Tutorial: Gigabit Ethernet Over Plastic Optical Fiber (GEPOF)

IEEE 802 plenary session

3 November 2014

Panel

- Bob Grow, GEPOF SG Chair, RMG Consulting
- Carlos Pardo, KDPOF
- Naoshi Serizawa, Yazaki Corporation
- Thomas Lichtenegger, Avago Technologies

Outline

- Overview of proposed p802.3bv project
- Technical / Economic Feasibility
- Home networking market
- Automotive market
- Industrial market
- Support
- Summary and questions

Objectives

History of Previous Ethernet Over POF Activities

VDE standard development

OVERVIEW OF PROPOSED P802.3BV PROJECT

Objectives

- Preserve the IEEE 802.3/Ethernet frame format utilizing the IEEE 802.3 MAC
- Preserve minimum and maximum frame size of the current IEEE 802.3 standard
- Support full duplex operation only
- Support a data rate of 1000 Mb/s at the MAC/PLS service interface
- For the automotive environment:
  - Specify operation over at least 15m of POF with 4 POF connections
  - Specify operation over at least 40m of POF with no POF connections
- For the home and industrial environment specify operation over at least 50m of POF with 1 POF connection
- Maintain a bit error ratio (BER) better than or equal to 10^{-12} at the MAC/PLS service interface
- Specify optional Energy-Efficient Ethernet for 1000 Mb/s over POF

History of Previous Ethernet Over POF Activities

- An Ethernet PHY project was initiated in VDE (Verband der Elektrotechnik Elektronik Informationstechnik)
- Issues with the VDE document were raised by IEEE-SA
  - Changes to draft requested
  - It was also noted that such work appropriately belongs in IEEE 802.3
- VDE choose to withdraw the document
- Participants want to do the work in IEEE 802.3

VDE standard development

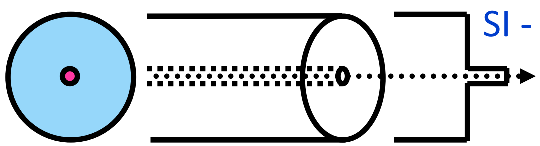
- VDE standardization was being driven by:
  - Siemens, Avago, Phoneix Contact, Firecomms, Franhoufer Institute, POF-Application Center, Innodul, Teleconnect, Diemount, KDPOF, …
- Multiple technical proposals considered:
  - Modulation: NRZ, PAM-4, OFDM, ***PAM-16***
  - Coding: Reed Solomon, MLCC, BCH, LDPC
  - Technical solutions adopted and specified in the VDE document

Introduction to POF
Introduction to light transmitter and receiver
Connections
Length objectives
How is the VDE proposal?
- Tradeoffs
- Non linearity
- Performance of the VDE standard

TECHNICAL AND ECONOMIC FEASIBILITY

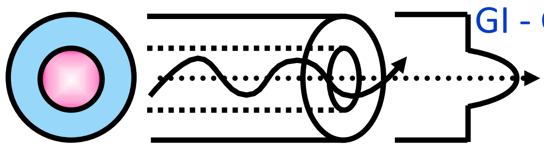
Introduction to POF

Typical optical fibers



SI - Step-Index
core: ⌀ 8 µm
clad: ⌀ 125 µm

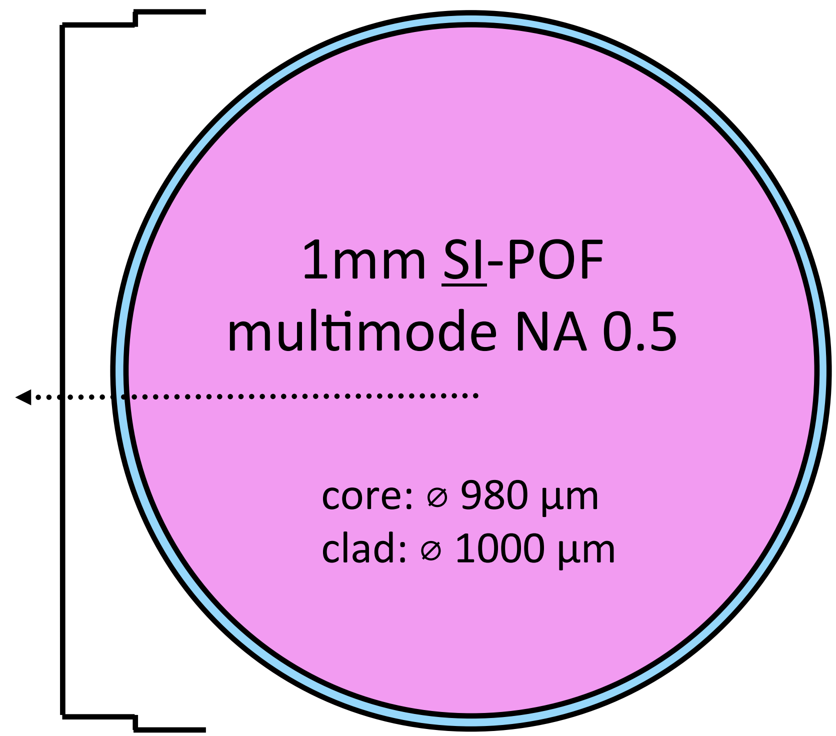
SM-GOF for long-distance transmission



GI - Graded-Index
core: ⌀ 50 or 62.5 µm
clad: ⌀ 125 µm

MM-GOF for data-centers, office-LAN

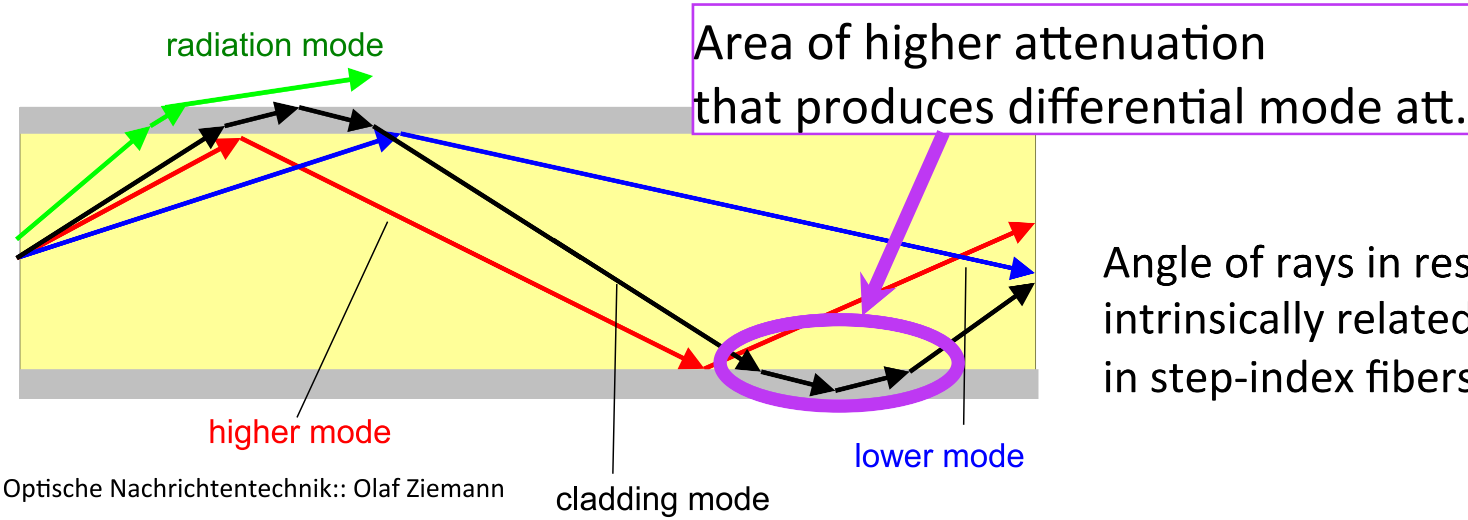
GEPOF target



Introduction to POF

- The Plastic Optical Fiber is made of 1mm PMMA
- Proposed POF is Step Index (SI-POF) according to: ***IEC 60793-2-40 .ed.3:2009: Type A4a.2***
- < 18 dB/100m if equilibrium mode distribution launch
- Optical bandwidth > 40 MHz at 100m
- Negligible temperature dependence
- Different jacketing available for various applications
- Dual fiber full duplex operation

Light transmission in SI-POF



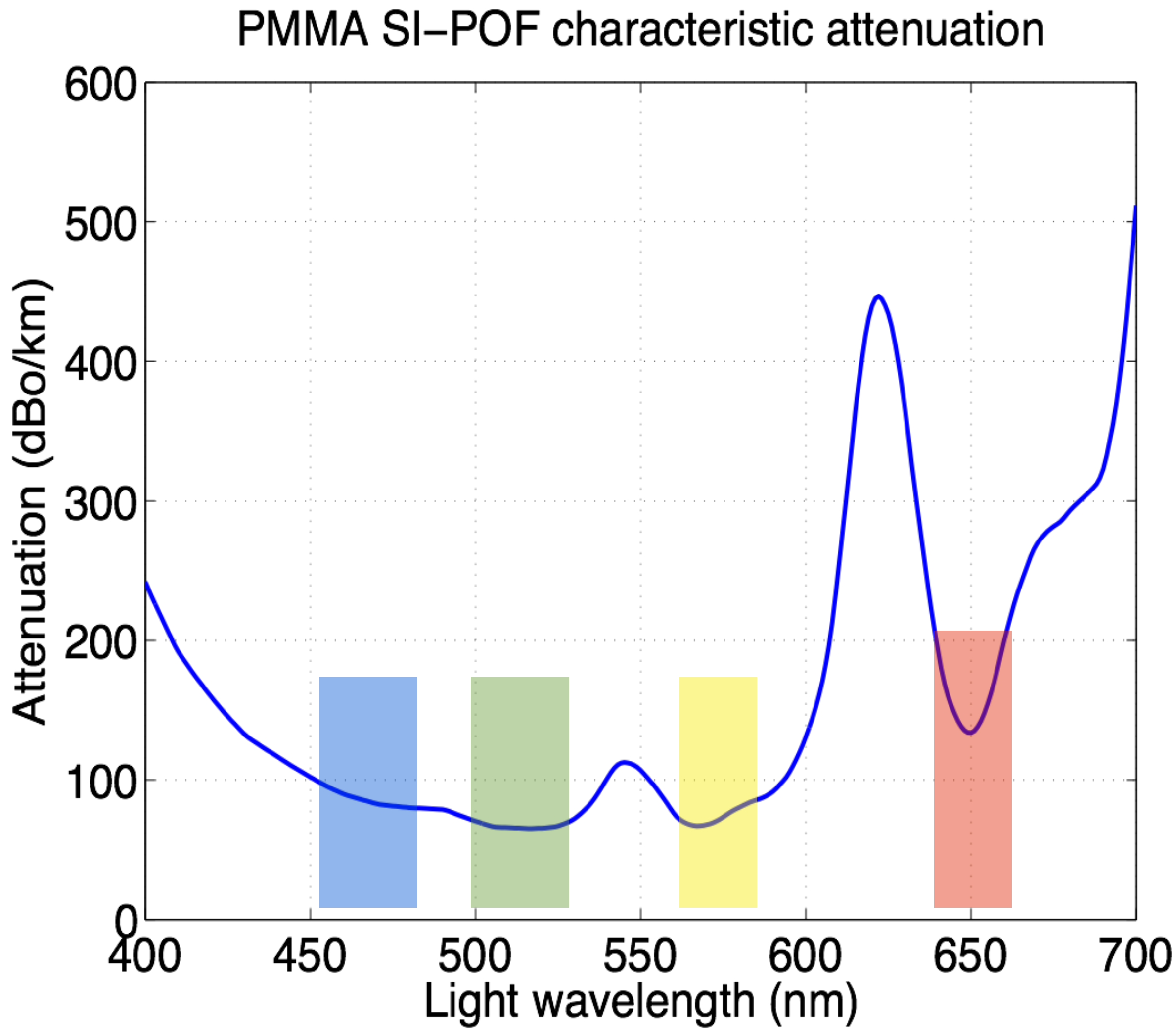
Optische Nachrichtentechnik:: Olaf Ziemann

Angle of rays in respect fiber axis is intrinsically related to TEM mode in step-index fibers

Differential mode delay — Relative mode delay — Mode mixing

$$\frac{\partial P(\theta,z,t,\lambda)}{\partial z} = -\alpha(\theta,\lambda)P(\theta,z,t,\lambda) - \tau(\theta,\lambda)\frac{\partial P(\theta,z,t,\lambda)}{\partial t} + \frac{1}{\theta}\frac{\partial}{\partial\theta}\left(\theta D(\theta,\lambda)\frac{\partial P(\theta,z,t,\lambda)}{\partial\theta}\right)$$

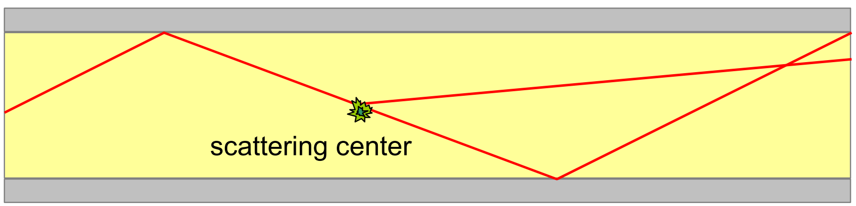
Introduction to POF



Obtained with laser collimated light source

Introduction to POF - mode mixing

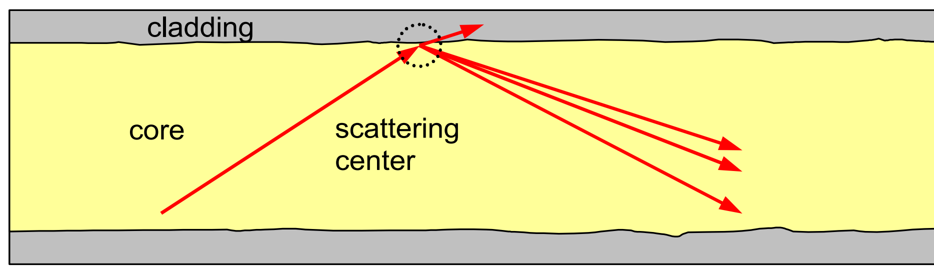
- POF has a big mode mixing effect
- Bending and length brings the launching mode distribution into the Equilibrium Mode Distribution (EMD)



