TECHNICAL REPORT

World's First Service Trial of ITU-T G.hn over Plastic Optical Fibre (POF)

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Executive abstract

We demonstrate the world’s first multi-service transmission trial over a bidirectional passive optical network topology utilizing ITU-T G.9960 G.hn technology and 1 mm core diameter standard step-index plastic optical fibre (POF). A full-scale fibre-to-the-home / fibre-in-the-home (FTTH/FITH) network scenario is shown. Commercial products are employed in this trial to successfully deliver triple-play (voice, data, and video) services to the user premises and therefore confirming the potential at short- and long-term customer service requirements in the home.

1. Introduction and drivers for plastic optical fibre networks

With fibre-to-the-home (FTTH) as the main driver, the abundant availability of bandwidth in the local loop presents the next challenge for network operators: how to distribute Internet protocol (IP) services to devices inside the user premises. We updated the empirical *Nielsen’s Law of Internet Bandwidth*[1] with recent global market figures that were gathered from public press [1]. This is shown in Figure 1.

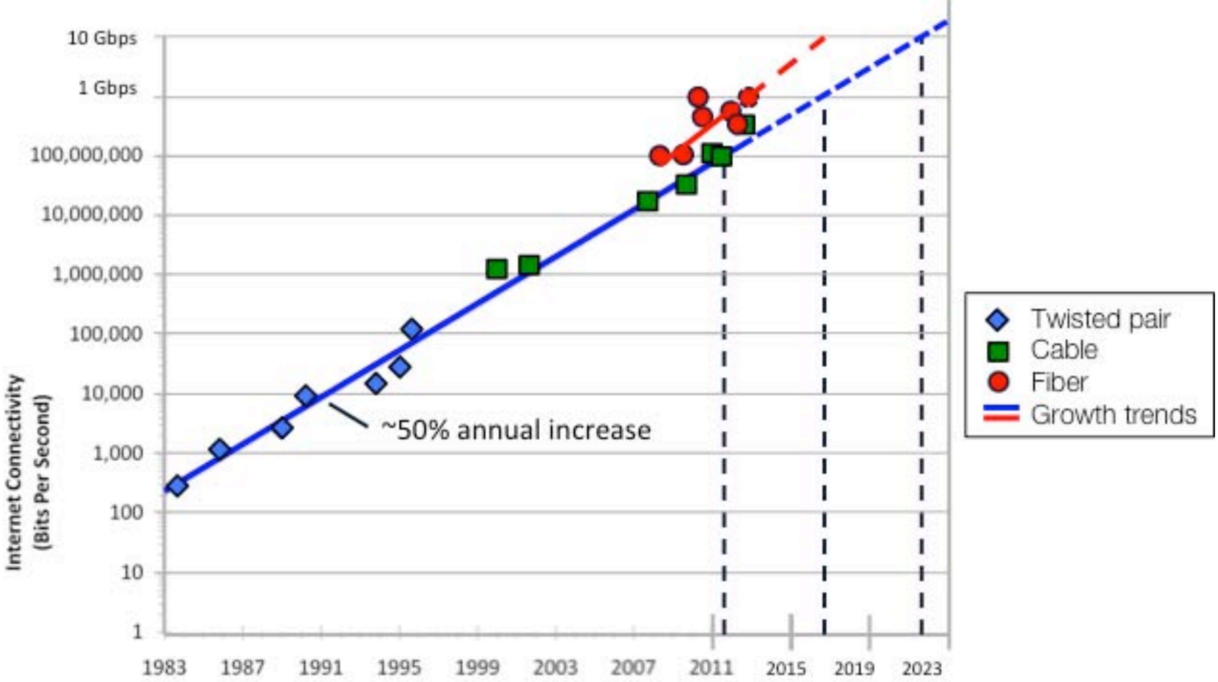


Figure 1: Updated Nielsen’s law of available bandwidth per user (from [1])

The 50% annual growth in bandwidth offerings has not slowed down for the past 30 years, and global IP traffic has increased eightfold over the past 5 years and will increase nearly fourfold over the next 5 years [2]. Interestingly, the FTTH operators are pushing bandwidth to the home at an even higher rate. It can be expected that 1 Gb/s to the user premises is a commodity in 2015 while at 2017 we could see rates up to 10 Gb/s appearing for the high-end users.

