Tutorial: Gigabit Ethernet Over Plastic Optical Fiber (GEPOF)

IEEE 802 plenary session

3 November 2014
Panel

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• 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

SM-GOF for long-distance transmission
- SI - Step-Index
  - core: \( \varnothing 8 \, \mu m \)
  - clad: \( \varnothing 125 \, \mu m \)

MM-GOF for data-centers, office-LAN
- GI - Graded-Index
  - core: \( \varnothing 50 \) or \( \varnothing 62.5 \, \mu m \)
  - clad: \( \varnothing 125 \, \mu m \)

GEPOF target
- 1mm SI-POF multimode NA 0.5
  - core: \( \varnothing 980 \, \mu m \)
  - clad: \( \varnothing 1000 \, \mu m \)
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

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

Area of higher attenuation that produces differential mode att.

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

Differential mode delay

Relative mode delay

Mode mixing
Introduction to POF

PMMA SI–POF characteristic attenuation

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)

![Diagram of mode mixing](image)

- Discontinuities and impurities of PMMA speed up mode mixing
- 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 inner cladding
2 rays, guided by the outer cladding behind the bend
3 rays, guided by the outer cladding over a limited distance
4 not guided rays behind the bend
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

![Graph showing single bending attenuation](image-url)

**Single bending attenuation**

<table>
<thead>
<tr>
<th>Bending radius</th>
<th>Attenuation (dBo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>0.56</td>
</tr>
<tr>
<td>8 mm</td>
<td>0.97</td>
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<tr>
<td>6 mm</td>
<td>1.95</td>
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<tr>
<td>5 mm</td>
<td>2.67</td>
</tr>
</tbody>
</table>

- **Bending at RX**
- **Bending at TX**
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

<table>
<thead>
<tr>
<th>Temp</th>
<th>-40ºC</th>
<th>0ºC</th>
<th>20ºC</th>
<th>70ºC</th>
<th>85ºC</th>
<th>95ºC</th>
<th>105ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOP</td>
<td>-1.8 dBm</td>
<td>-2.5 dBm</td>
<td>-3.0 dBm</td>
<td>-5.2 dBm</td>
<td>-5.8 dBm</td>
<td>-7.0 dBm</td>
<td>-7.5 dBm</td>
</tr>
</tbody>
</table>

- Linearity
  - -20 / -30 dBc typical. (2\textsuperscript{nd} / 3\textsuperscript{rd} 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
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

While keeping BER $< 10^{-12}$

Increase Attenuation

Measure Sensitivity (min power)
Sensitivity for 15m + 4 connections

Sensitivity as function of M levels of PAM

Target by link budget analysis

Symbol rate (MHz)

Sensitivity (dBm)

M = 32
M = 16
M = 8
M = 4
Sensitivity for 50m + 1 connections

Sensitivity as function of M levels of PAM

Target by link budget analysis
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

Driver + LED → POF → Photodiode → TIA → Antialias Filter

POF non-linear channel

\[ x(k) \rightarrow W_{o0} \rightarrow W_{o1} \rightarrow W_{o2} \rightarrow \ldots \rightarrow y(k) \rightarrow n(k) \rightarrow z(k) \rightarrow v(k) \]

POF non-linear channel

Volterra’s series model

\[ n'(k) \rightarrow \rightarrow v(k) \]

Linearized Channel

Linearizer
non-linear filtering
Non linearity - capacity penalty

Capacity penalty caused by the LED non-linear response

Capacity loss < 1dB for $\text{SNR}_e < 30 \text{ dB}$

High spectral efficiency schemes are feasible

Capacity recovery by linearization

Capacity (in detector dB) vs. Channel $\text{SNR}_e$ (in dB)
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
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)

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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:

<table>
<thead>
<tr>
<th>%cases(*)</th>
<th>Cat5/6</th>
<th>Wifi</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>Router Wifi only</td>
<td>-</td>
</tr>
<tr>
<td>20%</td>
<td>Router Wifi + STB/PC in the same room</td>
<td>OK</td>
</tr>
<tr>
<td>10%</td>
<td>Router Wifi + STB/PC in the same room</td>
<td>X(1))</td>
</tr>
<tr>
<td>25%</td>
<td>Router Wifi + STB/PC in other room/s</td>
<td>OK</td>
</tr>
<tr>
<td>15%</td>
<td>Router Wifi + STB/PC in other room/s</td>
<td>OK</td>
</tr>
<tr>
<td>10%</td>
<td>Router Wifi + STB/PC in other room/s</td>
<td>X(1)</td>
</tr>
</tbody>
</table>

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

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

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<td>OK</td>
</tr>
<tr>
<td>10%</td>
<td>X(1)</td>
<td>OK</td>
</tr>
<tr>
<td>25%</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>15%</td>
<td>OK</td>
<td>X(2)</td>
</tr>
<tr>
<td>10%</td>
<td>X(1)</td>
<td>OK</td>
</tr>
</tbody>
</table>