Discontinuities and impurities of PMMA speed up mode mixing

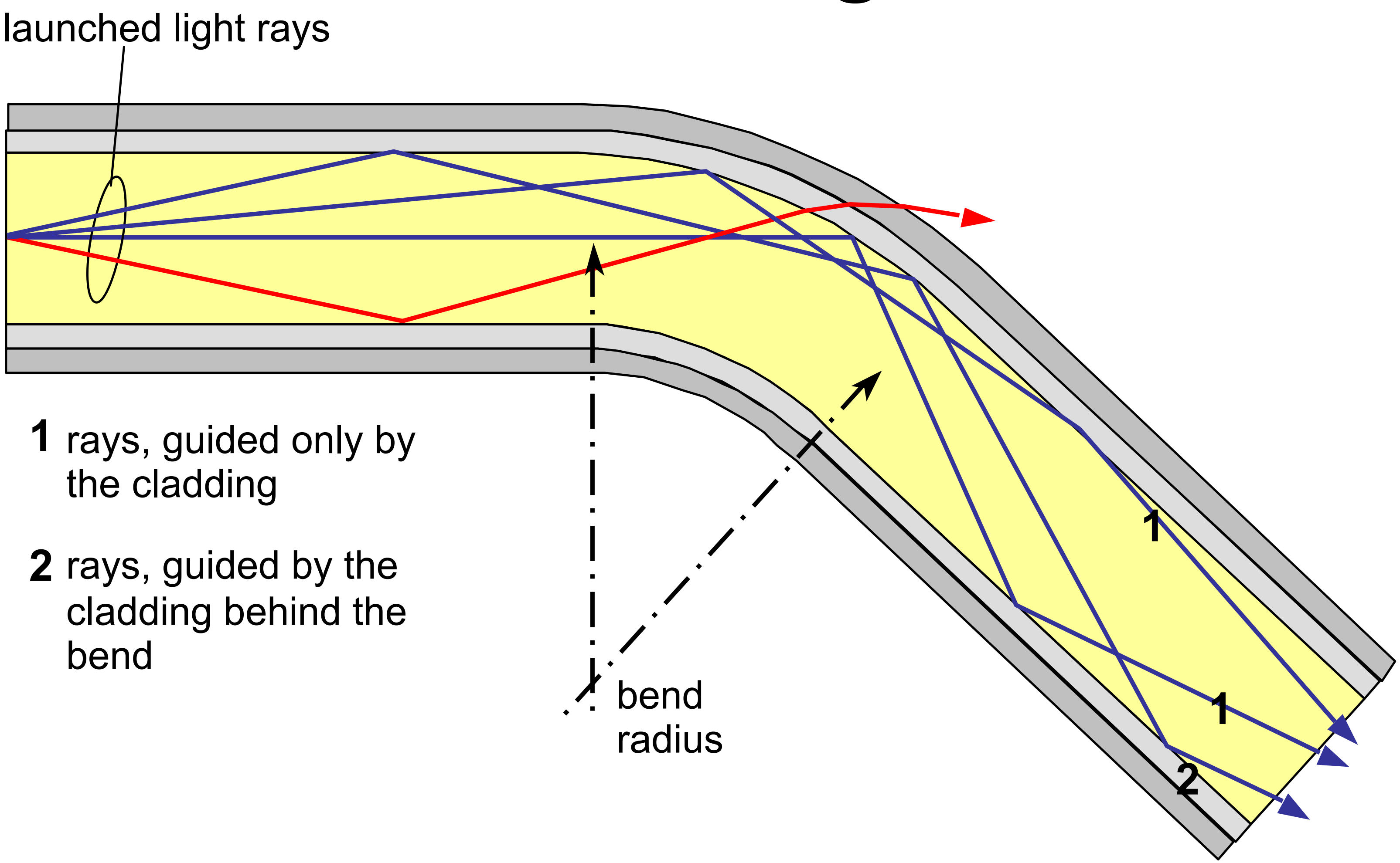
Optische Nachrichtentechnik:: Olaf Ziemann

Irregularities in the core-clad boundary also ease mode mixing



- Bandwidth·sqrt (Length) Product and Attenuation/Length approximate constants in EMD
- Typically, light sources are manufactured to launch almost EMD to have predictable performance and avoid excessive mode conversion in bends

Bending



1 rays, guided only by the cladding

2 rays, guided by the cladding behind the bend

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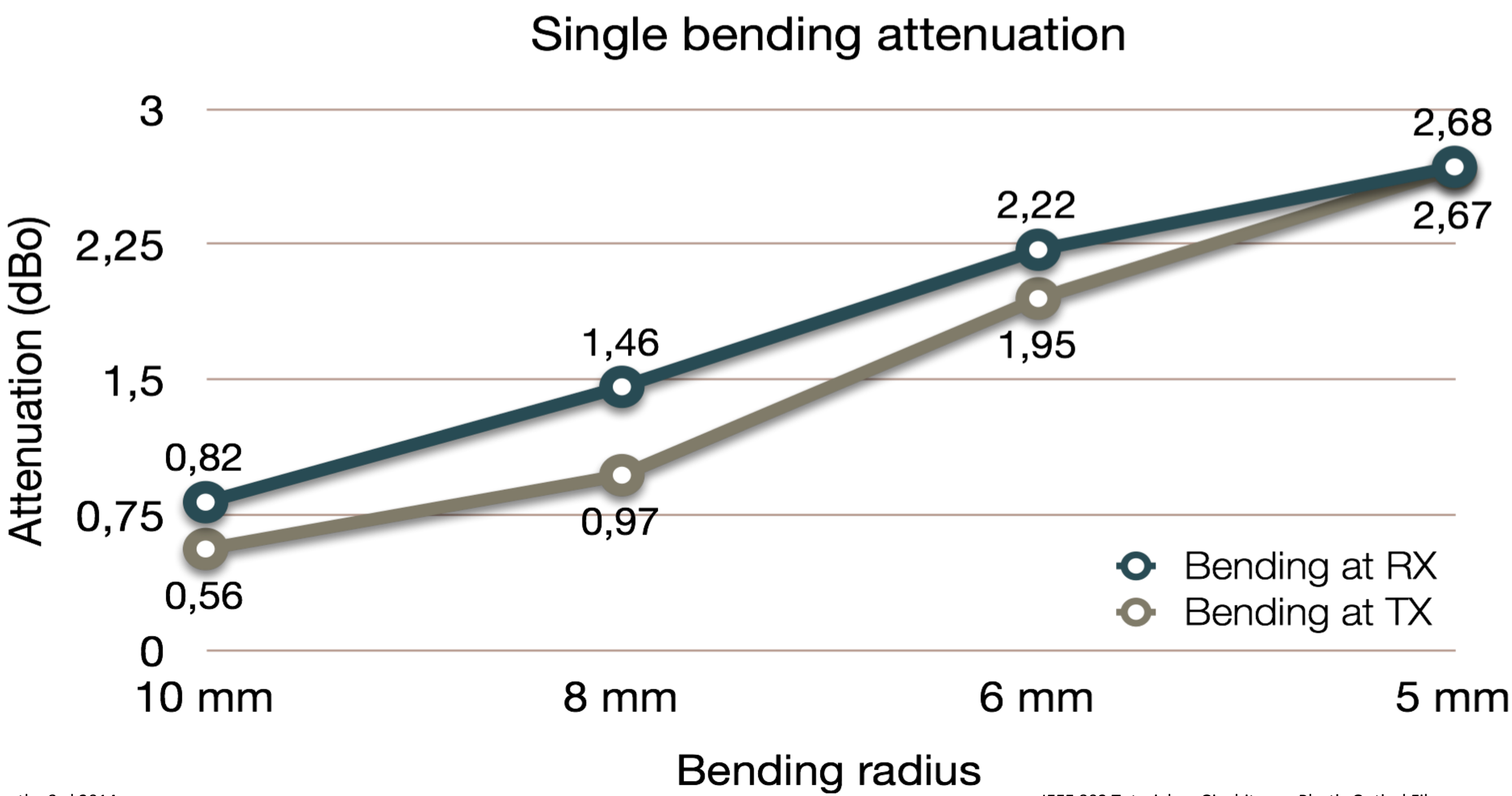
Bending

- During bending the mode distribution changes
  - Different mode distributions represents different channel responses in terms of bandwidth and attenuation
  - Dynamic bending requires continuous equalization of the channel response

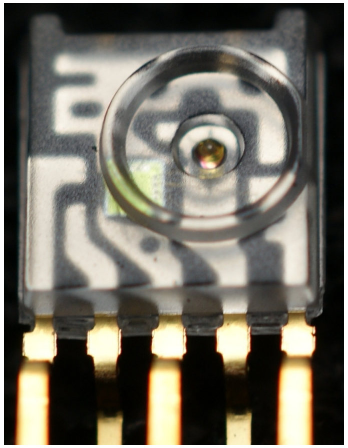
- There are backup slides with detailed technical description of the optical channel

Bending effects

- Down to 5 mm. No losses at 25 mm bending radius (Automotive)
- Bending reduce optical power, and destroy higher modes improving bandwidth
- Objectives can be reached even with bending



LED light source



- 650 nm (red) LED
  - Qualified for automotive up to 95ºC (HTOL 3000 h)
  - 105ºC Automotive feasibility demonstrated
- AOP: Average optical power coupled into fiber

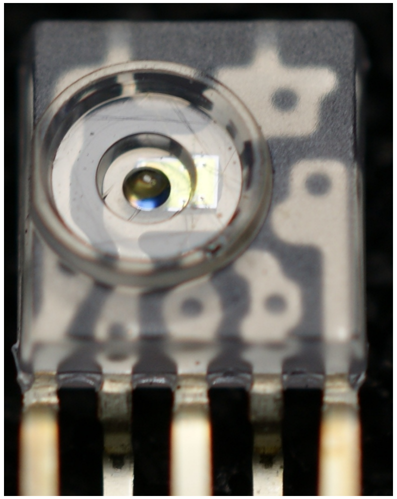
Temp	-40ºC	0ºC	20ºC	70ºC	85ºC	95ºC	105ºC
AOP	*-1.8 dBm*	*-2.5 dBm*	*-3.0 dBm*	*-5.2 dBm*	*-5.8 dBm*	*-7.0 dBm*	*-7.5 dBm*

- Linearity

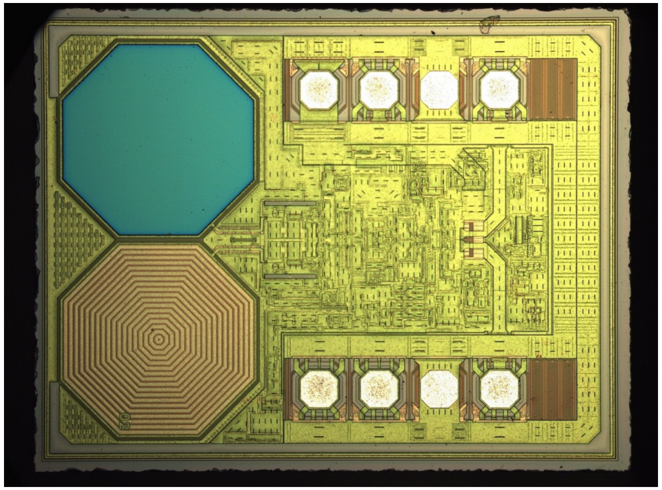
  -20 / -30 dBc typical. (2nd / 3rd harmonic distortion).
Varies with temperature and manufacturer

- Bandwidth (E to E @ -3 dB): Typically 75Mhz.
  Improved with driver pre-emphasis up to 150 MHz
- Different launch condition depending on the manufacturer.
  After lens the launch Numerical Aperture is approximately 0.3

Receiver

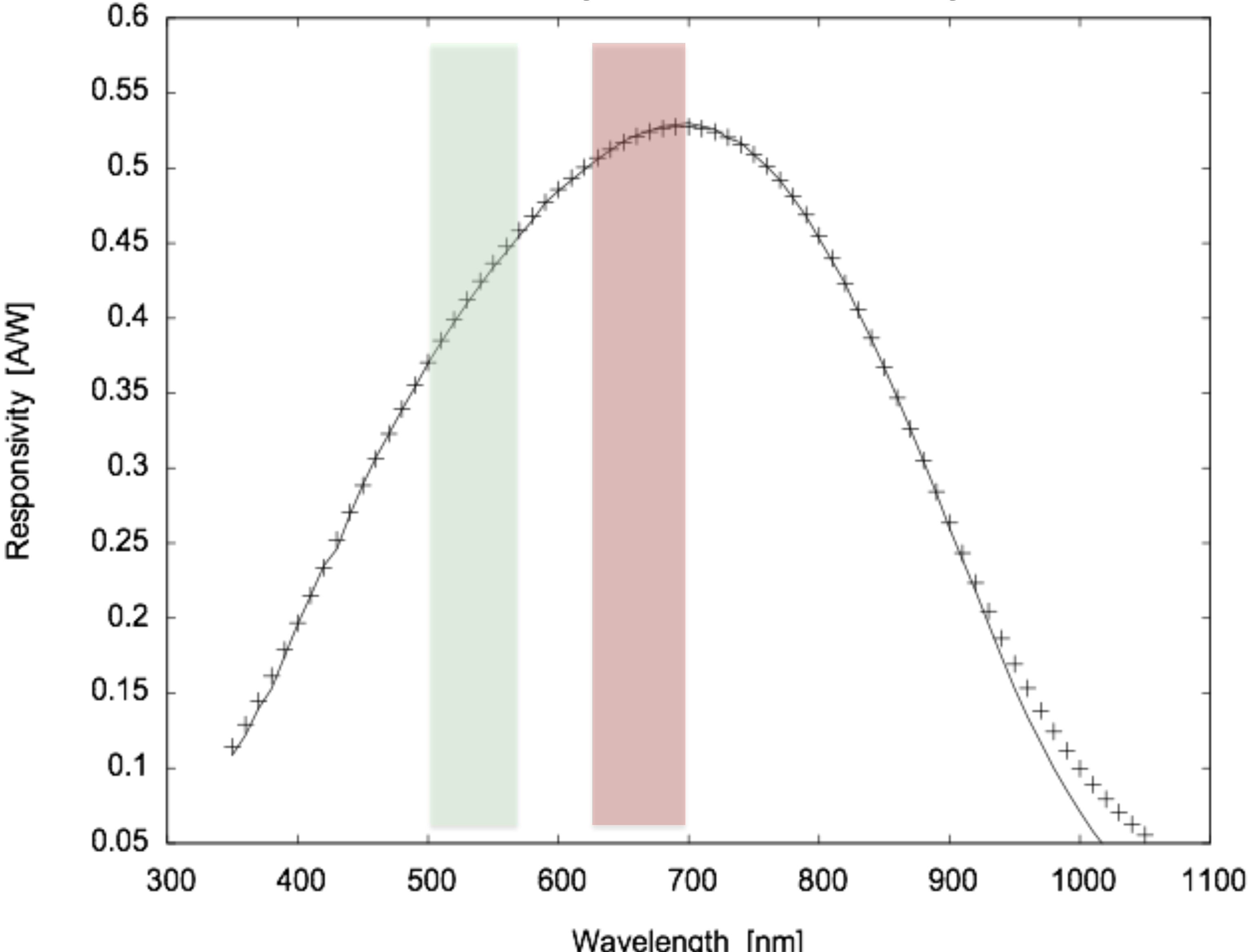


- Si-PIN Photo Diode(PD) is normally used
  - 400 um -> 600 um PD diameter
- Both, PD pseudo-differential and PD single ended solutions are available



- Might be embedded with TIA (Trans Impedance Amplifier) to reduce EMS (Electro Magnetic Susceptibility)
- Low dependency of response with temperature
- TIA bandwidth and noise depends on received power

PD Responsitivity



Connections (In-line connector)