The current in-home networking technologies, based on copper or wireless, cannot meet the high capacity and quality of service (QoS) requirements. Link reliability is often the main issue that leads to increased service calls and thus higher operational expenses for the operator. It is likely that the user is required to modify the installed cabling, and the end-terminal placement, such as the customer premises equipment (CPE), is not flexible. Cost-effective and self-installation of the CPE and in-home cabling is a significant benefit for FTTH operators such as Telefónica. A relevant percentage of surveyed customers would be willing to use Ethernet over POF, being POF a suitable medium for easy and cost-effective self-installation, which can save more than one hour of OPEX to operators per home.

Fibre-in-the-home (FITH) is deemed future-proof and promising, in particular when the technology is based on standard step-index 1 mm core diameter plastic optical fibre (SI-POF). It offers many benefits such as “do–it–yourself” installation, no electro-magnetic interference (EMI), and tolerance to bending. Moreover, SI-POF can be

[1] Nielsen’s Law of Internet Bandwidth [Online]. http://www.useit.com/alertbox/980405.html. Last accessed: 15 November 2012

cost-effectively produced and multiple manufacturers can provide such fibre.

The HomeGrid Forum held a recent survey amongst service providers. It showed that in-home networking technologies must support the following: multicast, up to 4 high-definition (HD) streams, co-existence with other network domains and installed technology base, green features, remote management, security, and CPE certification [3]. On the other hand, studies of the real end-users behaviours show that it is a typical case now to have up to three TV screens at home, one or two computers or handheld devices connected to Internet, and some internal traffic for backup or media sharing. So, the proposed service scenario has three HD video streams, two Internet traffic services (web browsing and YouTube), and, on the top of all that, peer to peer traffic. Using typical data from services used today (see Table 1), this means a total of up to 70 Mb/s of traffic in the home area network (HAN).

Table 1: Typical values for describing today’s services [4]

Service	Bit rate	Delay	Jitter	Packet Loss
Internet	1 - 10 Mb/s	Relaxed specification	< 10 ms	None (BER<10^{-8})
IPTV	2 – 10 Mb/s (for HD)	< 400 ms; 200 ms recommended	< 50 ms	< 1% <0.1% recomm.
File sharing (peer-to-peer)	1 Mb/s - 20 Mb/s	Relaxed specification	< 10 ms	None (BER<10^{-8})

If the quality of the services is higher or the content is sent less compressed, it will be necessary to have a Gb/s link instead of a 100 Mb/s. Gigabit speed will also be essential for customer cloud storage, making the download of large multimedia files as fast as a transfer from a hard drive. This is considered to be a medium-long term scenario. Also, the number of IP-enabled devices in the home is expected to be more than 10 in a few years time.

A previous study evaluated 12 different home networking devices covering most commercially available home networking technologies in an extensive lab test environment at Telefónica I+D [5]. It was demonstrated through QoS and quality of experience (QoE) experiments that the current state of the in-home network is not sufficient to support short-term and long-term services. On the other hand, in-home fibre networks based on POF provide an attractive alternative for in-home service distribution.

