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Prospects and roadmaps for the transport of wireless and wired signals over optical fibres

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Abstract

This white paper provides an overview of key results in optical transmission achieved within the ALPHA project. The prospects and roadmaps for optical Orthogonal Frequency Division Multiplexing (OOFDM) and Radio-over-Fibre (RoF) technologies for single-mode and multi-mode fibres are described along with the latest results and a roadmap for the solutions based on large-core plastic optical fibres.

Keyword list – Optical transmission, optical OFDM, real-time OOFDM transceivers, Radio-over-Fiber, Plastic Optical Fiber, Gigabit POF, High-capacity POF

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Introduction

The fast development of new broadband telecommunication services pushes developing and upgrading of the access infrastructure as a necessity. Emerging video-based services and advanced Internet applications among others require that customers in the access and in the in-building domains have the availability of a platform capable of delivering higher bit rates with significant bandwidth efficiency. In the ALPHA project, different transmission solutions have been proposed and demonstrated over different transmission media, such as single-mode (SMF), multi-mode (MMF) or plastic optical fibres (POF). A big effort has been put in developing new transmission and shared-access techniques to improve the performance of the future networks and adapt to new services. Those solutions include the optical orthogonal frequency division multiplexing (OOFDM) and Radio over Fibre (RoF) techniques which aim at providing high bandwidth links with low susceptibility to fibre non-linear effects and tolerant to dispersion impairments while reusing the installed base of SMF or MMF in access and in-building scenarios. Within the ALPHA project the first ever Gigabit *real-time* end-to-end OOFDM transmission by using off-the-shelf components has been demonstrated. The approach for POF has followed the strategy of preserving the Do-It-Yourself capability while improving the capacity of the POF based systems based on more efficient modulation formats and optimisation of key components.

The ultimate goal of the transmission solutions developed in the ALPHA project has been to enable an effective migration path towards the future optical access networks and in-building networks. This document reports on prospects of and provides roadmaps for the transport solutions of wireless and wired signals over optical fibres for the upcoming 10 years. These prospects and roadmaps are based on the results achieved in the framework of the ALPHA project.

Following this introduction, this document is divided into three main parts: the first reports on the latest results and prospects for the optical orthogonal frequency division multiplexing (OOFDM) technology, the second one does the same on Radio-over-Fibre (RoF) signal transmission for both SMF and MMF, and the third one deals with the POF solutions.

1 Optical OFDM technology

1.1 Latest results from ALPHA

Over the past several years, big efforts have been devoted to optical OFDM transmission, which is a promising technique for application in both access and in-building networks. Extensive experimental investigations on real-time OOFDM transceivers in terms of adaptive transceiver design, low-cost intensity modulators, novel synchronisation techniques, optical power budget improvement and simplified OOFDM network architectures have been undertaken within the ALPHA project. These investigations have led to the design and successful demonstration of the fast ever end-to-end real-time DSP-based OOFDM system employing adaptive loading techniques in an 11.25Gb/s, 64-QAM-encoded OOFDM signal over 25 km standard SMFs [1]. For signal bit-rates of less than 15 Gb/s, all the key technical challenges have been solved successfully, and low-cost (price comparable to the current available GPON transceivers) OOFDM modems are expected to be made commercially available within the next few years. For 40 Gb/s OOFDM systems, low-cost optical/electrical components can still be employed, but innovative solutions should be identified to further improve the optical power budget. For >100 Gb/s OOFDM systems, coherent transmission and detection should be adopted.

Furthermore, several types of light sources have been experimentally investigated and evaluated for OOFDM in order to upgrade the access network capacity, aiming at achieving a bit rate target higher than 10 Gb/s by using low-cost components. For the NG-PON2 scenarios, a 40 Gb/s bit rate has been obtained in a back-to-back configuration and a 32 Gb/s bit rate has also been obtained in 20 km SMFs using a prototype DFB laser with a bandwidth of 17 GHz provided by an ALPHA partner 3S Photonics and off-line DSP processing [2]. The laser was directly modulated with an AMOOFDM signal encoded using power-bit loading algorithms. The evaluation of the laser in terms of power budget, bandwidth and temperature has demonstrated the feasibility of using the laser to perform direct modulation to obtain high bit rates for NG-PON networks.