- From 1.0 dB to 2.5 dB attenuation
- No real impact on bandwidth

Length objectives consider application temperature & connection requirements

Root cause: LED AOP decrease with increased temperature

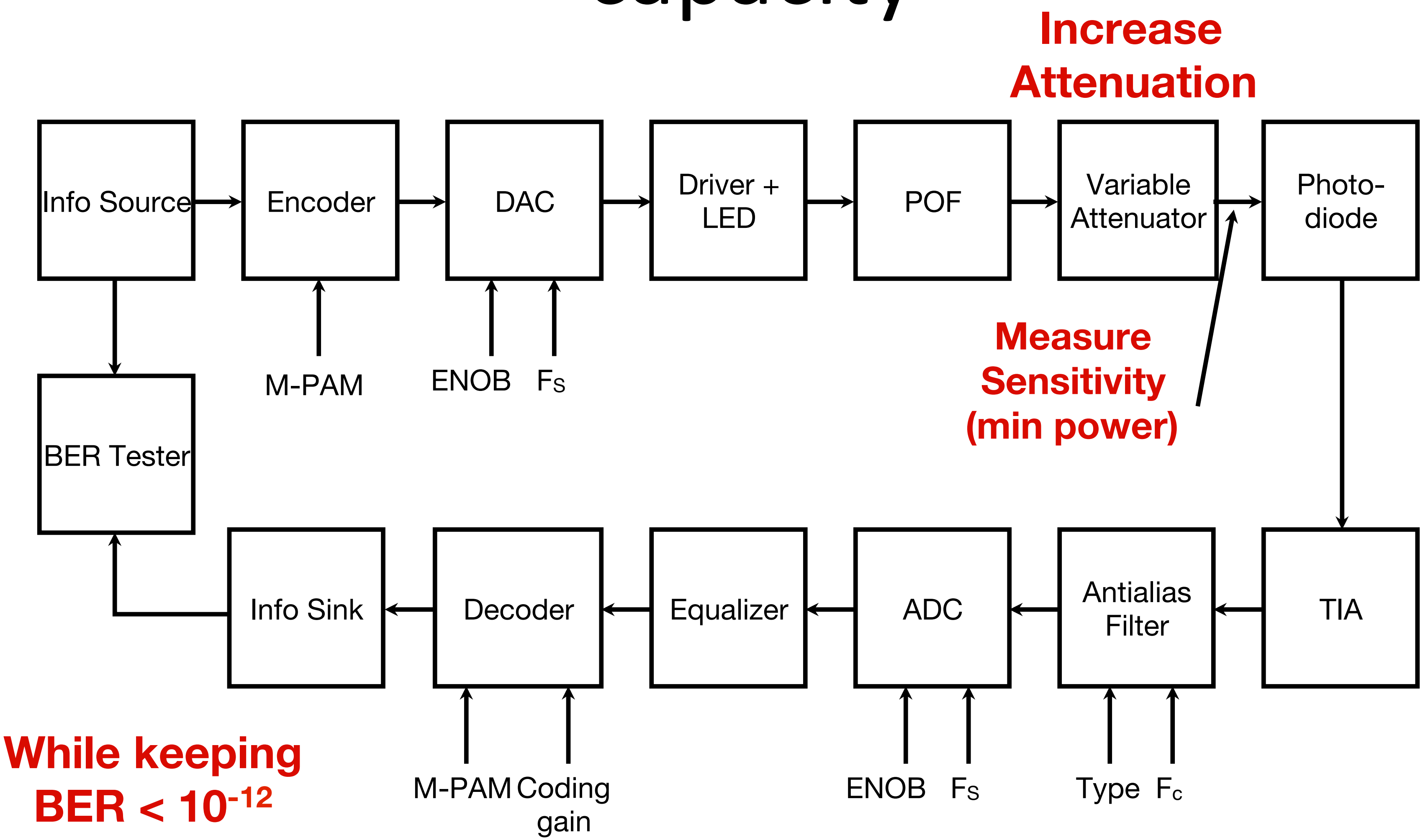
- Automotive (-40ºC to +105ºC):
  - 15 m with 4 connections
  - 40 m no connections
- Industrial and Home Networking (-20ºC to 85ºC):
  - 50 m with 1 connection
- All three length objectives can be met with a single PHY specification

VDE proposal

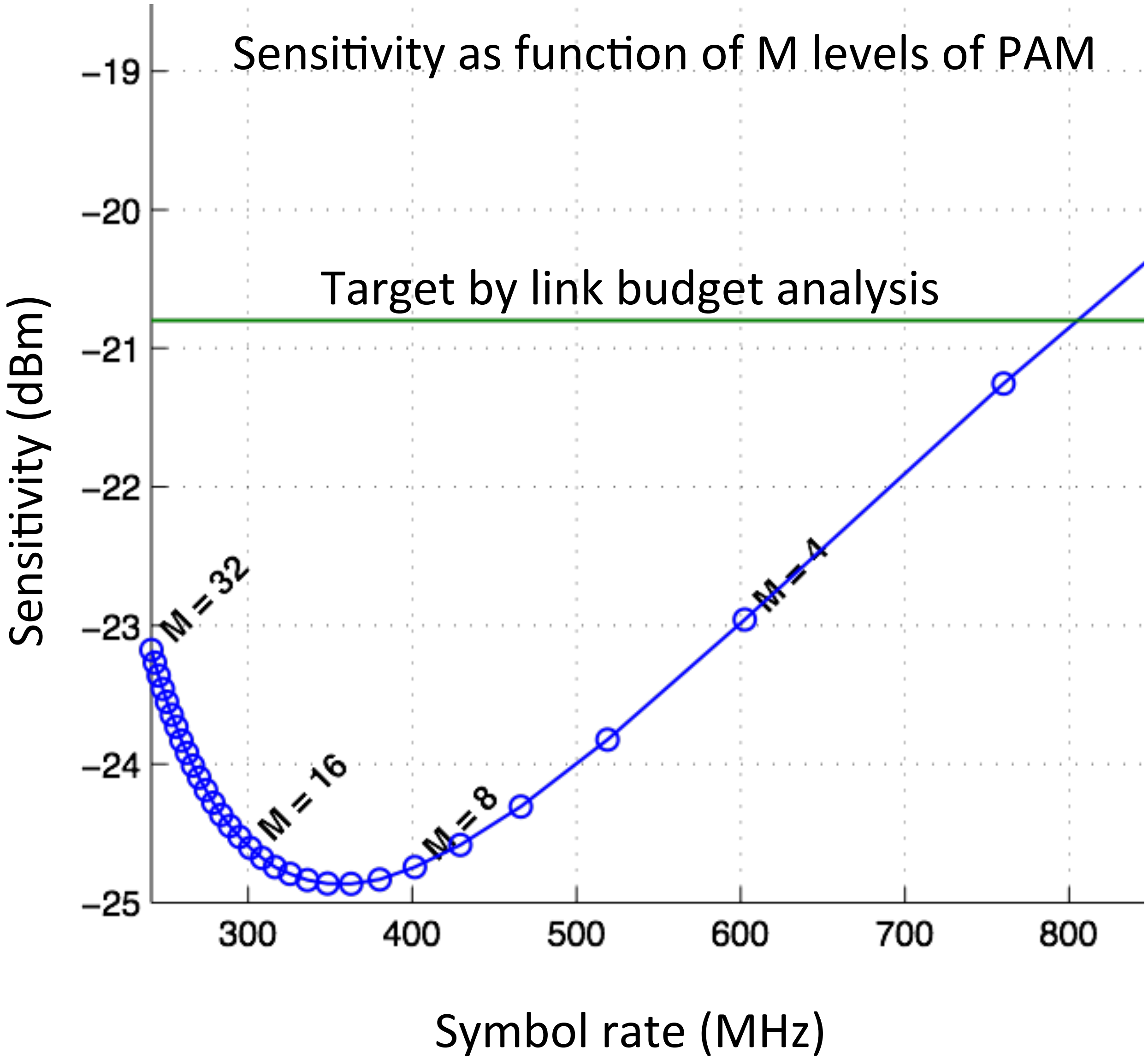
- Provided to 802.3 as a contribution
  Economical and technical feasibility
  SG has not adopted technical proposals

- PAM-16 with THP (312.5 Mbaud)
  Optimum solution for current LED, Fibre and PD and feasible TIA
- THP is used to:
  Solve Inter Symbol Interference (ISI) in combination with high spectral efficiency coded modulation
  Allows whitening of TIA non-white noise

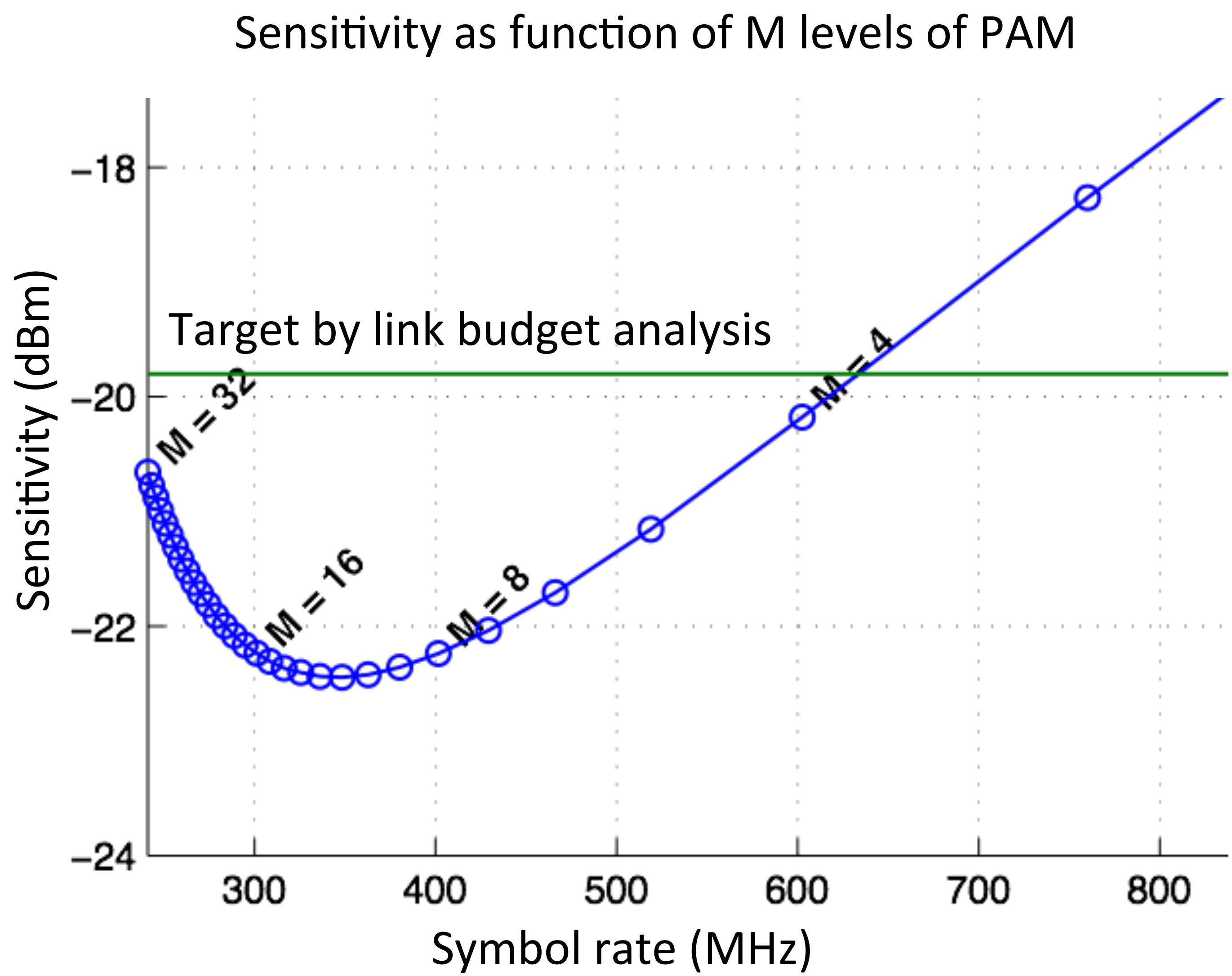
Sensitivity based on Shannon capacity



Sensitivity for 15m + 4 connections



Sensitivity for 50m + 1 connections



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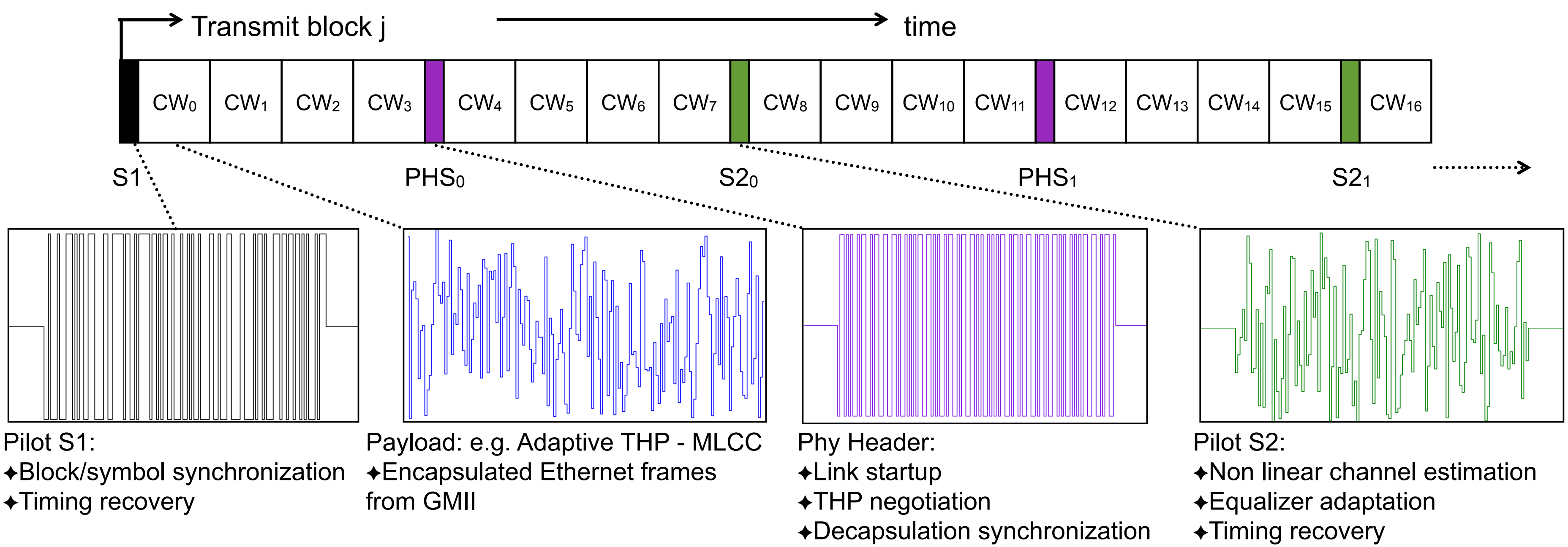
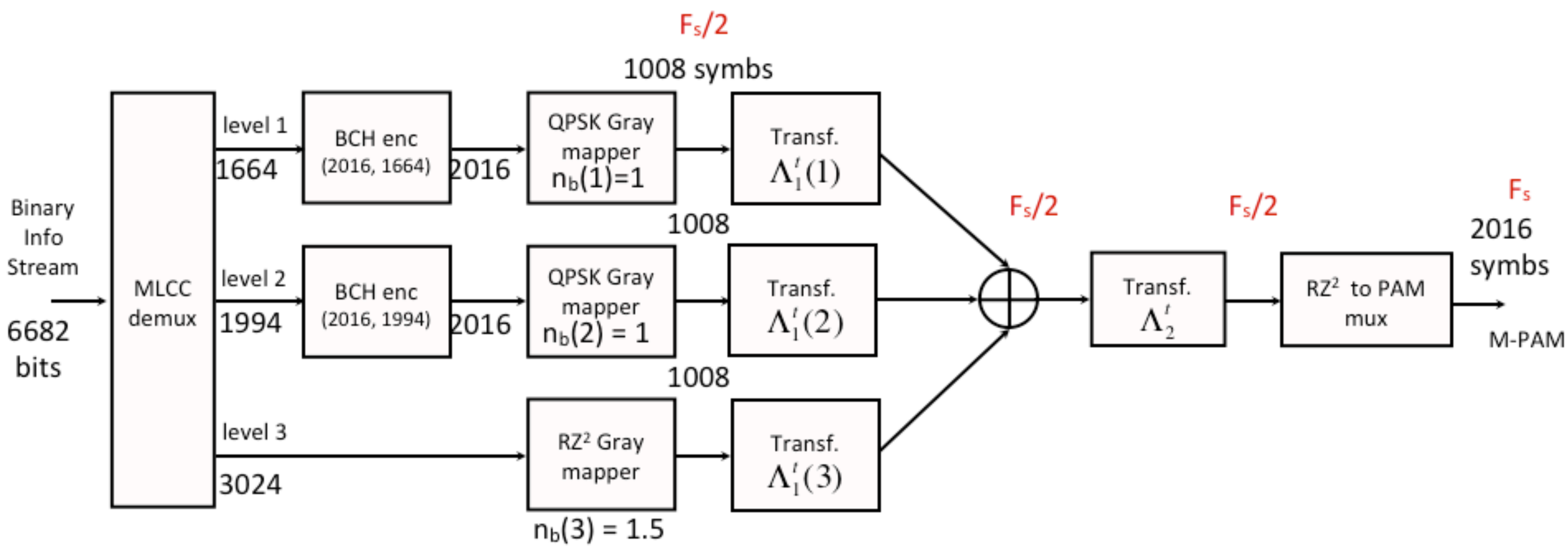
VDE data encapsulation