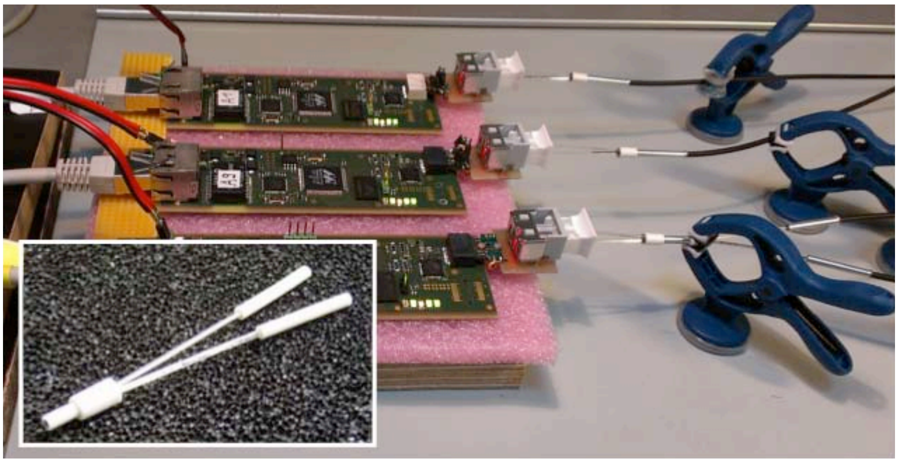
The ITU-T G.hn standards family matches the aforementioned requirements for home area networking. Major service providers and silicon vendors are strongly developing its market potential. It is worth mentioning that G.hn supports coax, phone and power line, and, recently, SI-POF was added in Annex F of [6]. It is therefore a versatile standard that allows for migration scenarios. One may therefore start or migrate towards fibre-based in-home networks using G.hn.

In this technical report, point-to-multi point (PTMP) and bidirectional transmission results are shown, for the first time ever, of using G.hn over large core SI-POF. The experimental setup comprises an end-to-end triple-play service delivery scenario using all commercial products over a combined FTTH and FITH network.

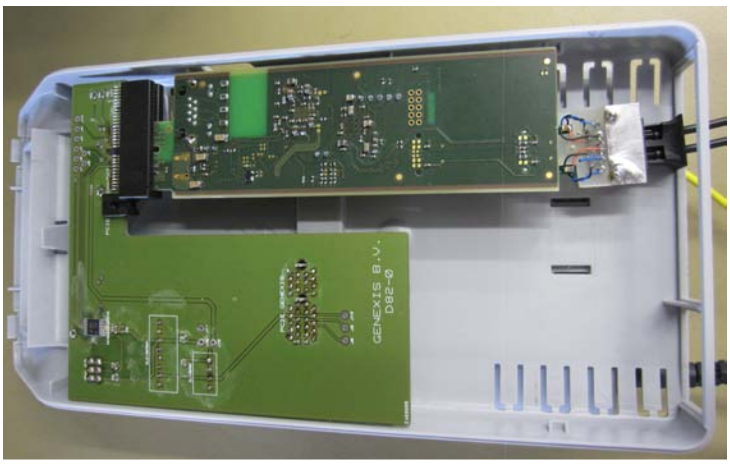
2. ITU-T G.hn over 1 mm step-index plastic optical fibre (SI-POF)

Commercially POF data network systems are based on 4B5B NRZI Fast Ethernet modulation. In order to increase bit rates up to 1 Gb/s, established modulation schemes like 8B10B 1 Gb/s Ethernet and novel modulation schemes like discrete multi-tone (DMT)/orthogonal frequency division multiplexing (OFDM), pulse amplitude modulation (PAM) 16 TH are proposed and developed. The ITU G.hn employs OFDM modulation. Each proposed system has its advantages, and in order to cope with such diversity a novel pluggable system was designed: the omniPOF™[2] approach [7]. The basic idea is the use of pluggable, modular electronic units including the optical POF transceiver that fit into a standard interface of electronic equipment like media converters, switches and routers. Depending on the required modulation scheme, various modules can be used without the need to substitute the electronic backplane.

The omniPOF™ concept defines a universal module from a mechanical and an electrical point of view. The module is used as a stand-alone unit or as a pluggable module, whereby the mechanical and electrical parameters of both are the same. Various omniPOF™ modules provided the G.hn over SI-POF functionality in this trial as depicted in Figure 2.