For in-building network applications, the performance of OOFDM using directly modulated VCSELs has been experimentally examined using both MMFs and bending insensitive MMFs. The results have shown the potential of achieving very high net spectral efficiency of more than 5.76 bit/(s·Hz) within a 156.25 MHz electrical bandwidth, corresponding to a net bit rate of 0.9 Gb/s. These results indicate the feasibility of implementing IMDD OOFDM systems in in-building networks.

To obtain an in-depth understanding of the OOFDM system performance, a simple and illustrative analytical model has been developed in order to estimate the performance of IM OOFDM system, in particular in terms of minimum required optical power at the input of the receiver. Based on the analytical model, the drawback of IM OOFDM has been identified: reduced power efficiency (in comparison with M-ASK scheme) due to presence of large optical carrier that is not used for data transmission. This drawback may be offset against its other attractive features such as dynamic bandwidth allocation, adaptive bit rate and tolerance to channel dispersion when designing the system and selecting an optimum signal modulation format for high-speed transmission using SMFs, MMFs and POFs [3].

In order to improve the quality of detected OOFDM signals in the receiver, achievements have also been made by proposing a new technique capable of utilising the unwanted intermodulation products generated in photodetection of OOFDM signals. Although the external modulation is a more expensive approach than the direct-modulation, the radio-over-fibre simultaneous transmission of millimetre frequencies and baseband signals is expected to become feasible using OOFDM in a period of time of 6-8 years. Optical phase modulation of OOFDM signals has also been demonstrated as an effective way of increasing the performance of directly modulated OOFDM systems, which future deployment will depend on the use of an integrated phase modulator and the feasibility to overcome experimental difficulties such as the signal synchronization.

1.2 Prospects and roadmap

The OOFDM technology roadmap can be divided into three major phases including short term (1-2 years), medium term (3-5 years) and long term (5 years or more), as shown in the figure below.

In the short-term phase, the development of low-cost OOFDM transceiver modems/chips operating at approximately 20 Gb/s/ch using low cost optical/electrical components is a key focus. In addition, advanced synchronisation techniques and corresponding MAC layer protocols will also be made available to enable WDM OOFDMA PONs compatible with existing WDM/TDM PONs to offer multi-end-users with hybrid WDM/TDM DBA. In such a phase, IMDD is still a preferred choice for both SMF and MMF links, where the utilisation of adaptive modulation will be extensively explored to compensate for imperfect transmission link spectral characteristics associated with existing components/systems/network components. It is also expected that, towards the end of this phase, first generation OOFDM transceiver modems/chips may be made commercially available to support virtual point-to-point/point-to-multi-point operations. Coherent detection is an option which is being studied and can prove to be interesting provided integrated optics become available to enable this technology. This solution would meet the optical budget requirement in PON (splitter losses and extended reach). ITRI (Industrial Technology Research Institute from Taiwan) has implemented a chip for 10 Gb/s OOFDM application and has already been in a process of defining the specifications for 40 Gb/s transmission. In addition, NEC Labs has demonstrated real-time 40 Gb/s OOFDM receivers in a WDM-OFDMA PON using FPGA-based DSP [4].