- Periodic transmission structure
  - To have a fast link establishment (Less than 50 ms)
  - To have big tolerance to clock frequency mismatch (>+-200 ppm)
  - To have a fast negotiation of THP TX coefficients
  - To track and equalize channel changes with temperature, bending and vibration
  - To implement Low Power Idle mode (EEE)

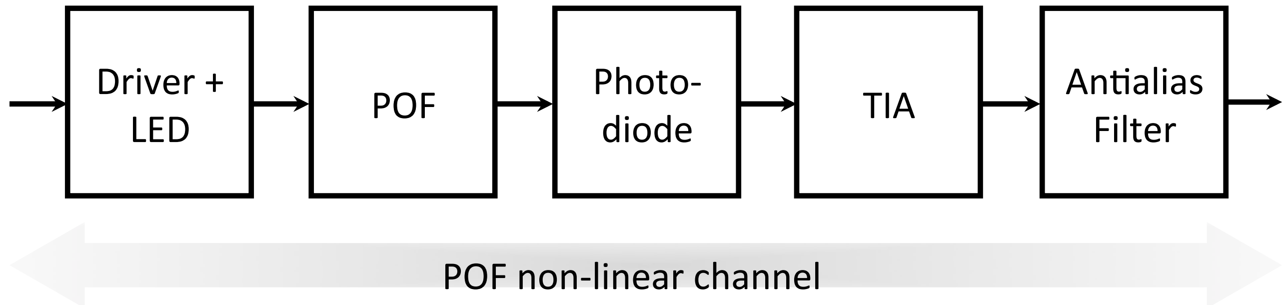


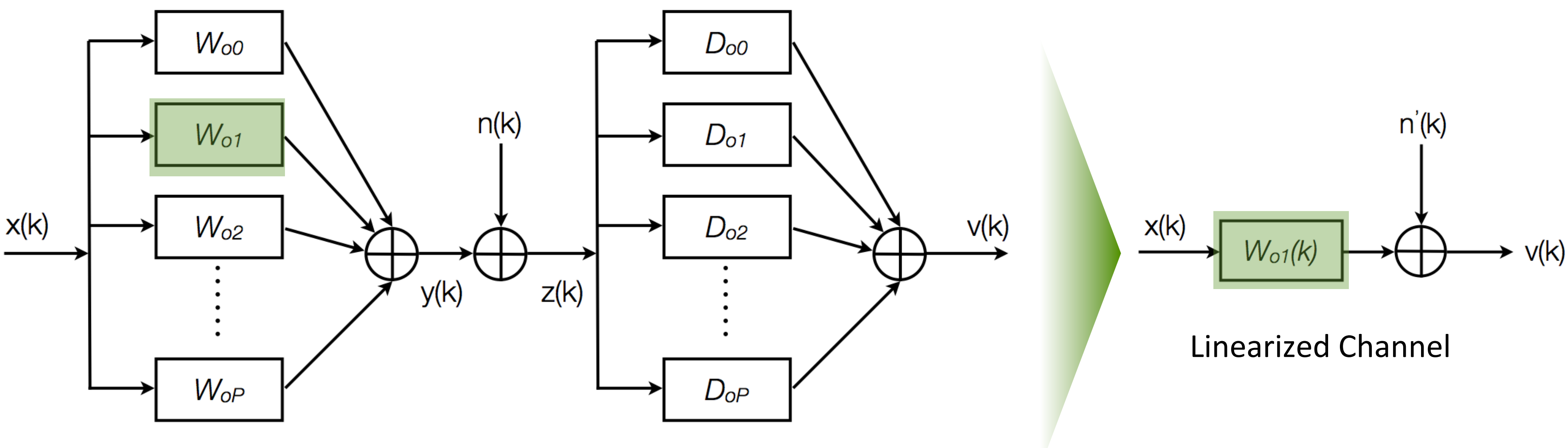
VDE encoding

- MLCC with three levels based on BCH component codes
  - Low cost implementation
  - Low power implementation
  - Coding gain of 6.7dB @ BER 10^{-12} with multi-stage hard decoding



Non linearity

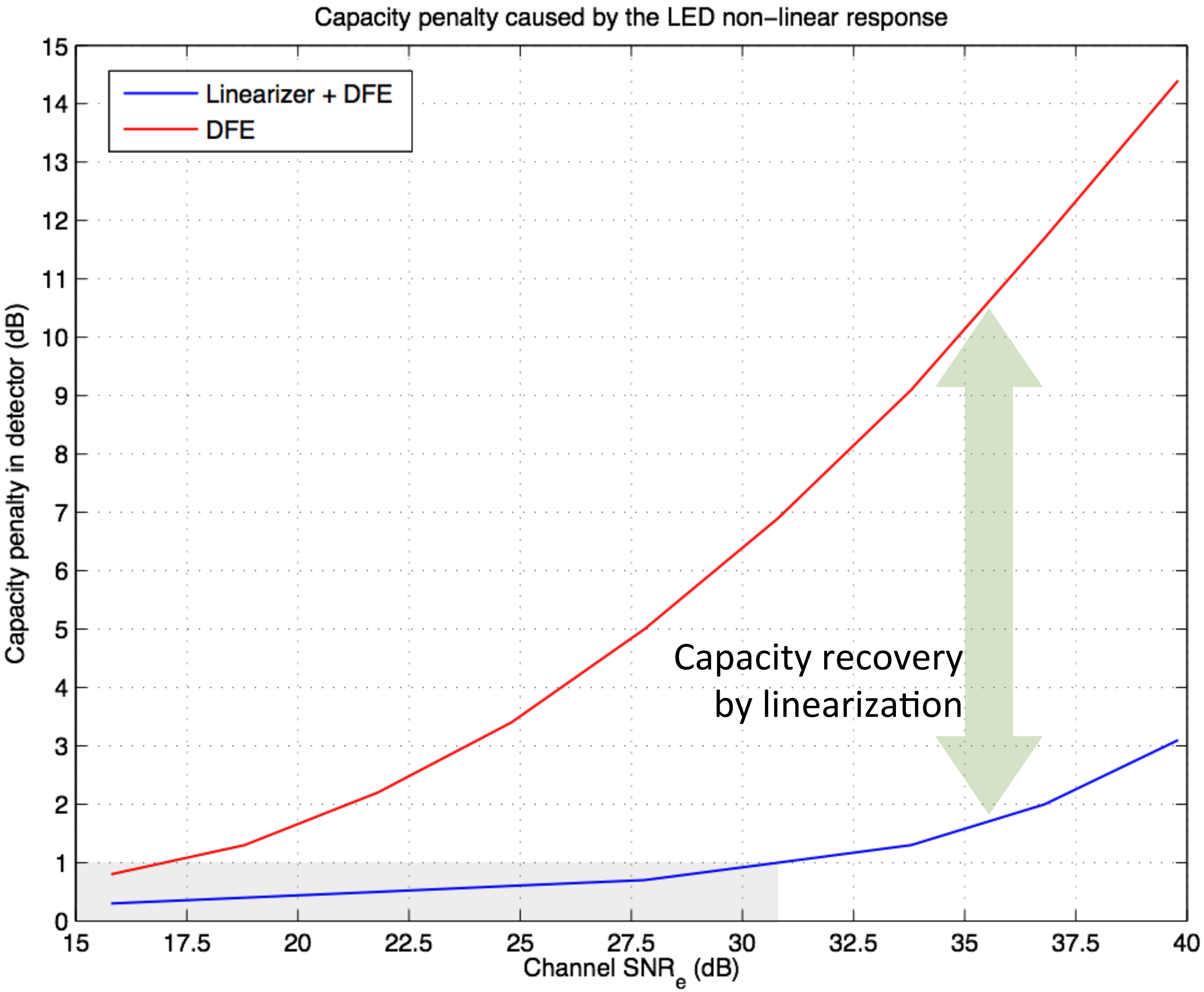




POF non-linear channel
Volterra's series model

Linearizer
non-linear filtering

Non linearity - capacity penalty



Capacity loss < 1dB for SNR$_e$ < 30 dB

High spectral efficiency schemes are feasible

VDE proposal performance

- Sensitivity –19.0 dBm at output of the fiber for BER 10^{-12} & 50 m. (Compromise between vendors)
- Latency of 25 us
- Overhead of Headers, Pilots and encapsulation: 3.5%
- Multi-protocol encapsulation
- Complexity:
  – 50% of average 1000BASE-T implementation
- Royalty free license LOA from KDPOF

- Bandwidth requirements on the Home Network
- WiFi & PLC limitations
- Benefits of POF in the Home Network
- Length requirements
- POF installation examples
- POF as backhaul
- European Home Network study
- Other Market examples
- Conclusions

HOME NETWORK MARKET

Bandwidth requirements on the home network

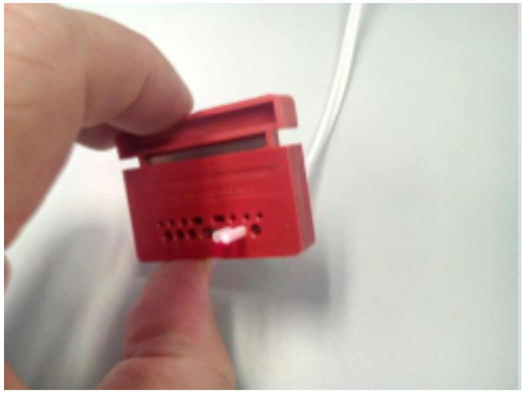
- FTTH and other broadband access technologies offers increasing access speeds
- Smart Home services is pushing the required Home Network speed beyond 100 Mbps
  - “All in the cloud”
  - VPN – remote working
  - 4K video, multi-room DVR
  - high speed Internet, Internet of things…

- Gigabit Ethernet assures the home network will not be a bottleneck

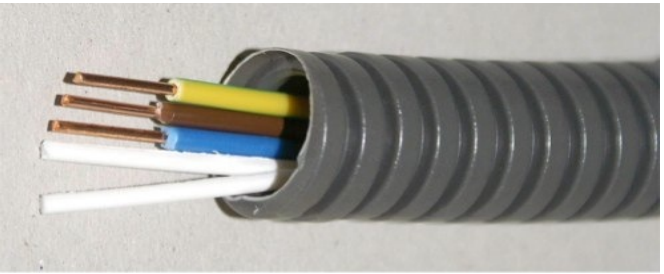
WiFi & PLC limitations

- In many households (E.g., Europe, Latin America, etc.), neither Wi-Fi nor Power Line Communications (PLC) are able to provide high speeds with full house coverage
- WiFi
  - Additional attenuation in brick houses over wooden ones is around 3.5dB per wall and 12 dB per floor. (ITU-R M. 1225 Appendix 1 to annex 2)
  - WiFi channels are saturated in urban areas even with the new 5 GHz bands
- PLC
  - Noisy PLC limits speed and robustness
  - Many ISPs stopped offering PLC due to unpredictable quality

Benefits of POF in the Home Network



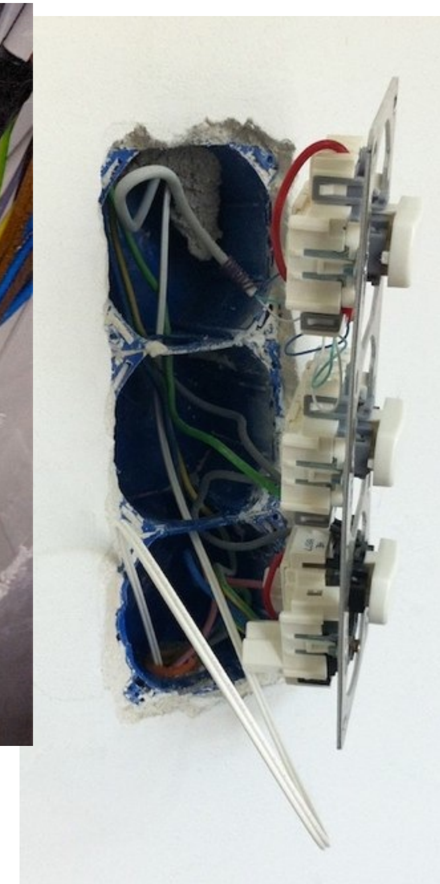
- Easy to install
  - Low qualification or light training required
  - Connectorless option
  - Cut and plug
- Electro Magnetic Immune, Galvanic secure
  - To be installed together with the mains
  - To be installed in houses with electrical noise problems
- Flexible and robust



Length requirements in HN

- 50 m covers worst cases for:
  - Europe, Asia, Latin America and Africa
- US and Canada
  - In big downtown areas, required lengths are similar to Europe ones
  - 50 m covers most HN length requirements
  - What is a worst case is arguable

