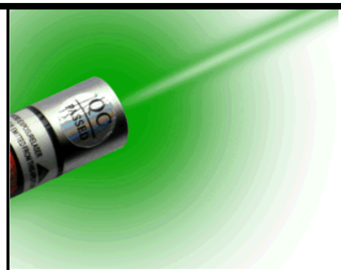
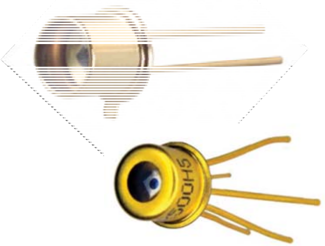


Light penetration in the eye

- **propagation losses**:
  - *scintillation*: air refractive index changes due to temperature differences between ground and air; (de)focussing of beam by events comparable to beam size
  - *aerosol scattering*, by rain, snow, but most important by fog and haze related to particle size relative to wavelength
  - *Mie scattering* if relation is about unity
    in IR region mostly by water vapour and CO_2,
    below 200 nm losses too high by O_2 and O_3,
    above 22 µm by water vapour
    may be up to 10-100 dB/km

[D. Kedar and S. Arnon, IEEE Comm. Mag. May 2004]
[Z. Ahmed, ISSLS 2004]

OWC classification by Optical Frontend

	VLC			IR
Transmitter / Receiver				
	Very low speed, dominated by the transmitter	Low speed, dominated by the receiver		
		Medium speed	High speed	Very high speed *

* IrDA aims for 5 and 10 Giga-IR

[K.-D. Langer - FHG-HHI, ECOC2012, Mo2G5]

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Visible Light Communications (VLC)

- Omnipresence of LEDs: signaling and illumination
- LEDs offer significant potential for modulation
- Combination of illumination (or signaling) with data transmission → data transfer as “piggyback”
- Attractive for offices, industrial settings, medical areas, public transport, …
- Other benefits:
  no EMI with RF, unregulated spectrum,
  worldwide available, enhanced privacy, …

[K.-D. Langer - FHG-HHI, ECOC2012, Mo2G5]

High-speed Indoor VLC: State of the Art

- Fully-fledged OFDM system providing 100 Mbit/s (net)
- FPGA implementation: Mod./ demod., FEC, Sync., specifically developed MAC
- 16 LED lamps covering an area ~10 m^2
  demonstrated at ORANGE Labs, Feb. 2011

http://www.youtube.com/watch?v=AqdARFZd_78

Recent lab record using single color LED: 800 Mb/s

Fraunhofer Heinrich Hertz Institute

[C. Kottke et al., ICTON 2012]

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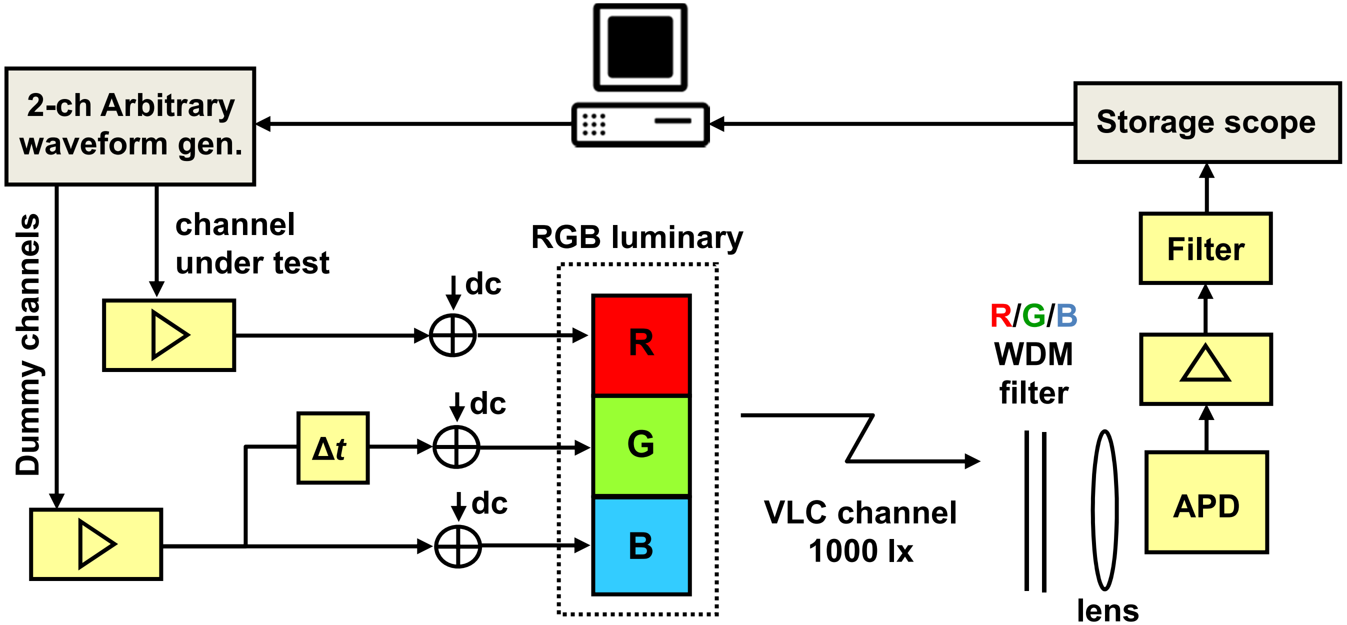
WDM Feasibility Experiment