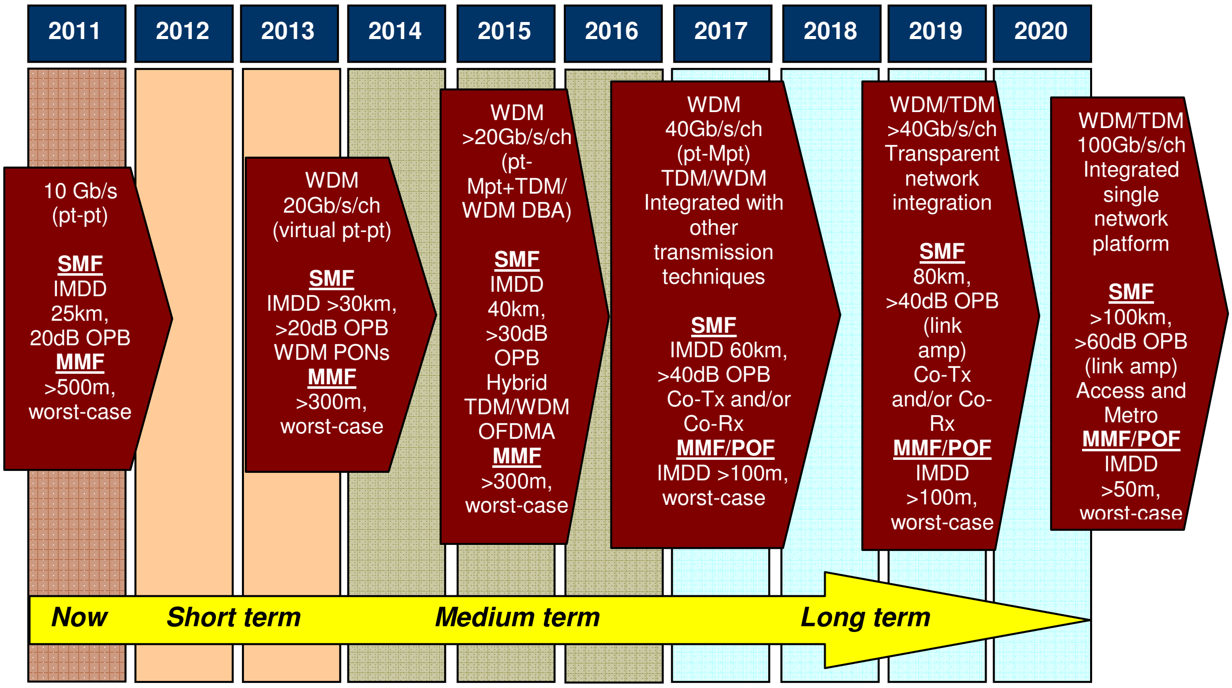

Fig.1. Roadmap for OOFDM technologies.

From a medium to long term phase, by making full use of the market–available high-speed ADCs/DACs at high resolution and high-quality laser sources, 40 Gb/s/ch real-time OOFDM transceivers are expected to be made available. Such OOFDM transceivers will be capable of overlaying with all other transmission technologies, and furthermore, offer backward compatibility with existing PON technologies for applications in access scenarios. For MMF/POF-based in-building networks, compared to other conventional techniques including coherent detection, IMDD using directly modulated DFB lasers is still a preferred option due to fundamental limitations set by modal noise. Owing to the differential mode delay effect, the corresponding transmission distance is expected to be in a range of 100 m for worst-case MMFs and much shorter for POFs.

In the long term phase, 100 Gb/s/ch transceivers are expected to be made available, which directly inherit all valuable features from OOFDM transceivers developed previously . For SMF-based systems, apart from significantly improved signal capacity versus reach performance with required optical power budget, another key feature is the capacity to integrate various networks into a single network platform. For MMF/POF-based LANs, IMDD is still preferred and the achievable signal capacity versus reach performance is significantly reduced due to the physical limitations set by modal noise and differential mode delay.

2 Radio-over-fibre technology

2.1 Latest results in ALPHA

The research activities within the ALPHA project on Radio-over-Fibre (RoF) have followed two main directions: the new techniques for generation and transmission of broadband micro and millimetre wave signals, and investigations on RoF transmission for access and in-building networks.

To this effect, an approach has been taken to explore the feasibility of RoF networking by means of distributed antenna systems (DAS) over MMF suitable for in-building scenario. The use of RoF in conjunction with DAS, to shift the electronic processing from the antenna base station towards a central location, is already well-known and employed as a cost-effective solution for radio coverage in places with a high traffic demand. However, to bring RoF technology closer to residential or home users, DAS needs to be integrated with the access network. For this reason, in the ALPHA project the possibility to integrate the RoF into the PON architecture has been investigated, the outcomes and main challenges of RoF transmission over PON networks are reported in ALPHA Deliverable D2.4.

The comprehensive theoretical and experimental research performed within ALPHA has clarified the physical mechanisms of the main transmission impairments of Radio-over-Multi-Mode-Fibre (RoMMF) systems, and made possible to develop fundamental design guidelines for their best performances [5]. The major detrimental effects for in-building applications (link gain fluctuations, increment of distortion effects), which are in most instances related to modal noise, have been proved to be adequately controllable when the central launch (as opposed to offset launch) technique is applied, and when a RoMMF receiver able to collect a relatively larger amount of optical power is utilized, e.g., by using a ball lens case to enable a better focusing capability. Recent activities have shown that by using currently available opto-electronic components, more than 15 Gb/s (5 M-QAM sub-carriers) transmission capacity over more than 4 km MMF link is feasible. With the optical frequency multiplexing technique, on the same link 120 Mb/s-64-QAM can be transported onto 25 GHz carrier frequency. Moreover, a high performance over cost ratio is feasible by reusing the DFB transmitters originally developed for radio over SMF operation, attaining for the final product an expected considerable market penetration.