Examples of POF installation at home

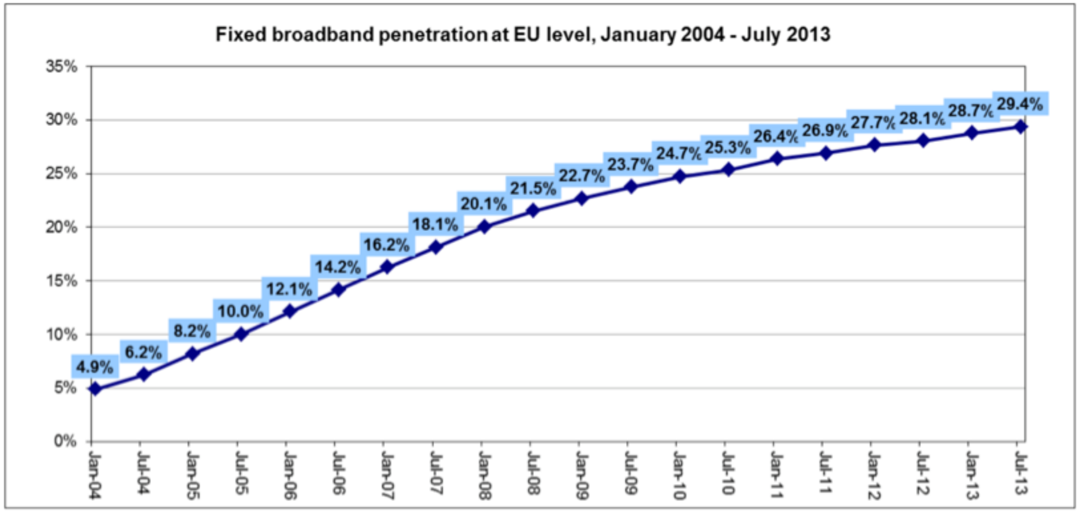


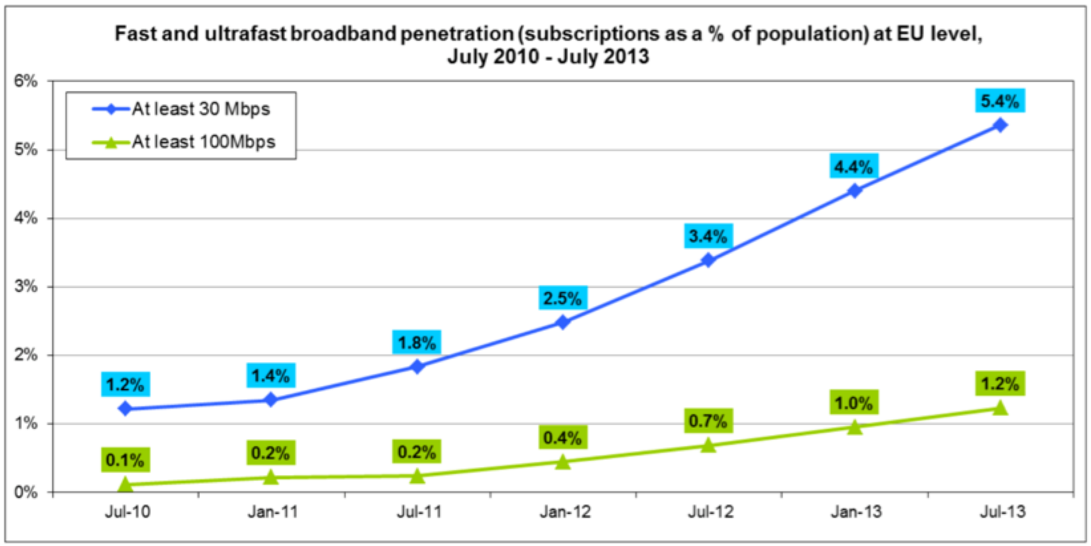
POF as a backhaul interconnecting devices and WiFi AP´s

- Optimal combinations of technologies: WiFi for mobility and Optical for broadband
- Enables minimal power WiFi AP´s tailored to optimal room coverage: Less cross-talk and radiation
- Distributes the broadband all over the home

European home network study

- What is happening in the Broadband Market in EU?
- High growth of broadband connections
  - Which leads to greater capacity consumption
  - Which leads to greater speeds
- This is also driven by the "multiscreen explosion" (increasing number of devices)

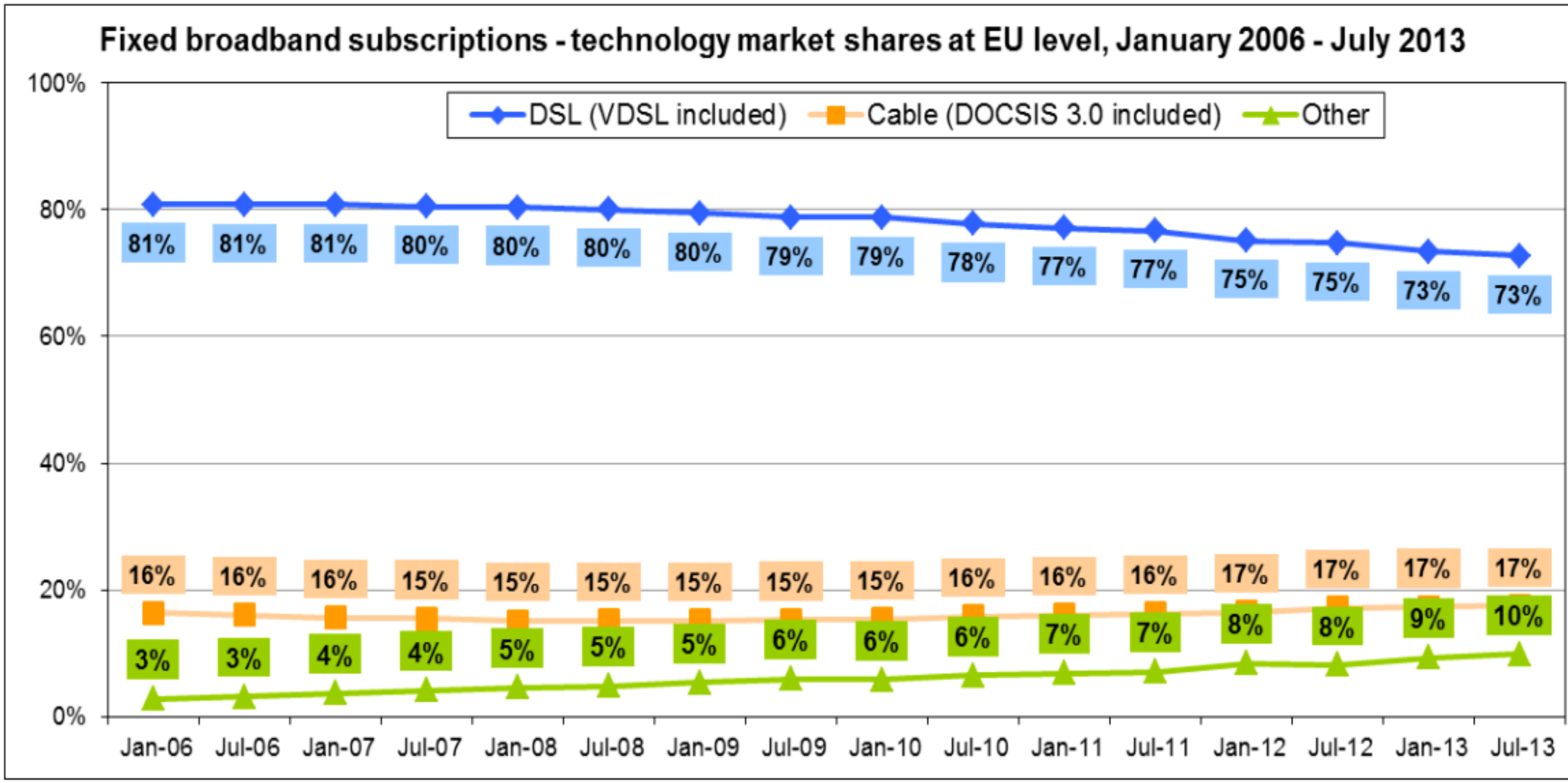




Data from "Broadband access in the EU: Situation at 1 July 2013", on Tue, 25 Mar 2014

European home network study

- Operators are investing heavily in deploying networks: DSL, Coax, FTTH.



Data from “Broadband access in the EU: Situation at 1 July 2013”, on Tue, 25 Mar 2014

European home network study

- Ironically, the increase in nominal speed (beyond 20Mbps) is creating more dissatisfaction in some cases:
  - For Wi-Fi connections (most common), there are typically problems with speed , particularly in EU thick-wall housing
  - For PLC (sometimes used as an alternative by Operators), there are many interferences
  - For Ethernet Cat 5/6 (best current solution), the problem is often times resistance by house owners to outside wall cabling
- Operators need to find an easy way to "match expectations" between what they sell and what the customer perceives.

European home network study

- Telcos are typically finding several topologies for home networking in case of successful setup:

%cases(*)		Cat5/6	Wifi
20%	Router Wifi only	-	OK
20%	Router Wifi + STB/PC in the same room	OK	OK
10%	Router Wifi + STB/PC in the same room	X(1)	OK
25%	Router Wifi + STB/PC in other room/s	OK	OK
15%	Router Wifi + STB/PC in other room/s	OK	X(2)
10%	Router Wifi + STB/PC in other room/s	X(1)	OK

STB = Set Top Box

1: Not OK, because of esthetical reasons

2: Not OK, because Wifi has difficulties in penetrating walls.

(*) Source: estimation by JAL21, based on industry reports and interviews.

European home network study

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15%	Router Wifi + STB/PC in other room/s	OK	X(2)
10%	Router Wifi + STB/PC in other room/s	X(1)	OK

35% POF Opportunity (aprox).

STB = Set Top Box

1: Not OK, because of esthetical reasons

2: Not OK, because Wifi has difficulties in penetrating walls.

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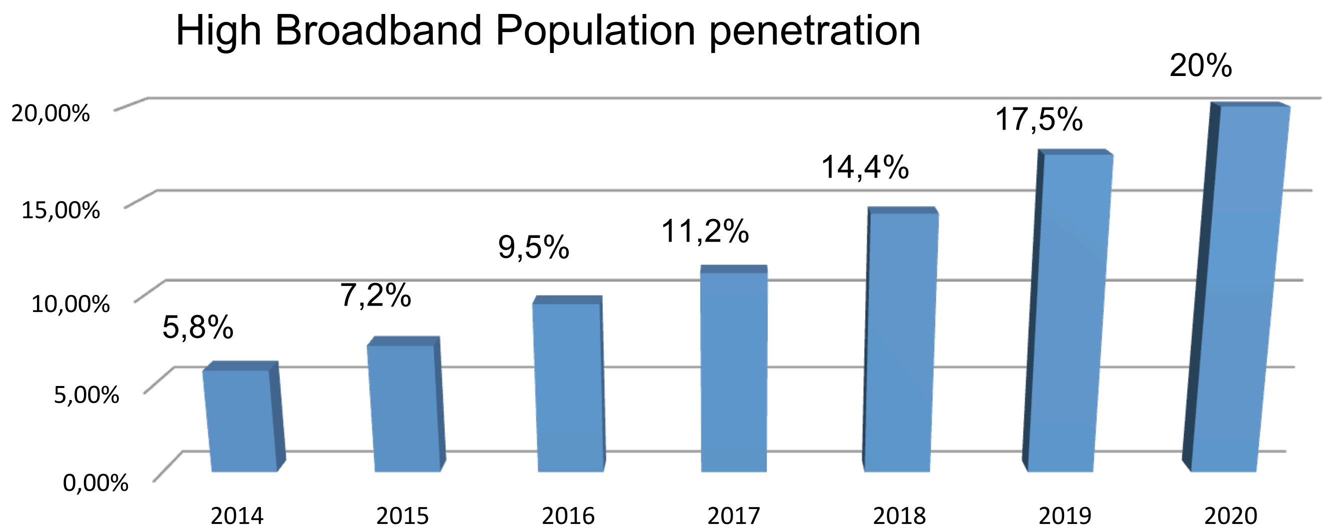
European home network study

POF opportunity in EU 2015 – 2020 is more than 15 mill. Households which represent approximately 60 million POF connections.

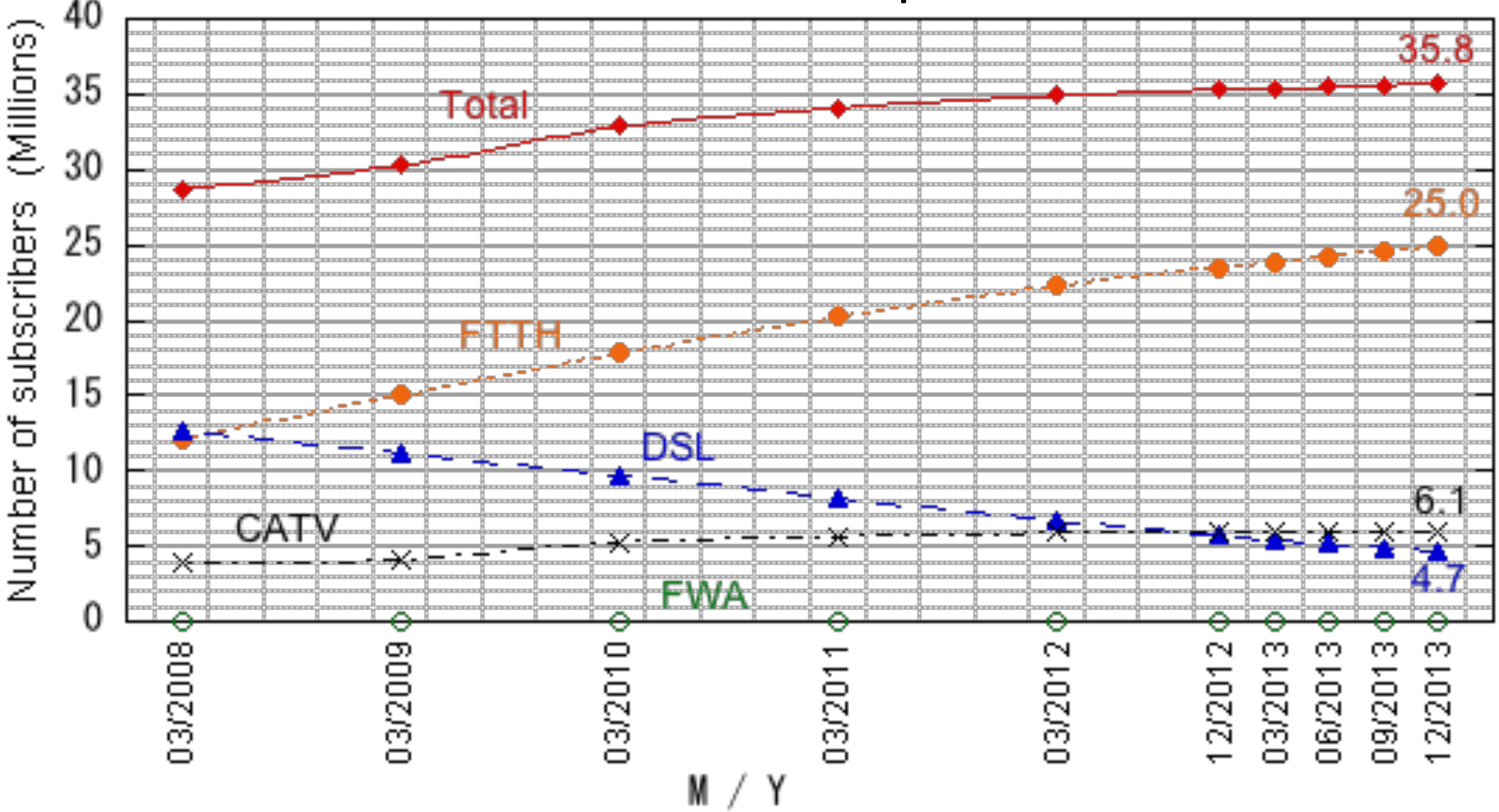


Total Population EU	507.416.607	508.273.750	509.130.893	509.988.036	510.845.178	511.702.321	512.559.464
Total households EU	219.203.974	219.574.260	219.944.546	220.314.831	220.685.117	221.055.403	221.425.689
Population HBB EU	29.430.163	36.595.710	48.367.435	57.118.660	73.561.706	89.547.906	102.511.893
Households HBB EU	12.713.831	15.809.347	20.894.732	24.675.261	31.778.657	38.684.695	44.285.138
POF Opportunity Households	4.449.841	5.533.271	7.313.156	8.636.341	11.122.530	13.539.643	15.499.798
POF Opportunity connections	17.799.364	22.133.084	29.252.624	34.545.364	44.490.120	54.158.572	61.999.192