(a) Stand-alone media converter (PON case); inset: 1:2 POF splitter



(b) Pluggable module integrated in a Genexis Hybrid FTTH gateway

Figure 2: omniPOF™ implementation of POF FITH G.hn

[2] omniPOF is a registered trademark of the German High Speed POF project consortium

A selection of the optical transmitter (TX) and receiver (RX) G.hn specifications is shown in Table 2.

Table 2: SI-POF G.hn optical specifications [6]
(λ: Wavelength, $\Delta\lambda$: Spectral width)

λ_{center}	640-660 nm
$\Delta\lambda_{max}$	30 nm
$P_{TX,max}$	0 dBm
$P_{RX,min}$	-20 dBm

The resonant-cavity light emitting diode (RC-LED)-based TX powers used for the optical signal generation complies with eye safe output power levels. The physical medium dependent (PMD) sub-layer of G.hn is based on OFDM. The OFDM band plans are specified as well in [6]. A selection of parameters is shown in Table 3 for the two SI-POF profiles.

Table 3: SI-POF G.hn band plans (N_{SC}: Number of sub-carriers, F_{SC}: Sub-carrier spacing, B: Bandwidth)

Profile name	100 MHz – SB	200 MHz - SB
N_{SC}	512	1024
F_{SC} [kHz]	195.3125	195.3125
B [MHz]	100	200

It is important to note that 200 MHz-SB band plan provides an aggregated rate above 1 Gb/s, including a forward error correction (FEC) overhead. Each OFDM sub-carrier is modulated individually with *M*-ary quadrature amplitude modulation (QAM) for highest and adaptive data throughput.

3. Considerations on POF installation in residential homes

Currently, installation of the optical termination point (OTP) of FTTH customers can take around 15% of the total customer connection time. That percentage is increased up to 30% when the cabling for IPTV set-top-boxes (STB) is done as well. In the latter case, the POF approach can significantly reduce the customers’ connection time by increasing cabling cost-efficiency.

In PON massive deployments, the optical network termination (ONT), residential gateway (RG), and other end-user terminals such as STBs are generally installed at a different instant and by different technicians (or even by the customer in case of self-installation kits) than the fibre termination point. The optimal location of the RG inside the customer premises can be far away from the ONT and can change with time. For example, some FTTH customers can even ask for an OTP re-installation to a different room. This can lead to cabling difficulties and high cost when using copper-based cables to connect the ONT and RG. A POF in-home network solves this restriction as it saves cable cost, reduces installation time, and it even allows the self-installation and reconfiguration by the customer.

There are some considerations to be made when designing and installing an in-building POF network. Let us assume that a typical residence for the large majority of the population does not have more than 5 rooms, namely 1 living room, 1 kitchen, and 3 bedrooms. The fastest way to deploy a fibre network in the home is to use external wiring or on-the-wall mounted ducts. Deployment using buried ducts in the home leads to a solution that is protected from external effects such as customer tampering. Intuitively, installation of fibre using buried ducts is more labour intensive than placing ducts on the wall. Several different commercially available options are presented in [8], and evaluated for a scenario typically encountered in the USA.

POF, and optical fibre in general, allows to reuse the electricity tubes because of its small cable size and, most importantly, due to its invariance to electro-magnetic interference. Furthermore, it is useful to integrate a fibre outlet with a power outlet so the networked end-user device receives powering next to the access to connectivity. A fibre or power pass-through should be used to externally connect devices to a shared outlet; however, ideally, more than one connectivity and power outlet should be present per room.

A cost comparison is made in [9] between the kinds of installed ducts considering CAT-5E, simplex multi-mode glass fibre (MMF) and simplex POF cables. The results are shown in Figure 3.