ALPHA has also performed an extensive work on the generation and distribution of ultra wideband (UWB) radio signals through different techniques: intensity modulated direct detection, optical frequency multiplication, optical heterodyning and coherent transmission [6], [7]. In this context, by employing optical routing of radio signals in the home network, the possibility of using the same optical transmission system for wired as well as wireless signals through the use of electrical bandwidth division multiplexing has been experimentally demonstrated. A 2 Gb/s baseband signal along with 2 Gb/s RoF signal using IR-UWB was successfully achieved and compatibility with both MMF and SMF transmission was experimentally demonstrated. The IR-UWB RoF signal could be transmitted over up to 4 m wireless link, demonstrating the suitability of this system for wireless local area networks [8]. Finally, an optical scheme at 1310 nm for the up-conversion of baseband MB-OFDM UWB signals to frequencies around 24 GHz over MMF transmission based on the OFM technique was demonstrated. OFM provides high-order harmonic subcarriers generation with good SNR to support flexible UWB signal up-conversion. Only 0.5% (0.5dB) EVM penalty between the up-conversion UWB signal and the original baseband UWB signal was observed. The overall requirements of ECMA-368 standards are well satisfied in both back-to-back and MMF transmission cases. After up-conversion to 24 GHz, transmission over 400m, 750m MMF, and down conversion to baseband for analysis, the EVM performance of 10.7% (-19.4dB) and 11.8% (-18.6dB) is achieved with acceptable penalty. The use of off-the-shelf optical components would enable the potential integration of this all-optical technique on-chip for widespread deployment.

2.2 Prospects and Roadmap

Radio over fibre may be deployed in two application domains:

- *Access networks*: for mobile telephony networks (GSM, GPRS, UMTS, LTE)
- *In-building and home networks*: for wireless broadband (WLAN, 60GHz, UWB, …)

Steadily growing capacity demands are put on the wireless connectivity for communication terminals. These growing capacity needs per user can be solved in several ways: by decreasing the radio cell size, by increasing the transmission capacity per radio frequency channel, and by multiple antenna techniques (MIMO). In radio-over-fibre technologies, one may hereto discern the following evolution phases:

- *Baseband over fibre*: the data signal is fed from the central site in digital baseband format via fibre to the antenna station, where the signals are modulated on a locally generated radio carrier.
- *IF over fibre*: the data signal is modulated in the central site in multilevel-multiphase digital (e.g. QAM/OFDM) format on a (relatively low frequency) IF radio carrier, and transported by analogue IF techniques via fibre to the antenna station, where it is locally up-converted to a high-frequency radio signal by means of a locally generated radio carrier.
- *RF over fibre*: the data signal is modulated in the central site (e.g. in QAM/OFDM format) on a high-frequency RF radio carrier, and transported by analogue or digital RF techniques via fibre to the antenna station, where only simple O/E conversion is needed (and vice-versa for the return path).
- *RF over PON*: this is RF over fibre in an optically-split network connecting as a rule multiple antenna stations to the central site. Multiple access techniques (e.g. FDMA) might be needed to arrange the shared fibre access. Combination with wired services yields a converged wired-wireless services network.
- *Dynamically routed RF over PON*: optical routers (switched or passive) may route the RoF signals to specific antenna sites, in order to provide capacity on demand, i.e. delivering wireless connectivity only there where and when the users demand it.

This evolution phases with an indicative timeline of RoF technologies for access and in-building networks are illustrated in Fig. 2.