Other HN market opportunities

- European retrofit and new houses
  - 3 M households per year
- Latin America
  - New construction in Mexico, Chile, etc. requires low traning network installation
- Japan

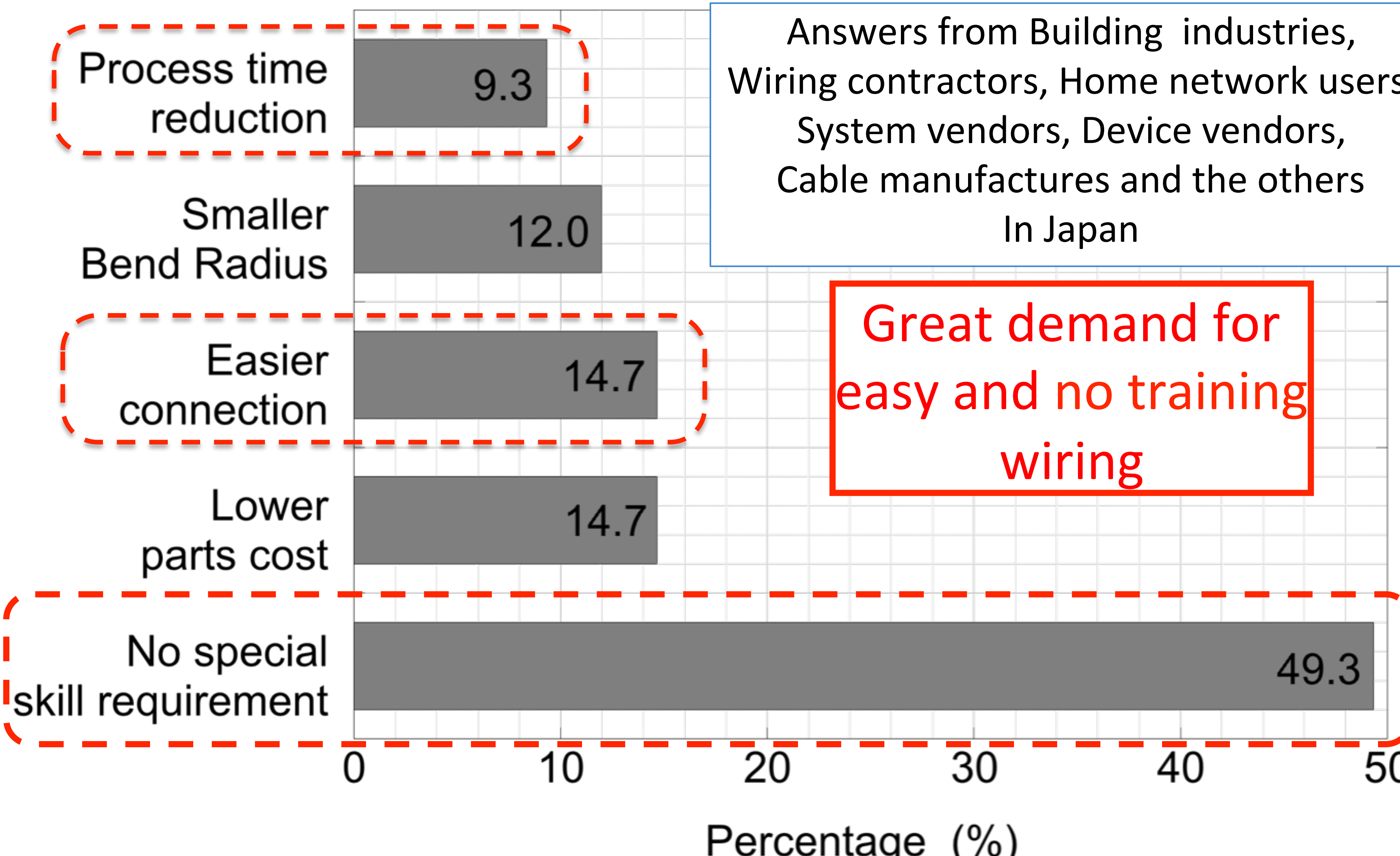
The Numbers of Fixed Broadband Access Service Systems Subscribers in Japan



Source: Japan Ministry of Internal Affairs and Communications

Broadband Access service spread widely in Japan

Japanese Survey for the demand of Optical Wiring



Answers from Building industries, Wiring contractors, Home network users, System vendors, Device vendors, Cable manufactures and the others In Japan

Great demand for easy and no training wiring

Conclusions

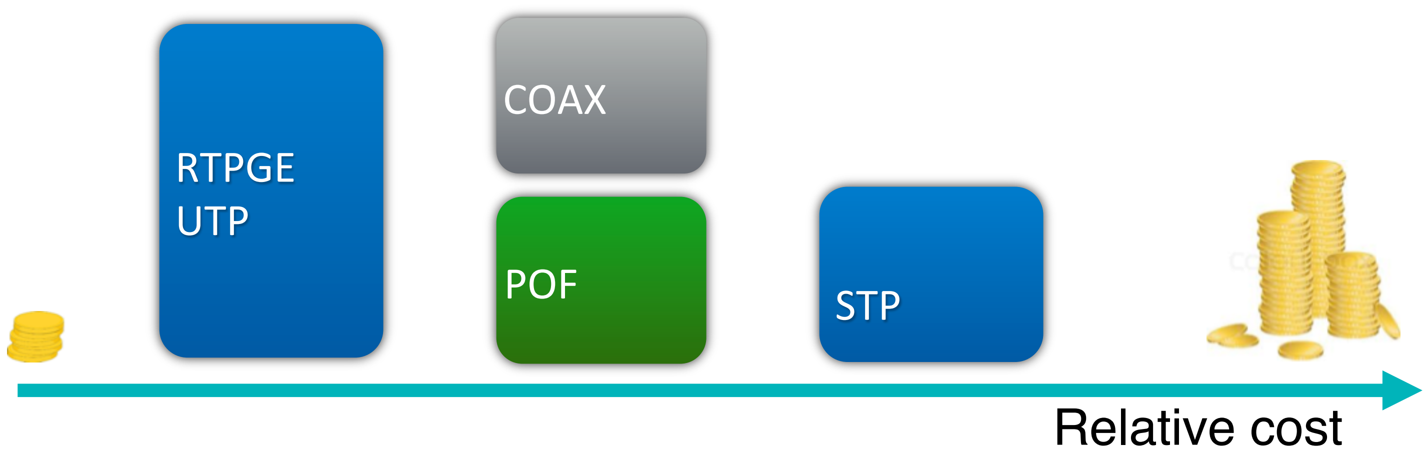
- POF is an optimum media for Home Network backbone for many house construction types around the world
  - Easy to install
  - Can share the mains conduit
- FTTH deployment, and new services requires a robust home network capable of handling new access bit rates
- Copper is not usable in many old houses, where POF is usable

Automotive networking
Market potential
JASPAR
O-GEAR Project
Open Alliance TC7

AUTOMOTIVE

Automotive networking

- Complements RTPGE/1000BASE-T1
  - Addresses those applications that can't be serviced with 1000BASE-T1 UTP cabling
  - E.g., high electromagnetic noisy areas, galvanic isolation, long distances
- POF is already used in automotive for information and entertainment with the MOST technology
  - Re-use of current MOST LED will guarantee automotive qualification
  - Leverages on already qualified connectors and cables



Market potential

- As stated in RTPGE CFI (March 2012)
  - Overall automotive Ethernet market up to 270 Million ports in 2019
- Brings current automotive POF users to a fully seamless Ethernet solution
  - Stronger Ethernet automotive market potential growth
- Complementarity use of RTPGE and Gigabit POF solutions

	RTPGE	GIG-POF
Weight	✓	✓✓
EMI/EMC	✓	✓✓✓
Galvanic Isolation	✓	✓✓✓
Temperature	✓✓	✓
Length	✓	✓✓
Cost	✓✓	✓

JASPAR

One voice of JAPAN - JASPAR was established, in 2004, in order to pursue increasing development efficiency and ensuring reliability, by standardization and common use of electronic control system software and in-vehicle network which are advancing and complexing.

Board: TOYOTA, Nissan, Honda, DENSO, Toyota Tsusho Electronics

Members: Regular: 75 / Associate: 56 (as of Jan. '14)

WGs:

- Next Generation High-Speed Network WG
- Functional Safety WG
- AUTOSAR/FlexRay Standardization WG
- Multimedia Architecture WG
- Bluetooth Conformance WG
- Mobile Device Interface WG

Next Generation High–Speed Network WG

Chair: TOYOTA

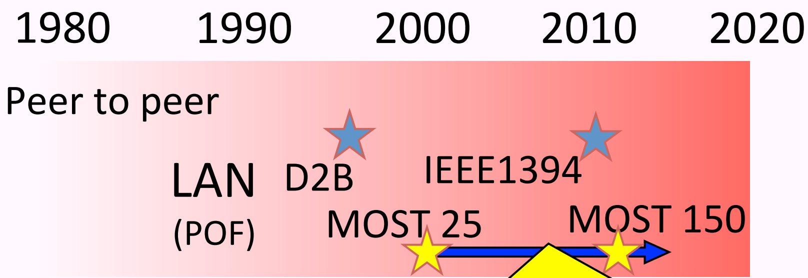
Nissan, Honda, Denso, Renesas Electronics, Sumitomo Electric, Murata Manufacture, Toyoda Gosei, Clarion, Bosch Japan, NXP Japan, Micrel Japan, Yazaki, Furukawa Electric, Toyota Central R&D Labs, Marvell Japan, TE Connectivity, Nippon Seiki, Fujitsu TEN, Nippon Seiki, Isuzu Motor, Clarion, Mitsubishi Electric, Fujitsu Semiconductor, Toshiba Information Systems, Hitachi Automotive Systems, Calsonic Kansei, Micware, OTSL, Analog Devices, Vector Japan, ETAS, Marvell Japan, Sunny Giken, Telemotive AG, Ricoh, MegaGhips, Tokai Rika

Requirements Definitions of the WG

- Recommendation's application
- Network
- Function profiles
- Physical layer and wiring design
- Data description format

Optical Network Systems for Automotive

Optical Communication in Cars

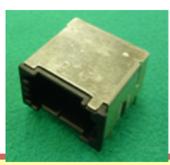


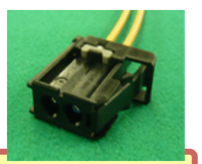
More than 100,000,000 nodes
More than 150 car models
Over 10 years

Features of Optical Components

- High speed
- Scalability/Expandability
- EMC/EMI
- Dimensions
- Weight
- Small cable diameter
- Small bending radius
- Robustness

In-vehicle Optical Components





Header Connector

POF

Model link

Cost Competition Strategy

- No more measures against noise
- Standardized test methods and components
- Full automation manufacturing
- Use proven technologies from other industries
- Avoid price staging

International standardization and dissemination project for high-speed communication network performance over large core multimode optical fiber

*- Technology integration for **O-GEAR**: Optical Gigabit Ethernet for Automotive aRchitecture*

From Oct. 2014 to Mar. 2017

Problems

- No simulation tools of the system design for O-GEAR
- No bandwidth guaranteed harness and connectors in high speed, 1 Gpbs - 10 Gbps
- Required reliable system which target is similar to FlexRay, BER 10^{-12}@10 Mbps

Team

- Toyota Central R&D Labs.
- Utsunomiya University 5 companies
- AIST (a national institute) 6 companies

Assignment

Design Tool Development
Develop simulation tools for optical link system which include mode conversion function of mode power distribution in SI-MMF defined by EAF. Link system design will be achieved in simple and low cost.

Physical Layer Development
Develop physical layer components which have bandwidth guaranteed wire harness and connector at 1 to 10 Gbps followed by JasPar requirements and IEEE802.3 Stds. Create int'l standards in IEC and ISO.

System Demonstration
In order to achieve higher reliability network system, demonstration of BER 10^{-14} at 1 Gbps Ethernet for automotive is the key target. Such lower BER will be required for future autonomous driving system and ADAS.