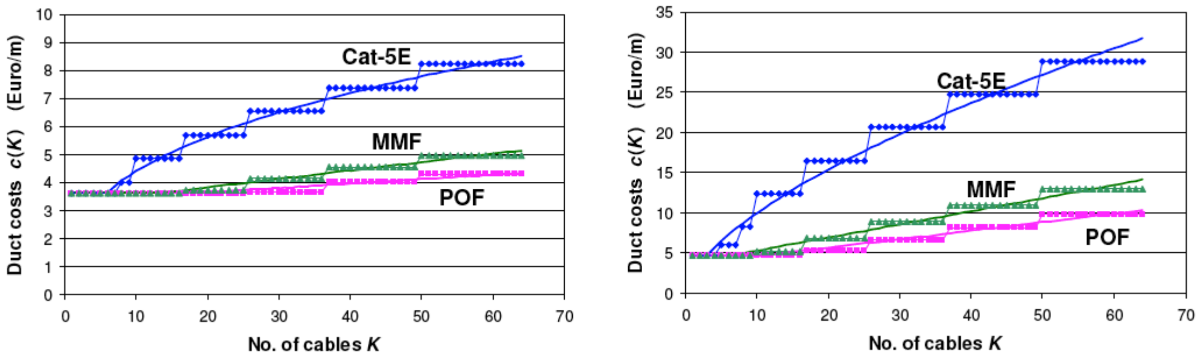


Figure 3: Costs of installed ducts; on-the-wall mounted (l.) and buried (r.) (from [9])

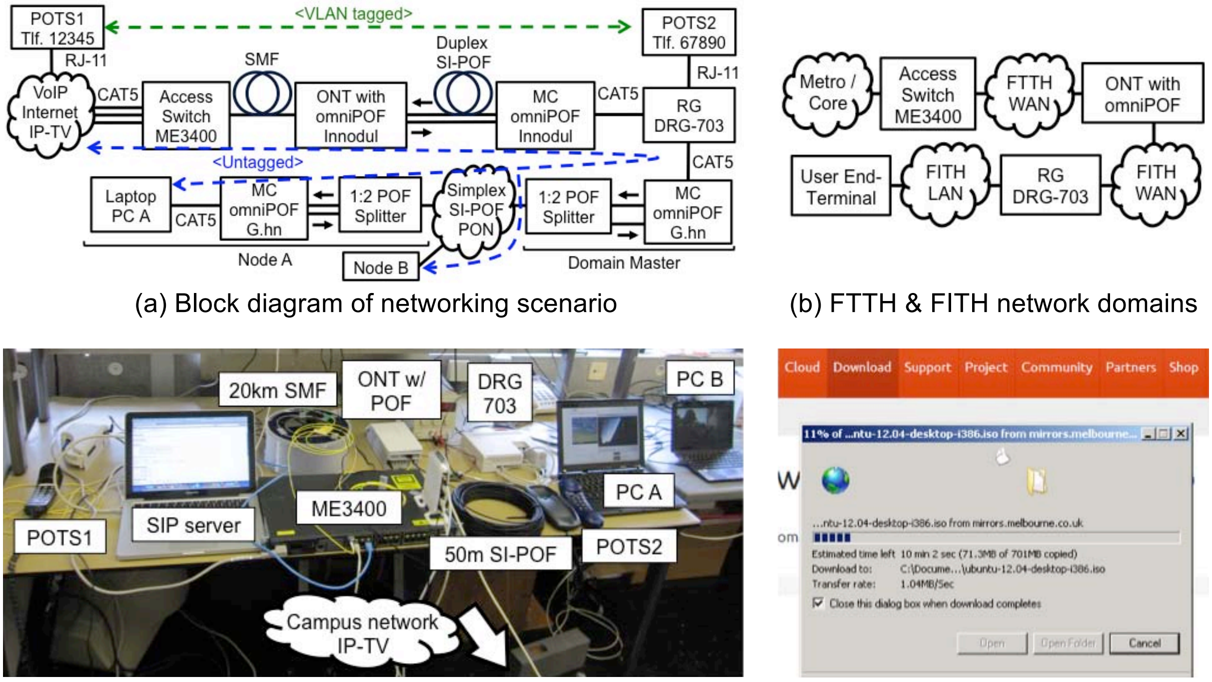
The installation cost for POF is lowest and, considering a few cables per duct, the difference between buried and on-the-wall mounting is not so significant.