An important scenario where the RoMMF technology can find application in the short term (1-2 years) is to perform wireless coverage extension within the application range of the LAN (Local Area Networks). Indeed, we are witnessing today, particularly in vertical deployments in buildings, the proliferation of interconnection solutions based on standard 10 Gigabit Ethernet (10GbE), where the physical transmission channel, due to the short distances involved, relies mainly on the MMF, because of the less stringent requirements of the corresponding devices and components. It has therefore seemed justified to exploit the same physical channel in applications of wireless coverage extension through Fibre-Distribute Antenna Systems (F-DAS) using Radio-over-Fibre and therefore open up new market opportunities. It has to be noted that, since the analogue RoF can be regarded as a mature technology, the wireless in-building coverage utilizing RoMMF systems can also be seen in principle applicable today. However, this application of the MMF can be regarded as new and consequently has been so far relatively little investigated. The research activity on RoMMF performed within ALPHA has made possible to deepen the knowledge of the physical mechanisms that determine in these systems the impairments of the MMF as a transmitting medium. This allowed the implementation of solutions using typical commercial components and without the need of using particular launching techniques, improving in this way the product market competitiveness. In the short-term perspective (by ca 2013), it will be possible to add the RoMMF, in a cost effective way, to the current F-DAS, extending its application range and making the final solution fibre-agnostic.

Regarding UWB, two aspects are important for its deployment over fibre systems. The first one is the maturity of RoF technology for UWB transmission. The second one is the maturity, development and presence on the market of terminals equipped with UWB connectivity. When talking about UWB, it is important to make a distinction between UWB systems in the 3.1-10.6 GHz frequency band, and UWB systems in the 57-64 GHz frequency band. In ALPHA, the development of UWB transport technologies was focused in the 3.1-10.6 GHz band.

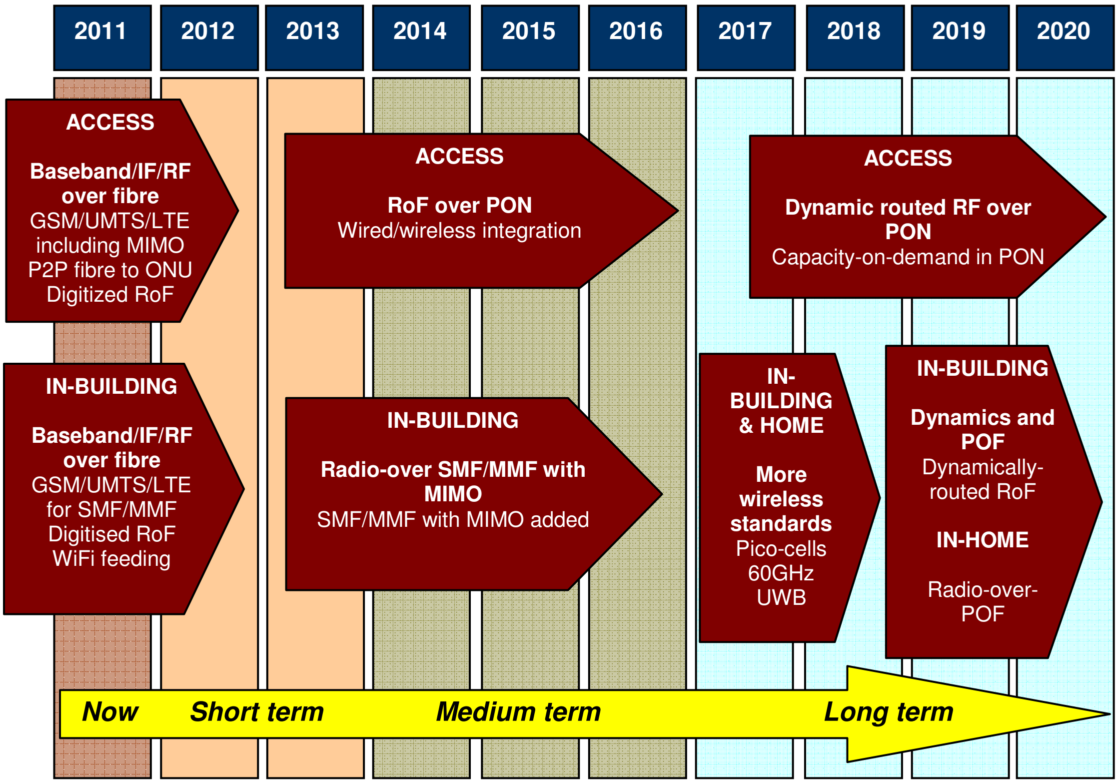

Fig.2. Roadmap for Radio-over-Fibre technologies.