STB = Set Top Box

**35% POF Opportunity (aprox).**

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

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Population EU</th>
<th>Total households EU</th>
<th>Population HBB EU</th>
<th>Households HBB EU</th>
<th>POF Opportunity Households</th>
<th>POF Opportunity connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>507,416,607</td>
<td>219,203,974</td>
<td>29,430,163</td>
<td>12,713,831</td>
<td>4,449,841</td>
<td>17,799,364</td>
</tr>
<tr>
<td>2015</td>
<td>508,273,750</td>
<td>219,574,260</td>
<td>36,595,710</td>
<td>15,809,347</td>
<td>5,533,271</td>
<td>22,133,084</td>
</tr>
<tr>
<td>2016</td>
<td>509,130,893</td>
<td>219,944,546</td>
<td>48,367,435</td>
<td>20,894,732</td>
<td>7,313,156</td>
<td>29,252,624</td>
</tr>
<tr>
<td>2017</td>
<td>509,988,036</td>
<td>220,314,831</td>
<td>57,118,660</td>
<td>24,675,261</td>
<td>8,636,341</td>
<td>34,545,364</td>
</tr>
<tr>
<td>2018</td>
<td>510,845,178</td>
<td>220,685,117</td>
<td>73,561,706</td>
<td>31,778,657</td>
<td>11,122,530</td>
<td>44,490,120</td>
</tr>
<tr>
<td>2019</td>
<td>511,702,321</td>
<td>221,055,403</td>
<td>89,547,906</td>
<td>38,684,695</td>
<td>13,539,643</td>
<td>54,158,572</td>
</tr>
<tr>
<td>2020</td>
<td>512,559,464</td>
<td>221,425,689</td>
<td>102,511,893</td>
<td>44,285,138</td>
<td>15,499,798</td>
<td>61,999,192</td>
</tr>
</tbody>
</table>

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

• European retrofit and new houses
  – 3 M households per year

• Latin America
  – New construction in Mexico, Chile, etc. requires low training 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

- Process time reduction: 9.3%
- Smaller Bend Radius: 12.0%
- Easier connection: 14.7%
- Lower parts cost: 14.7%
- No special skill requirement: 49.3%
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

<table>
<thead>
<tr>
<th></th>
<th>RTPGE</th>
<th>GIG-POF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>EMI/EMC</td>
<td>✓</td>
<td>✓✓✓</td>
</tr>
<tr>
<td>Galvanic Isolation</td>
<td>✓</td>
<td>✓✓✓</td>
</tr>
<tr>
<td>Temperature</td>
<td>✓✓</td>
<td>✓</td>
</tr>
<tr>
<td>Length</td>
<td>✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Cost</td>
<td>✓✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
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

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

<table>
<thead>
<tr>
<th>Year</th>
<th>LAN (POF)</th>
<th>D2B</th>
<th>MOST 25</th>
<th>MOST 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
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<td>1990</td>
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<tr>
<td>2000</td>
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<td>2010</td>
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<td>2020</td>
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</table>

- Peer to peer
- 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

Features of Optical Components

- 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

<table>
<thead>
<tr>
<th>Problems</th>
<th>Team</th>
<th>Assignment</th>
<th>Standardization</th>
</tr>
</thead>
<tbody>
<tr>
<td>No simulation tools of the system design for O-GEAR</td>
<td>Toyota Central R&amp;D Labs.</td>
<td><strong>Design Tool Development</strong></td>
<td><strong>OITDA (Project administrator) 9 companies</strong></td>
</tr>
<tr>
<td>No bandwidth guaranteed harness and connectors in high speed, 1 Gpbs - 10 Gbps</td>
<td>Utsunomiya University 5 companies</td>
<td><strong>Physical Layer Development</strong></td>
<td><strong>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.</strong></td>
</tr>
<tr>
<td>Required reliable system which target is similar to FlexRay, BER $10^{-12}$@10 Mbps</td>
<td>AIST (a national institute) 6 companies</td>
<td><strong>System Demonstration</strong></td>
<td><strong>Promoted by METI Japan</strong></td>
</tr>
</tbody>
</table>

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.

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.

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.
## Schedule, In-vehicle Gigabit Ethernet

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<tbody>
<tr>
<td><strong>Automotive</strong></td>
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<td>1 G bps Car</td>
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<td>1 G bps Cars</td>
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<td>Development for mass production</td>
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<td>Product release</td>
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<td><strong>O-GEAR</strong></td>
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<td>(Japan)</td>
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<td>1 G bps Demonstration</td>
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<td></td>
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<td>Support</td>
<td>Conformance Test Office</td>
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<td><strong>IEEE802.3</strong></td>
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<tr>
<td>Ethernet for Automotive</td>
<td></td>
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<td></td>
<td>1 G bps Ethernet Std.</td>
<td></td>
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<td></td>
<td></td>
<td>IEC/ISO Standards</td>
<td></td>
</tr>
</tbody>
</table>
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

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

POF is the best optical solution for short distances and has easy termination.