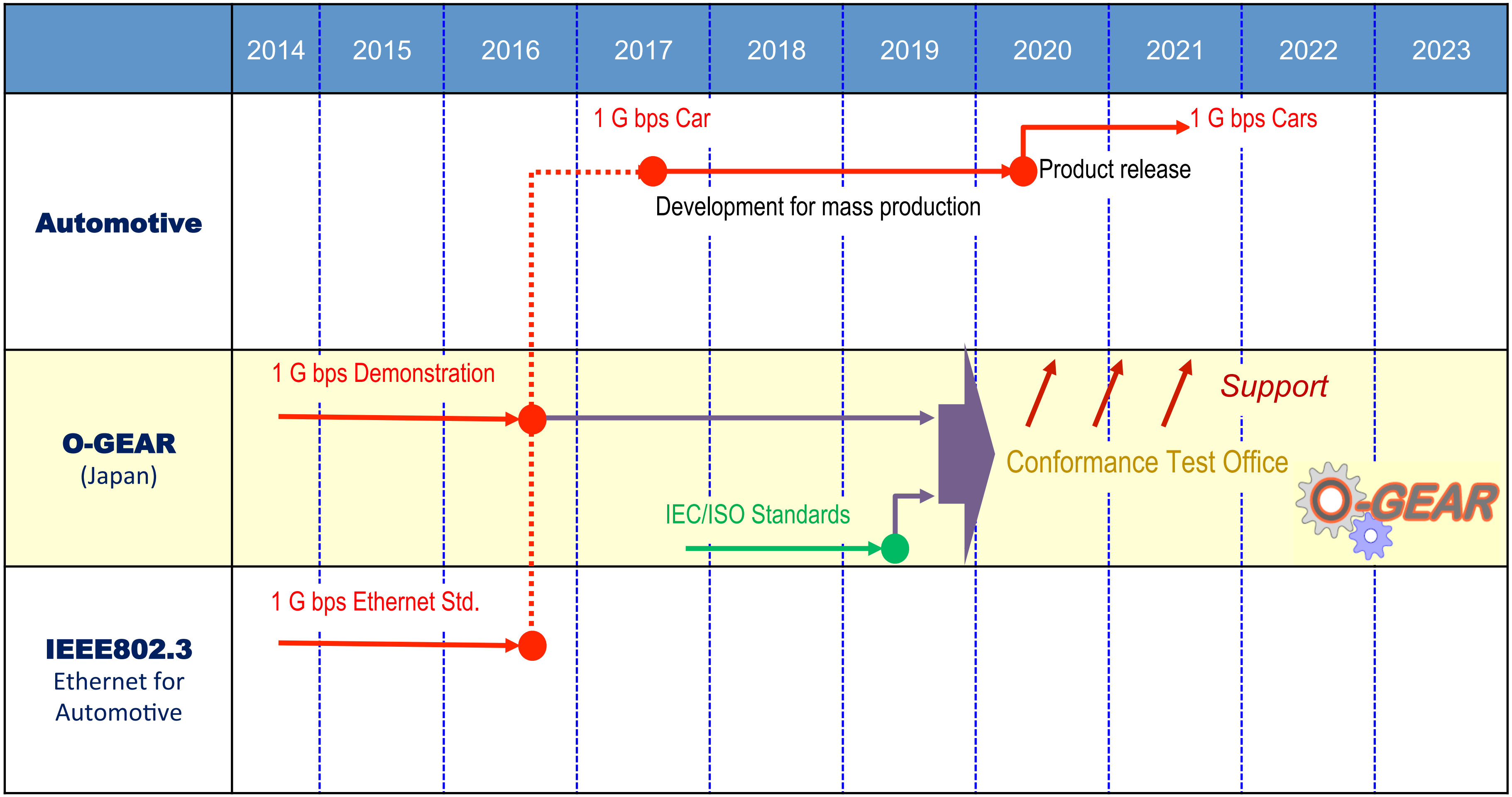
Standardization

OITDA (Project administrator) 9 companies

Promotion of Int'l Std.
De jure standards, IEC/ISO/IEEE, are required instead of traditional de-facto and OEM standards. Achieve low cost network systems with the use of international standardized components and systems.

Sponsored by METI Japan

Schedule, In-vehicle Gigabit Ethernet



Open Alliance – TC7

- Open Alliance has created a Technical Committee to support the Ethernet optical links in automotive
- Participants to this group are:
  - Avago, Broadcom, Cadence, C&S Delphi, Denso, Excelfore, Furukawa, KDPOF, Ruets, Sumitomo, TE, Toyota, Vittese, Yazaki
- Goal of the group is:
  "Work on Gigabit-Ethernet over POF solution for Automotive use"
  - Summarize Automotive requirements and support IEEE802.3 GEPOF standardization activity.
  - Create supplement documents/ Specifications (Connector interface, Footprint, test suits, etc.) for automobile installation

Summary for Automotive Applications

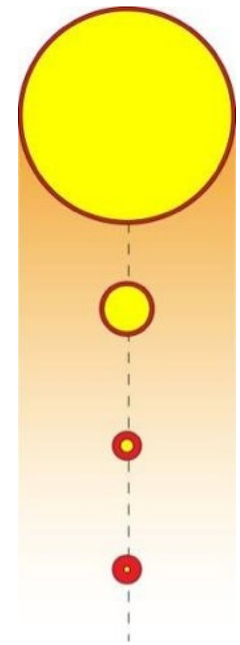
- Complementary technologies, electrical and optical, bring benefits for customers
- Plastic optical fiber is a proven technology in automotive
- Gigabit Ethernet enhances future applications
- Member companies from JASPAR contributes to the standardization works

Overview of industrial POF fibers
Evolution of POF based industrial Automation Network Systems
Environmental conditions
Factors of success of POF in industrial networking
Mechanical characteristics of POF
Industrial Example
How to terminate POF with an industrial connector
Conclusions

INDUSTRIAL MARKET

Overview of industrial fibers

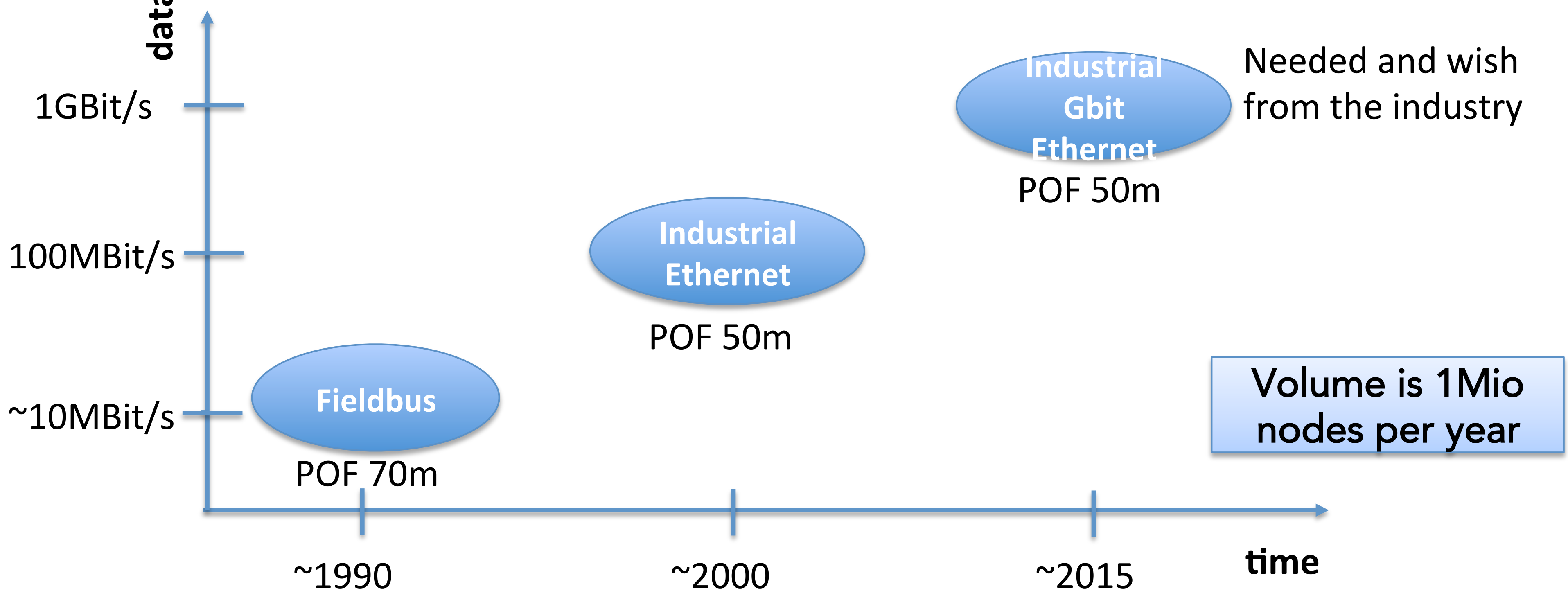
	Polymer Optical Fiber	Hard Cladded Silica	Multimode	Singlemode
Shortform	POF	PCF	GOF-MM	GOF-SM
Standard IEC 60793-2	A4a	A3c	A1a/ A1b	B1
Absorption [db/km] with λ [nm]	230 660	6 850	3,0/ 3,5 850	0,5 1300
Core diameter [µm]	980	200	50/ 62,5	9



POF → **best optical solution for short distances**

POF → **easy termination**

Evolution of POF based Industrial Automation Network Systems



Fieldbus e.g.	PROFIBUS, INTERBUS, ControlNet™, sercos the automation bus
Industrial Ethernet e.g.	EtherNet/IP, PROFINET, Modbus, EtherCAT

Industrial communication systems are successfully using POF since more than 20 years.

Environmental conditions

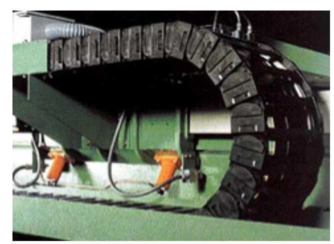
commercial:

MICE	1 = Commercial environment covered by IEC 11801	2 = Light industrial environment	3 = Heavy industrial environment
Mechanical	M_1	M_2	M_3
Ingress	I_1	I_2	I_3
Chemical	C_1	C_2	C_3
EMC	E_1	E_2	E_3

industrial:

Three alternatives:

1. reinforce, e.g. with IP67-components
   ⟹ the trend with local automation
2. Isolation, e.g. with housings
3. seperation, e.g. in seperatet rooms



Tough solutions are required in Industrial applications!

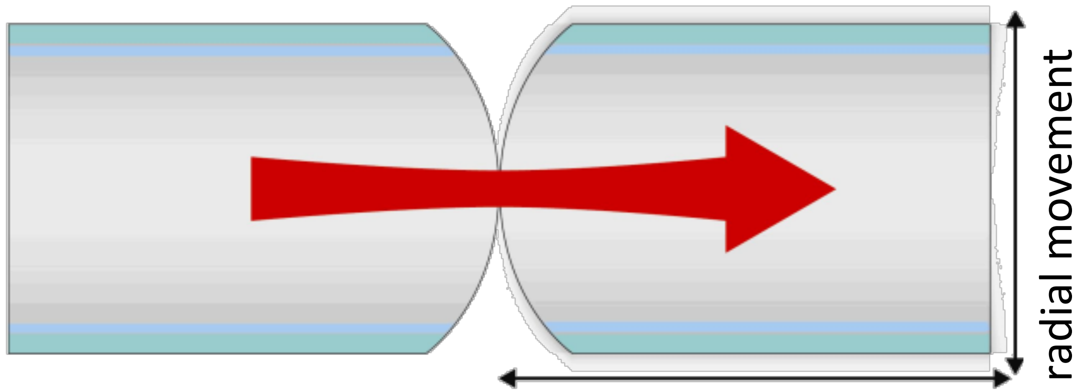
Factors of success of POF in Industrial Networking

Industrial Networking requires:

- EMC-resistant systems
- Environment-resistant systems
- Galvanic isolation
- Easy wiring
- Easy field termination
- Easy planning

POF fulfills the requirements for Industrial applications

Mechanical Characteristics of POF



Fiber displacement caused by:

Shock, Vibration and Temperature

⇒Fiber displacement results in slightly higher attenuation but no loss of connection

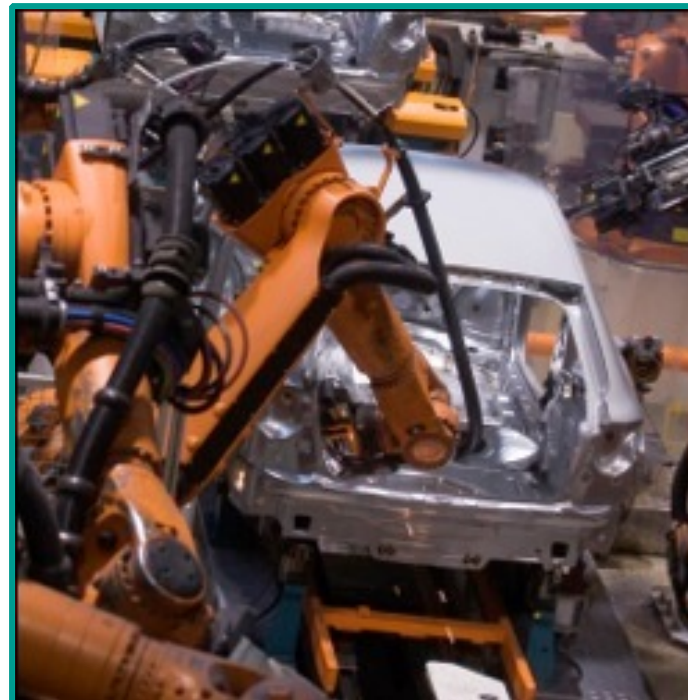
⇒e.g. Radial fber displacement of 100µm would result in a link down for 62.5µm MM fiber but has only a minor attenuation impact to a POF link

POF has excellent bending and torsion properties. Tests have shown that the POF can withstand more than 1000k bending and torsion cycles

POF has mechanical advantages due to the large diameter and material

Example robot cell in automotive industry

- Cable length from the robot to the control cabinet typically 20 m
- Welding tools and drives cause EMC-troubles
- Rough environment
- Field cable termination necessary
- Data- and power cable very close
- Low weight
- Bending/torsion durability of POF
- Monitoring of link quality



POF fulfills the requirements perfectly

Termination of POF-Connectors

Remove cable coating
Pulling boot over wire

Fix connector in the intake

Cut the fiber

Put wires in the boot
Tighten the screws

Remove isolation

Done!

Attenuation max. 1,5 dB

Fast and easy

Reliable process

Field termination possible

Conclusion

Industrial technology has:

- Applications with short link distance

Industrial requires:

- Robust solutions in respect of EMC and harsh environment
- Galvanic isolation
- Easy field cable termination
- Easy rules

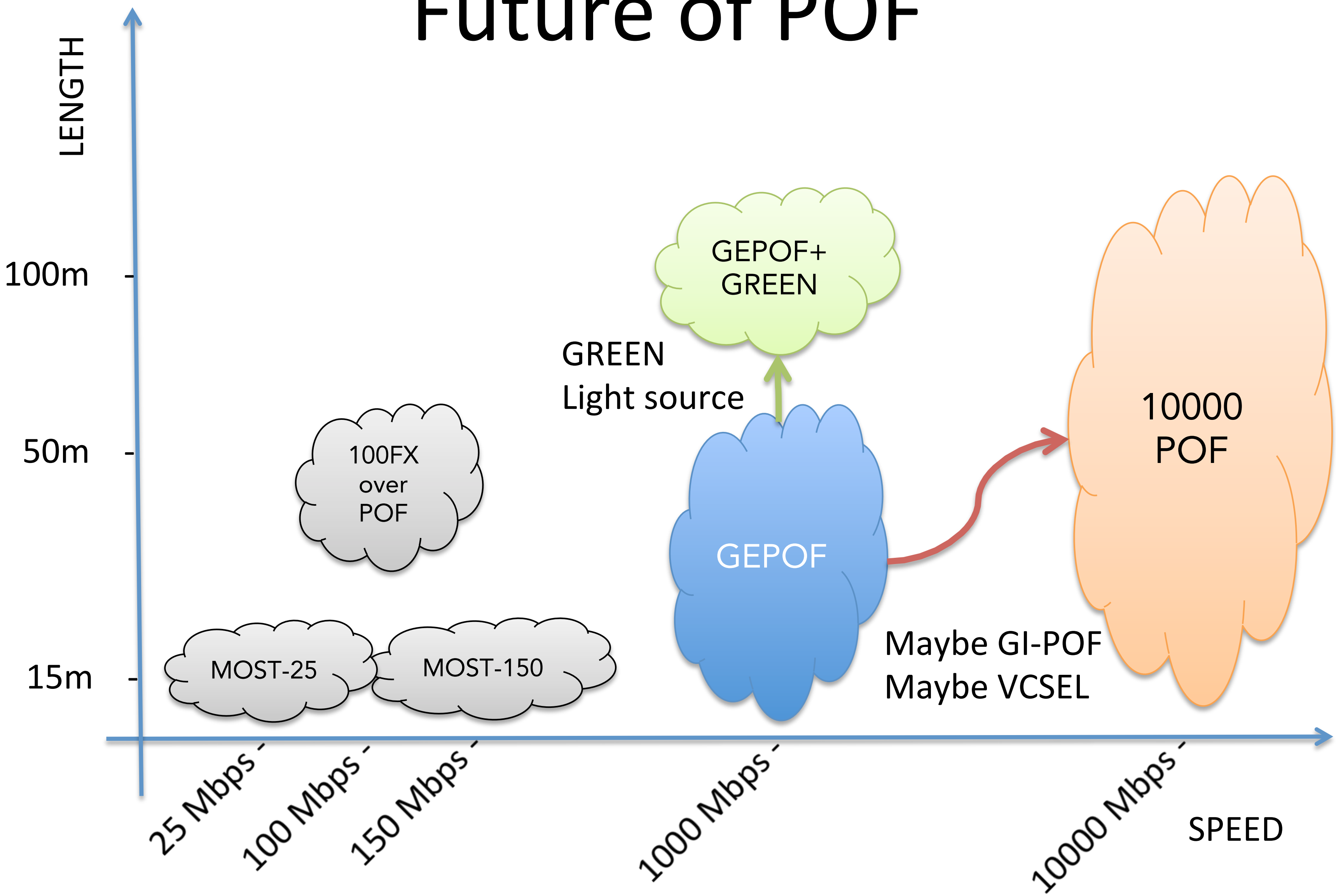
POF is the best choice for communication systems in Industrial networking