UWB radio for ultra high bit rate wireless applications in the 3.1 to 10.6 GHz frequency band has undergone a lot of ups and downs during the last years. After the split up of the IEEE group in charge of UWB standardisation (due to the difficulties of making a choice between IR-UWB and MB-OFDM UWB), a big number of companies joined the *Wimedia Alliance* that edited the ECMA 368 standard based on MB-OFDM UWB. During 2007 and 2008, some UWB products appeared on the market for wireless USB applications. However, a major obstacle to UWB development is related to regulatory issues: the frequency bands assigned to UWB are different in Europe, US, Japan and Korea, thus the interoperability becomes a fact. In 2010, the company *Wisair* and the *Wimedia* alliance announced new UWB products, but the future of UWB in the 3-10 GHz frequency band seems now uncertain. In this context, as IR-UWB has been abandoned for high bit-rate systems, it can find application in ultra low power and low bit rate systems as sensor networks or RFID (similar to Zigbee).

The evolution is completely different for UWB in the 57-64 GHz frequency band where Multi Gigabit/s bit rates can be achieved. A few standards (Wireless HD, IEEE 802.15.3c and ECMA 387) have been published, and some products appeared on the market in 2009-2010. Moreover, IEEE 802.11ad group is preparing a standard in this frequency band for the next generation of WiFi products. The WiFi diffusion all around the world is a guarantee for the rapid adoption of such products. 60 GHz technology is now mature: WirelessHD devices are already available on the market for wireless High Definition Multimedia Interface (HDMI) applications and IEEE 802.11ad WiFi certified products could be available by the end of 2012. The radio coverage at 60GHz is limited to a few meters inside a room, thus 60GHz UWB over fibre is a promising candidate to ensure the coverage of an entire building. As a consequence, if UWB over fibre systems continue in the way towards low cost and integration, they are expected to reach the market in 5 years.

3 Large-core Plastic Optical Fibres for in-building networks

3.1 Latest results in ALPHA

The ALPHA project has substantially contributed to the transmission and architectural solutions for home networking based on Plastic Optical Fibres (POF). The current conventional step-index POF (SI-POF) offers a solution for home networking that can be immediately used due to the existing commercial products (mostly for Fast Ethernet), and can be upgraded in the medium (3-5 years) to long term (more than 5 years) with innovative solutions, in particular, those demonstrated within ALPHA. POF is seen as a valid alternative to the electrical solutions, like Cat-5e/6a or coaxial cables.

To the best of our knowledge, ALPHA has been the first project where a Gigabit POF transceiver prototype has been developed. The continuous development has led to improve the receiving section in order to increase the signal-to-noise ratio, this way, the target of 1 Gb/s error-free transmission over 50 m of POF was successfully achieved. Furthermore, the developed prototype is close to the production level, it was developed using only commercially-available components and its cost (based on a small lot of production) is a few tens of Euros. It is pluggable on the *Luceat*'s media converter and *Telsey* Residential Gateway (devices developed within ALPHA project). For future developments, the power budget of the system could be increased in order to make the solution more robust, in particular working on the coupling condition between fibre and photodiode. Another area to investigate is the use of blue or green laser diode: in these spectral regions the attenuation of the POF is lower than the attenuation at 650 nm. VCSEL could be used as sources in order to reduce the power consumption and improve the coupling condition with the POF, but VCSELs thermally stable at 650 nm are needed.

We have also reported on the most recent results on bidirectional transmission over a single POF demonstrating a reliable transmission up to 75 m running real Gigabit Ethernet traffic [9]. While the previous work was a preliminary proof-of-concept with significant limitations, the present work extends the demonstration of Gigabit bidirectional transmission over a single POF up to a level that may become of interest for practical home-networking scenarios in a medium term, as soon as reliable red VCSEL or low-cost red edge-emitting lasers becomes available.

The study of different modulation formats for POF show that single carrier modulation formats give better performance than DMT (another term used for denoting OFDM) on the considered channel based on LED and SI-POF. The only rationale for still considering DMT/OFDM as a candidate for POF is thus that the DMT/OFDM adaptive bit rate capability: even in the presence of a really bad installation with exceedingly high insertion loss, DMT/OFDM bit loading algorithm would still give an operational link, even if at low bit rate, while the single carrier modulation would go off-service when the BER becomes higher than approximately 10^{-3}.