- Tx: RGB white LED module (3 WDM channels)
- Rx: WDM pass-band filters + photodiode
- Bit and power loading applied → throughput maximization
- Successive off-line processing of R, G, and B channels

Aggregate bit rate 1.25 Gb/s

[C. Kottke et al., ECOC2012, We3B4]

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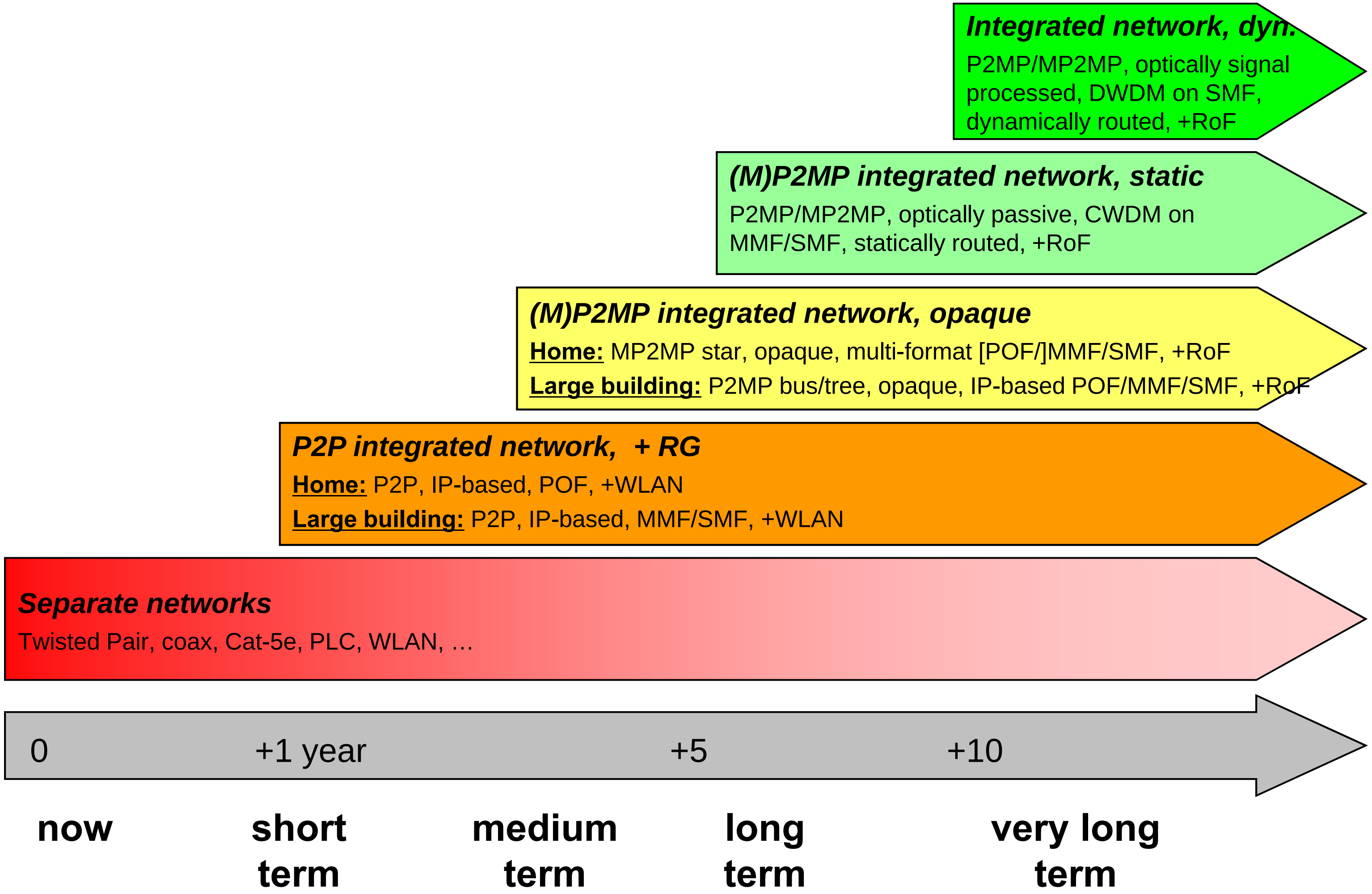
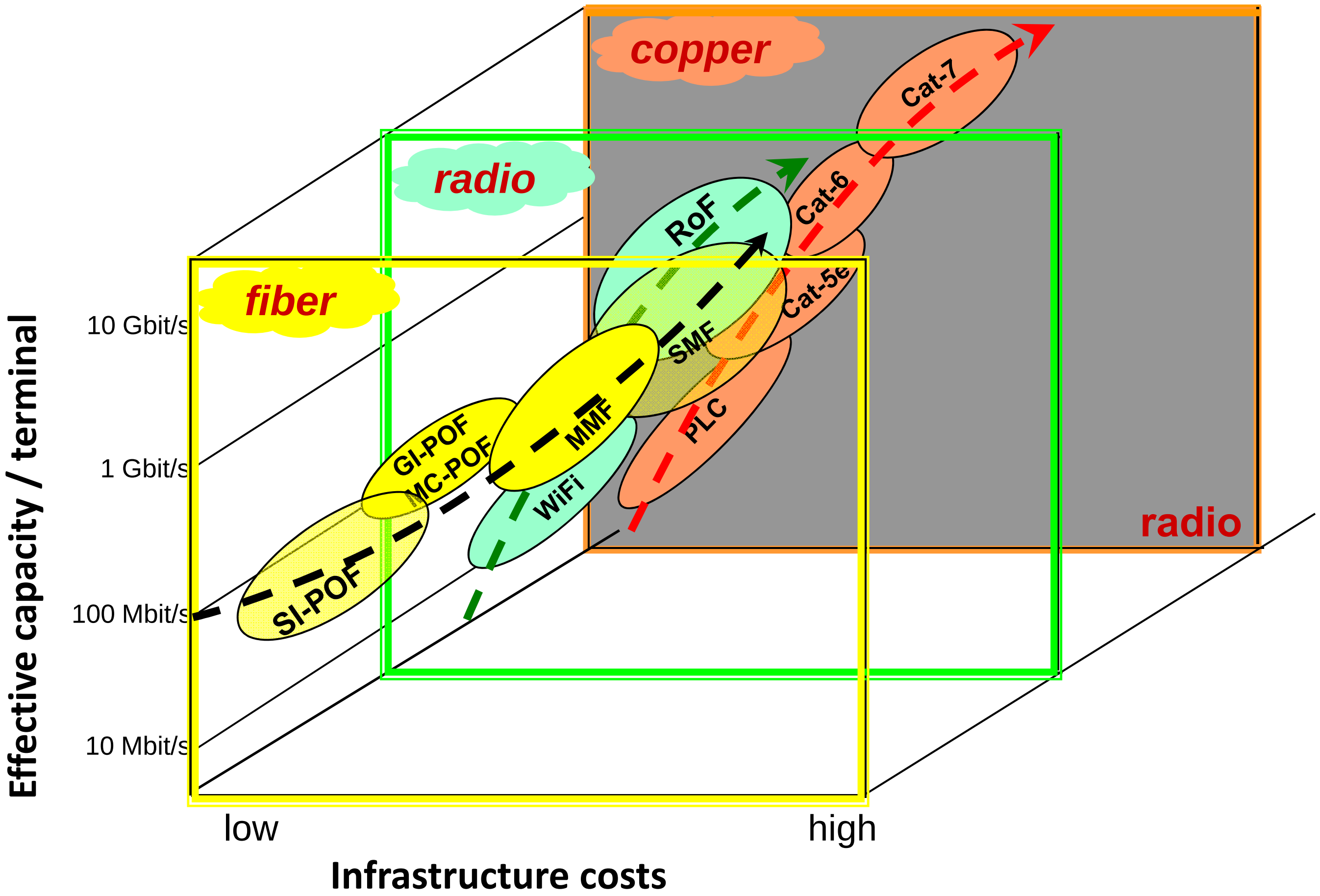
Roadmap of wired in-building networks