POF: Polymer Optical Fiber
PCF: Photonic Crystal Fiber
GOF-MM: Gigabit Optical Fiber Multimode
GOF-SM: Gigabit Optical Fiber Singlemode

<table>
<thead>
<tr>
<th>POF</th>
<th>Absorption [db/km] with λ [nm]</th>
<th>Core diameter [μm]</th>
</tr>
</thead>
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<td>230, 660</td>
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<tr>
<td>6, 850</td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

IEC 60793-2: International Electrotechnical Commission Standard
Evolution of POF based Industrial Automation Network Systems

- Fieldbus
  - POF 70m
  - ~1990

- Industrial Ethernet
  - POF 50m
  - ~2000

- Industrial
  - Gbit Ethernet
  - POF 50m
  - ~2015

Needed and wish from the industry

Volume is 1Mio nodes per year

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

Fieldbus e.g.

- PROFINET
- Interbus
- ControlNet™
- Profinet
- Sercos

Industrial Ethernet e.g.

- EtherCAT
- EtherNet/IP
- Modbus
- PROFINET
- PROFI

November the 3rd 2014
Environmental conditions

**commercial:**

<table>
<thead>
<tr>
<th>MICE</th>
<th>1 = Commercial environment covered by IEC 11801</th>
<th>2 = Light industrial environment</th>
<th>3 = Heavy industrial environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>M₁</td>
<td>M₂</td>
<td>M₃</td>
</tr>
<tr>
<td>Ingress</td>
<td>I₁</td>
<td>I₂</td>
<td>I₃</td>
</tr>
<tr>
<td>Chemical</td>
<td>C₁</td>
<td>C₂</td>
<td>C₃</td>
</tr>
<tr>
<td>EMC</td>
<td>E₁</td>
<td>E₂</td>
<td>E₃</td>
</tr>
</tbody>
</table>

**industrial:**

Three alternatives:

1. **reinforce**, e.g. with IP67-components
   ⇝ the trend with local automation
2. **Isolation**, e.g. with housings
3. **separation**, e.g. in separate 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 fiber 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

1. Remove cable coating
2. Pulling boot over wire
3. Cut the fiber
4. Remove isolation
5. Fix connector in the intake
6. Put wires in the boot
7. Tighten the screws

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

• 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 train want an 802.3 GEPOF standard
Future of POF

LENTH

100m

50m

15m

SPEED

25 Mbps - 100 Mbps - 150 Mbps -

1000 Mbps -

10000 Mbps -

GEPOF

GEPOF+
GREEN

GREEN
Light source

MOST-25

MOST-150

100FX
over
POF

Maybe GI-POF
Maybe VCSEL

10000
POF
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

DENSO

YAZAKI

Sumitomo

TE

ofS
Support

Some of the companies encouraging IEEE 802.3 to develop GEPOF:

*Industrial and others*
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 - , 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 the best cable solution is POF.” 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.):

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

• \( P \) is the optical power distribution in time instant (t), fiber length (z), propagation inner angle respect to fiber axis (\( \theta \)) and wavelength (\( \lambda \))

• \( \alpha \) is the Differential Mode Attenuation (DMA)

• \( \tau \) is the Relative Mode Delay (RMD)

• Initial conditions (launching conditions): \( P(\theta,0,0,\lambda) = P_0(\theta,\lambda) \)

• Boundary conditions to solve PDE:

\[
\left. \frac{\partial P(\theta,z,t,\lambda)}{\partial \theta} \right|_{\theta=0} = 0 \quad P(\theta,z,t,\lambda)\bigg|_{\theta=\frac{\pi}{2}} = 0
\]
Optical model for SI-POF

• The DMA from steady state Far Field Pattern (FFP) $Q(\theta)$ as*:

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

  - $\gamma(\lambda)$: characteristic attenuation of POF as function of wavelength

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

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

• The RMD is given by:

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

  - $c$ is the vacuum light speed, $n_{\text{core}}$ is the refractive index of core

• The diffusion coefficient may be fitted by:

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

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 $\eta_{PD}$ is the directivity
Introduction to POF - mode mixing

**Uniform Mode Distribution (UMD)**

![Graphs showing mode mixing and uniform mode distribution](image-url)
Introduction to POF - mode mixing

Real LED with almost EMD condition

LED + lens launching MD

FFP for EMD launching condition

Normalized power

Mode (inner angle °)

↑ length almost equal mode distribution
Effect of mode mixing in Attenuation and Bandwidth

Optical power attenuation of SI–POF

- Over–filled
- Under–filled
- EMD

E–to–E bandwidth (–3dB) of SI–POF

- Over–filled
- Under–filled
- EMD

Length(m)

E–to–E –3dB BW (MHz)

0 10 20 30 40 50 60 70 80 90 100

Attenuation (dB)

0 5 10 15 20

November the 3rd 2014

IEEE 802 Tutorial on Gigabit over Plastic Optical Fiber