For high capacity transmission over large-core POF, low-cost, simple and eye safety compliant VCSEL transmitter and a 400 µm active area Si photoreceiver to transmit high data rates over 50 m PMMA large-core Graded-Index POF were used. It is shown that by using these simple components in combination with spectrally efficient DMT/OFDM modulation techniques, FEC-limited error-free and robust transmission of 5.3 Gb/s over 50 m PMMA large-core POF can be demonstrated [10]. This excellent performance has been obtained exploiting a system bandwidth of less than 1.3 GHz, corresponding to a spectral efficiency of 4.1 bit/s/Hz. Successful transmission of more than 7.6 Gb/s, 7.2 Gb/s and 6.2 Gb/s are also achieved over 10, 20 and 35m respectively. All bit rates mentioned in this subsection includes the 7% FEC bits, cyclic prefix and preambles. This work demonstrates a robust and high-performance transmission over realistic link lengths proving that a large-scale cost-effective deployment for “Do-It-Yourself” home network scenarios at multi-gigabit rates is feasible. The results shown are the state-of-the-art of short-range transmission over 50 m GI-POF.

However, the success of POF technology in the in-building network segment will depend on some factors that are outside an EU research project. The results of the project have contributed to new developments and future products as well as comprehensive European experience, which will help to achieve that:

- POF products can have a critical mass for the mass market which will lead to a significant cost reduction of the POF hardware compared to today's estimated prices. While today a POF media converter is sold in the range of 100 €, we believe a decrease of the prices to the 10 € range (for each media converter or transceiver) is needed to enable a real diffusion of the POF technology inside the house.
- The interested companies have a clear view on the possible POF application scenarios and based on that, they can develop proper marketing strategies and related activities.
- A deeper and better standardization of POF technology is performed with activities that will cover the current gaps in international standards when dealing with POF products. Some significant work along this path has been done also within ALPHA by providing inputs to ETSI, CENELEC, ISO/IEC and VDE/DKE standards. The path towards POF standardization is anyway still quite open, since existing standards are mostly limited to the fibre itself, while there is a nearly complete gap on the definition of one (or more) PHY layer specifically designed for POF transceivers.

3.2 Prospects and Roadmap

The analysis on large-core POF carried out inside ALPHA has shown that the target of transmitting 1 Gb/s over approximately 50 meters of PMMA SI-POF is feasible, as shown by *Luceat* in a prototype, and by *Politecnico di Torino* and *Technical University of Eindhoven* by several transmission experiments with off-line processing. The Gigabit Ethernet media converter developed by *Luceat* is based on commercial available components and it has a maturity level close to the production.

An intense research work has been focused on analysing the best modulation formats and/or equalization structure, particularly for the short-term goal of designing a reliable 1 Gb/s over 50 m of PMMA SI-POF. The outcome is that the most performing solution in terms of system margin is the combination of pure binary transmission at the transmitter and adaptive electronic equalization at the receiver, and this was thus the solution adopted for the *Luceat* prototype. Other more complex modulation formats, such as OFDM/DMT did not give a significant advantage in terms of transmission performance. Nevertheless, they are not to be completely excluded, since:

- OFDM/DMT is an adaptive bit-rate solution (that is a new concept for optical backbone), so even in very critical installation (high bending, degraded components) the system will still be active, though at a reduced bit rate, while the pure binary systems, such as the one developed by *Luceat*, will run out of service when the link loss exceed the available power margin.
- OFMD/DMT is at the basis of many transmission standards and, focusing on home networking, it is at the basis of the ITU-T G.hn. The OFDM over POF investigation in ALPHA is in itself interesting if the ITU-T G.hn would decide to include POF among one of the media covered by this standard.

The increase to longer distances than 50 meter is critical, unless smaller diameter Perfluorinated GI-POF are used (but this is a solution that has been only marginally addressed inside ALPHA, since the Consortium decided to focus mostly on large core POF). This is required to increase the share of the buildings where the POF "do-it-yourself" solution can be deployed.