SUMMARY

Summary

- Three target markets have different: link length, number of connectors, and environmental constraints
  - All three markets can be addressed by a single PHY
  - Link budget allows for tradeoff of market constraints (e.g., fewer connectors for longer length)
- Royalty Free IEEE LOA from KDPOF
  - Covers technology adopted by VDE project if selected by TF
- IEEE 802.3 is a global standard
  - We need to address global requirements
  - Not all markets have similar opportunities
  - Users and vendors throughout the supply chain want an 802.3 GEPOF standard

Future of POF



Support

Quotes

SUPPORT

Support

Some of the companies encouraging IEEE 802.3 to develop GEPOF:

Home Network

Support

Some of the companies encouraging IEEE 802.3 to develop GEPOF:

Automotive

TOYOTA
HONDA
VOLVO
BMW
JAGUAR
LAND ROVER
RENAULT
DENSO
YAZAKI
Sumitomo
TE connectivity
FURUKAWA ELECTRIC GROUP

Support

Some of the companies encouraging IEEE 802.3 to develop GEPOF:

Industrial and others

SIEMENS
PHOENIX CONTACT
TE connectivity
BOEING
Avago Technologies
MITSUBISHI RAYON
Firecomms
Luceat
AsahiKASEI
HAMAMATSU
hp
TORAY
PoFLink
ALSTOM
KDPOF the knowledge development
BAE SYSTEMS

Quotes

- ***"The in-vehicle gigabit network will definitely be essential in the near future. Automobiles are vulnerable to noise, which is difficult to solve even with electric cables, especially in the Gigabit Ethernet. Thus, it is better to prepare a backup solution and I look forward to optical network standardization. However, cost reduction is a key factor for practical use in the automotive market; therefore, I hope everything goes well."*** Hideki Goto - Group Manager, Toyota Motor Corporation

- ***"Gigabit over POF utilises proven Physical Layer components and harness assembly procedures that are well understood by the automotive industry. For this reason, JLR believe, that such a standardised technology could offer a potentially fast time to market for certain use cases of gigabit Ethernet within the vehicle cabin."*** John Leslie - Communication Systems Technical Specialist, Jaguar Land Rover Limited

Quotes

- ***"… the only way to match expectations between the broadband speed we sell and what the customer perceives it´s the cable. I think POF is a great cable solution."*** Mario Diaz - Director for Home Fiber and broadband Offering, Telefonica

- ***"Vodafone, sees that POF is an easy way to "match expectations" between the broadband speed that we sell and what the customer perceives, potentially avoiding many problems with Wifi connections (and other problems in home networking) in a cost-effective way."*** Juan Manuel Sánchez – Managing Director Vodafone Spain

- ***''In this market, engineers are already using FPGAs to run high speed links with their own protocols for a variety of industrial networking applications over POF. (…) In the telecommunications world companies such as Orange, Telecom Italia, and Swisscom for example have completed trials validating the business case for POF but to move the solution forward they need a GigE solution as GigE is now the technical base line. (…) It would be a cleaner solution if that usage were to a published standard ensuring interoperability and a level commercial playing field and benefiting from the robustness that an IEEE standard provides."*** - Michael O'Gorman VP Marketing Firecomms

QUESTIONS

Optical model for SI-POF

BACKUP SLIDES

Optical model for SI-POF

- Power flow equation (Gogle's eq.):

Differential mode delay

Relative mode delay

Mode mixing

$$\frac{\partial P(\theta,z,t,\lambda)}{\partial z} = -\alpha(\theta,\lambda)P(\theta,z,t,\lambda) - \tau(\theta,\lambda)\frac{\partial P(\theta,z,t,\lambda)}{\partial t} + \frac{1}{\theta}\frac{\partial}{\partial \theta}\left(\theta D(\theta,\lambda)\frac{\partial P(\theta,z,t,\lambda)}{\partial \theta}\right)$$

- P is the optical power distribution in time instant (t), fiber length (z), propagation inner angle respect to fiber axis (θ) and wavelength (λ)
- α is the Differential Mode Attenuation (DMA)
- τ is the Relative Mode Delay (RMD)
- Initial conditions (launching conditions): $P(\theta,0,0,\lambda) = P_0(\theta,\lambda)$
- Boundary conditions to solve PDE:

$$\left.\frac{\partial P(\theta,z,t,\lambda)}{\partial \theta}\right|_{\theta=0} = 0 \qquad \left.P(\theta,z,t,\lambda)\right|_{\theta \to \frac{\pi}{2}} = 0$$

Optical model for SI-POF

- The DMA from steady state Far Field Pattern (FFP) Q(θ) as*:

$$\alpha(\theta,\lambda) = \gamma(\lambda) + \frac{1}{\theta Q(\theta)}\frac{\partial}{\partial\theta}\left(\theta D(\theta)\frac{\partial Q(\theta)}{\partial\theta}\right)$$

  – γ(λ): characteristic attenuation of POF as function of wavelength

- Q may be fitted by bi-sigmoid function*:

$$Q(\theta) = \frac{(1+e^{-\sigma_1^2\theta_1^2})(1+e^{-\sigma_2^2\theta_2^2})}{(1+e^{-\sigma_1^2(\theta_1^2-\theta^2)})(1+e^{-\sigma_2^2(\theta_2^2-\theta^2)})}$$

- The RMD is given by:

$$\tau(\theta,\lambda) = \frac{1}{c}\left(n_{core}(\lambda) - \lambda\frac{\partial n_{core}(\lambda)}{\partial\lambda}\right)\frac{1}{\cos(\theta)}$$

  – c is the vacuum light speed, n_{core} is the refractive index of core

- The diffusion coefficient may be fitted by:

$$D(\theta,\lambda) = \left(D_0 + \frac{D_1}{1+D_2 e^{\sigma_2^2\theta^2}}\right)\left(\frac{\lambda_0}{\lambda}\right)^4$$

(*) Mateo et al., "Global characterization of optical power propagation in step-index plastic optical fibers", Vol. 14, No. 20, OSA (2006)

Optical model for SI-POF

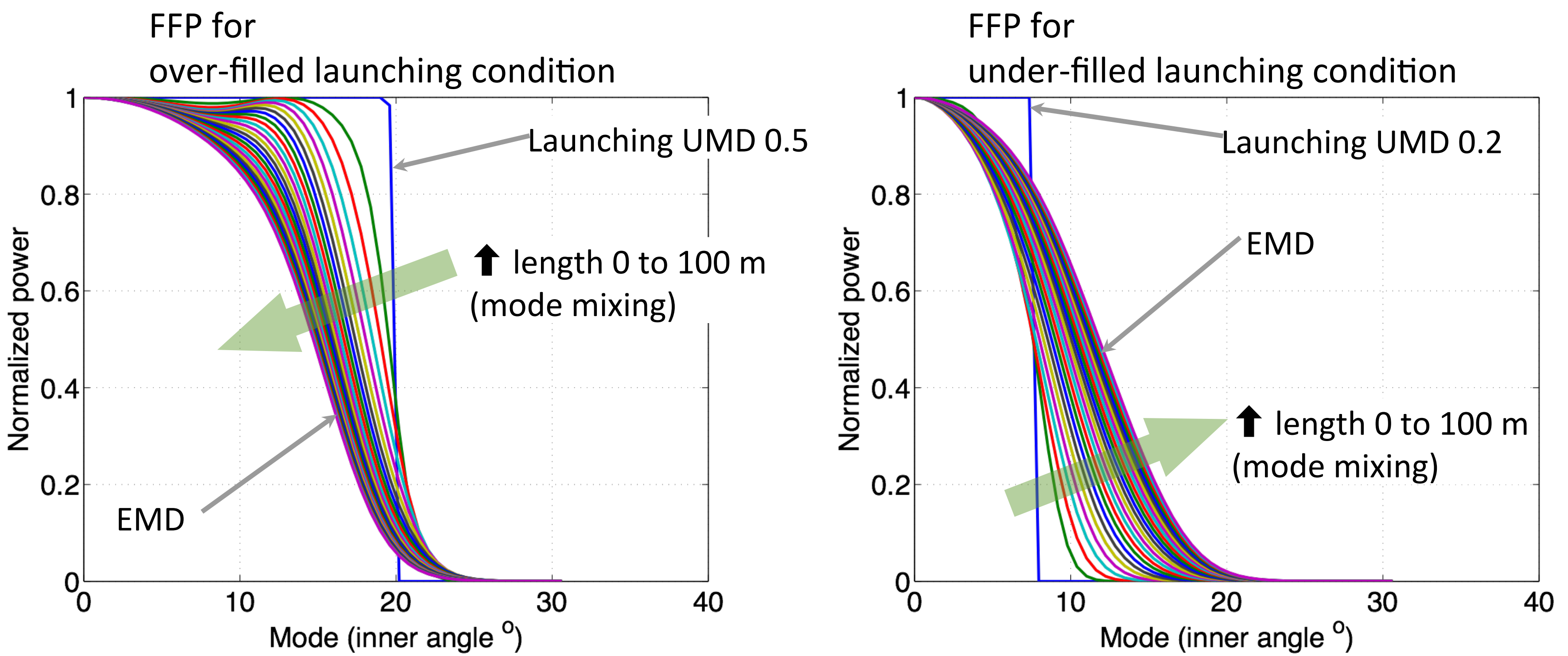
- Impulse response of SI-POF, including modal and chromatic dispersion:

$$I(z,t) = 2\pi\int_{-\infty}^{+\infty} S_{PD}(\lambda)\int_{0}^{\frac{\pi}{2}} \sin(\theta)P(\theta,z,t,\lambda)\eta_{PD}(\theta)\,d\theta d\lambda$$

- where S_{PD} is the sensitivity of photo-detector and η_{PD} is the directivity

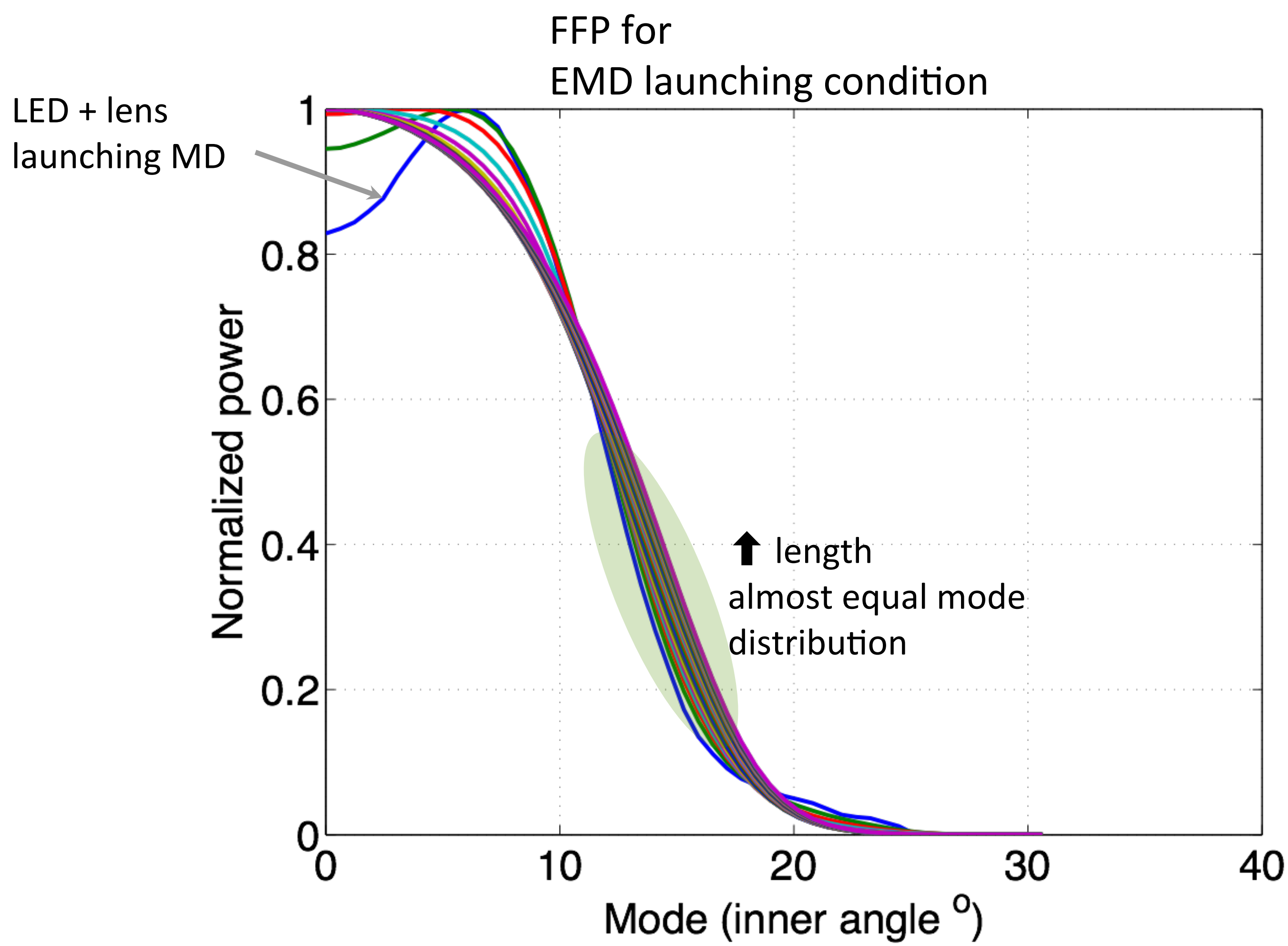
Introduction to POF - mode mixing

Uniform Mode Distribution (UMD)



Introduction to POF - mode mixing

Real LED with almost EMD condition



Effect of mode mixing in Attenuation and Bandwidth