Regarding the architecture, the FITH network can be deployed in a point-to-point (PTP) or point-to-multi point (PTMP) fashion to offer multiple POF outlets per room. In the PTMP case, a single POF cable is split at an intermediate node that is either active, i.e. requires powering, or passive. Finally, the PTMP architecture follows either a bus or a tree-and-branch configuration. The well-known PTP versus PON arguments hold in the residential space as well. Here, we consider a simplex POF PON in-home network for a low connector count at the gateway, a passive splitting node, and lowest cable count throughout the home.

To the best of our knowledge, G.hn is currently the only POF technology that supports PTMP communication. A G.hn network is organized into one or more domains that each consists of several nodes. Each domain can be set to one of the following modes: peer-to-peer, unified, and centralized. The latter is employed in the POF PON: a so-called domain master is the single relay node that coordinates all other nodes in the same domain. The domain master is located at the RG in the trials that are described in the next section.

4. Experimental setup and results

The network scenario is shown in Figure 4(a). Firstly, we describe the services and subsequently the setup. Then, the results are shown and analysed.



(a) Block diagram of networking scenario (b) FTTH & FITH network domains

(c) Trial setup with the POF PON located on table to the right (d) File download from Internet

Figure 4: Triple-play and bidirectional service delivery over an FTTH SMF and FITH POF network

The triple-play services are in the cloud shape, and the voice-over-IP (VoIP) service is sent via a virtual LAN (VLAN) tag following IEEE 802.1Q. The tag is removed at the residential gateway (Genexis model DRG-703). The Internet and IPTV data services are sharing an untagged data path and IEEE 802.1p is used for the priority settings. An Ethernet access switch (Cisco model ME3400) provides the connection between the standard single-mode fibre (SMF) link of length 20 km (type Draka BendBright-XS) and the service cloud that includes a live connection to the campus network of the Eindhoven University of Technology.

The optical network termination (ONT) depicted in Figure 4(a) is the device shown in Figure 2(b). It employs the 1000BASE-BX10 standard to communicate with the switch. We decided to implement a FITH WAN (Figure 4(b)) as well in this trial by using a second POF PHY available in the market. At the ONT, the integrated omniPOF™ module has the Innodul ID200 PHY on board that uses Firecomms' IDL300T digital optics. A similar Innodul-based media converter is placed at the end of a 50 m duplex SI-POF link (type Sojitz TC-1000W), which has the DRG-703 connected via 1000BASE-T. This scenario shows the option of using a POF backbone to allow a physical separation of the ONT and RG. In the future, it is desired to have the POF port integrated at the WAN-side of the RG instead of having a separate media converter.

The FITH LAN (Figure 4(b)) is established by three omniPOF™ G.hn media converters, which are all equipped with state-of-the-art analogue optics FC1000T from Firecomms. Four standard 1:2 POF splitters from DieMount (see inset Figure 2(a)) are used to build the 1:2 simplex POF PON. Short strands of POF were used to interconnect the POF PON splitters. The reader should note that this is a hero experiment and longer distances and higher split rates are expected to be feasible.

The trial setup is largely shown in Figure 4(c). The authors note that not enough omniPOF™ modules and 1:2 POF splitters were available in order to fully demonstrate the FITH WAN and LAN in simplex SI-POF and with only G.hn technology. At the end, homogeneity in the home is the goal; however, the results of this trial show that diversity can be easily supported in the home.