The increase to bit rate higher than 1 Gb/s for a standard length of 50m has also been demonstrated in ALPHA. A clear output is that the large core PMMA step-index POF are likely to be excluded for the multi-gigabit transmission due to their limited bandwidth of 70MHz at 50m. Using eye-safe launching powers and DMT technique, less than 2 Gb/s is feasible. Only large core PMMA graded-index POFs give the opportunity to reach 5-6 Gb/s over the target distances of approximately 50 m. But graded-index POFs have a reduced tolerance to bending which could decrease its suitability for home-networking. An interesting solution for multi-Gb/s taking advantage of high bending tolerance and large bandwidth-distance product to use multi-core step index POFs. Initial system works done in ALPHA using this type of fibre results in an improved transmission rate of 4.7 Gb/s which is close to those of a single-core graded-index POF [11].

The possibility to implement radio-over-fibre solution has been also demonstrated in ALPHA using large core PMMA graded-index POFs. This fact makes this type of POF an attractive solution for converged wired-wireless transmission over a single POF infrastructure [12].

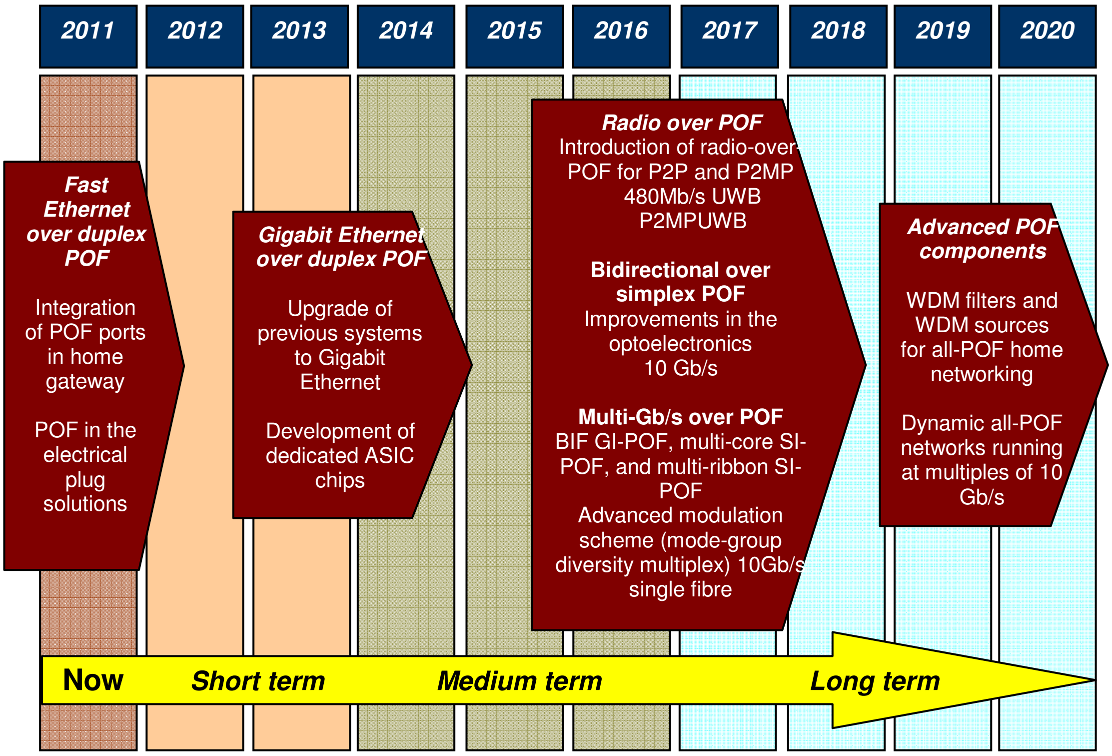

Fig.3. Roadmap for POF technologies

The future roadmap expected for POF technologies is illustrated in Fig. 3, and is conditioned by the home networking market evolution. The Luceat prototype has clearly shown a path towards Gigabit Ethernet over POF for up to 50 m, even though with a small system margin. The direction for further improvements have been clearly identified inside the ALPHA project, and can go along one or more of the following directions:

- Transmitter side: development of higher bandwidth and/or higher output power red LEDs, or resolution of the temperature problems of current red VCSEL.
- Receiver side: development of optimized opto-electonic setups for large-area photodiode receivers and ad-hoc ASIC chipsets for optimized electronic equalization strategies.
- System side: investigation on highly spectral efficient modulation formats other than DMT in order to ensure transmission throughputs close to the Shannon limit and sufficient link margins.

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