→ fiber-based solutions will pave the evolution path of in-building networks

[A.M.J. Koonen & M. Popov – ECOC 2012, Mo1G1]

Choosing the wired network medium



When increasing capacity per terminal, network infrastructure costs grow

- super-linearly for copper and radio solutions
- sub-linearly for fiber solutions

[A.M.J. Koonen & M. Popov – ECOC 2012, Mo1G1]

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Concluding remarks

- A single in-home fiber network can provide the universal backbone for delivery of wired and wireless services.
- Powerful dispersion-robust modulation techniques can overcome bandwidth restrictions of multimode silica fiber / POF.
- Large-core POF is already today cost-competitive with Cat-5E and other cabling solutions, but is in an early stage of standardization.
- Flexible routing improves network performance and use of network resources.
- Roadmap: the growing needs for capacity, QoS diversity and flexibility require fiber solutions, evolving from P2P, to P2MP opaque, to P2MP all-optical from static to dynamic.
- Network costs of fiber solutions increase less than linearly with capacity provided; those of copper and radio solutions more than linearly.
- **In-building fiber solutions are more future-proof, more cost-efficient at higher data capacities, and more sustainable than copper and radio solutions.**

COBRA

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- Corning Inc., USA (Anthony Ng'oma, Fred Sears, …)
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- Network of Excellence BONE

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