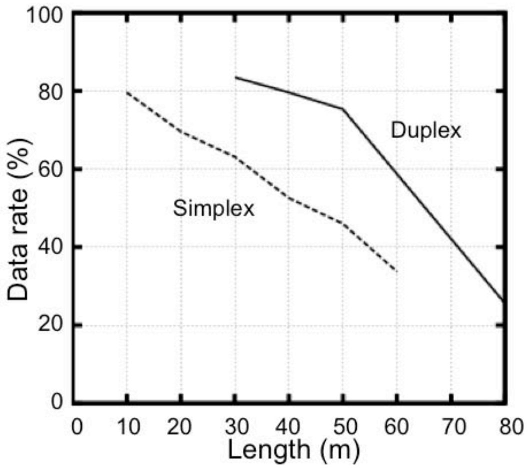
The Innodul’s non-return to zero (NRZ) link was analysed firstly following RFC 2544 [10]. The measured throughput was 192 Mb/s using a 1518 Bytes Ethernet frame size. The transmitted optical powers by the three G.hn nodes are -2.4 dBm, -3.1 dBm, and -2.6 dBm, respectively, for the domain master, Node A and Node B. The received optical powers are -10.9 dBm and -11.8 dBm at the inputs of Node A and B. Due to the prototype status of the provided G.hn chipsets, the band plans as shown in Table 3 were not yet available. Therefore a special coax profile was used that ranges from 2-80 MHz and uses 3202 sub-carriers with 24.41 kHz spacing.

Two high-definition (HD) 1080i video streams of 20 Mb/s were sent downstream using the VLC application. Each PC received a single stream without visual disturbances. In the other direction, Node A streamed a 15 Mb/s HD video to a receiver in the services cloud. At the same time, a YouTube movie was watched or a file was downloaded from the Internet. In the latter case, an 8 to 10 Mb/s download rate was obtained as shown in Figure 4(d). Lastly, a voice call was made at the same time between plain old telephone service (POTS) devices as shown in Figure 4(a).

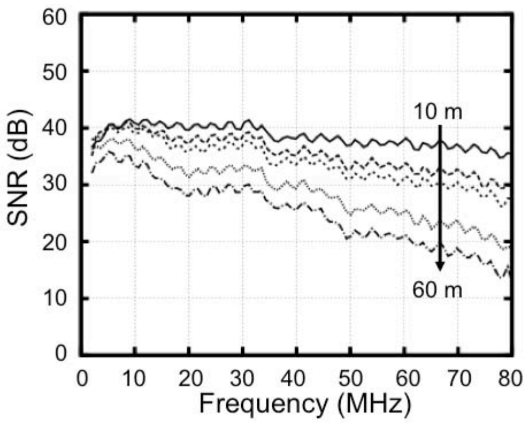
The analysis tool that came with the G.hn chipset had not yet been prepared to characterize a PTMP network scenario. As a result, only PTP link measurements are shown for different lengths of simplex and duplex POF. The focus here is on the impact of increasing POF length rather than reporting measured bit rates. Not only were prototypes used in this trial, the used band plan was not the one specified for POF, and the analogue optics still require enhancements for optimal performance. Gigabit operation of optical G.hn is found feasible. The presentation of detailed measurement results for an optimized system is part of future experiments.

Figure 5(a) shows the data rate versus POF length, in case of simplex and duplex PTP links. The 0 meters (or: 100%) reference data point refers to a direct electrical connection using twisted pair. The lower performance of simplex POF compared with duplex POF is due to a decrease in link budget of about 8 dB because of two cascaded 1:2 POF splitters.

The overall performance degradation can be attributed to non-optimal driving conditions that we had for the Firecomms resonant-cavity LEDs: automatic gain control is not yet implemented and the transmitter is always on. Hence, the RX saturates at low transmission distances or more optical noise is present. Future releases of G.hn hardware will address these limitations. The signal to noise ratio (SNR) is measured at the optical RX as shown in Figure 5(b) for the simplex case of Figure 5(a). The low SNR at long distances leads to a low transmission rate as shown in Figure 5(a).



(a) Data rate vs. POF length, simplex and duplex



(b) SNR at RX, simplex POF (10 m steps, 40 m not done)

Figure 5: Characterization of G.hn PTP POF links

5. Conclusions

Solutions based on G.hn over SI-POF provide a promising and future-proof approach to solve bandwidth and connectivity issues in the home. The demonstrated capability of delivering multiple services to multiple devices addresses the short-term needs for fibre network operators.

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