Towards converged broadband wired and wireless in-home optical networks

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Towards Converged Broadband Wired and Wireless In-home Optical Networks

D. Visani, G. Tartarini
Dipartimento di Elettronica, Informatica e Sistemistica
Università degli Studi di Bologna
Viale Risorgimento 2, 40136 Bologna, Italy
e-mail: davide.visani3@unibo.it

Y. Shi, H. Yang, C.M. Okonkwo, E. Tangdiongga, and A.M.J. Koonen
COBRA Research Institute,
Eindhoven University of Technology
P.O. Box 513, 5600 MB, Eindhoven, The Netherlands
e-mail: y.shi@tue.nl

Abstract—In this paper we present an in–home optical network infrastructure based on 1 mm core diameter graded–index plastic optical fibre. A combined transmission of a multi–gigabit baseband data stream, based on discrete multitone modulation, and a radio frequency signal, based on ultra wideband technology, is shown. A detailed experimental study on the performance of the two types of signals in the combined transmission is carried out in order to demonstrate the feasibility of a converged wired and wireless in–home network using plastic optical fibre.

Keywords: Home communication systems; Optical fibre communication; Plastic optical fibre; Radio over fibre

I. INTRODUCTION

Due to increasing bandwidth requirements from emerging applications, in-home networks represent an emerging field of study. The required bandwidth is not exclusively attributed to line capacity of the access network, but also to new bandwidth–hungry services inside the home, such as high definition television and gaming, which can outstrip the traffic transmitted to the home [1]. Moreover, at present, a plethora of different transport media is employed to deliver different services; e.g., coaxial cable for video broadcasting, twisted pair for wired telephony, and wireless Local Area Networks (LAN) for internet access.

The complexity of the existing scenario leads to expensive service costs to the home users. Hence, in order to simplify the current situation a common backbone infrastructure is becoming of primary importance. In contrast, an optical backbone based on silica fibre is considered to be future-proof. However, the application of silica fibre to in–home networks leads to increased hardware, installation and maintenance costs, which are unsustainable for home users. Recent advances in plastic optical fibres (POF) provide the prospect of reducing installation complexity hence reducing cost.

In this paper, POFs with large core diameters (~ 1 mm) is an attractive solution to obtain an acceptable bandwidth with the potential for “do–it–yourself” installation [2]. In fact, due to the use of visible light transceivers, high tolerance to misalignment and bending, and very simple connectorisation, a POF based system can in principle be deployed by the home user without the need of a fibre installer. Moreover, due to its electromagnetic immunity, heating resistance properties, and small size (2.2 mm cable diameter including external coating), POF can also be deployed in the existing ducts for electrical power cable [3], as well as under flooring.

In recent years, a comprehensive study on large core POF systems has been carried out to achieve high capacity transmission over 50 m using low–cost eye–safe optical transceivers. 1 Gbps over step–index POF has been demonstrated [4], as well as 4.7 Gbps over multi–core step–index POF [5] and 5.3 Gbps over graded–index POF [6]. The achieved transmission capacity can be considered sufficient for current and emerging in-home services. It also demonstrates the possibility to obtain high speed wired LANs employing POFs. For maximum benefit, the optical home backbone should be able to support various services delivery methods using plastic optical fibre technology.

Figure 1 shows the proposed scenario; a POF–based backbone is used to distribute data coming from the access network, through the residential gateway, and from different rooms. The user access technology can be wired, as exemplified by the home server, the high definition television and the traditional phone technology, or wireless, using laptop or any mobile device. Thus, the coexistence between wired and wireless services should be provided inside the home.

Different approaches can be suggested to achieve this goal. Firstly, an all digital baseband POF backbone can be used to distribute data coming from the access network, through the residential gateway, and from different rooms. The user access technology can be wired, as exemplified by the home server, the high definition television and the traditional phone technology, or wireless, using laptop or any mobile device. Thus, the coexistence between wired and wireless services should be provided inside the home.

A possible solution to this problem is to apply radio over fibre (RoF) technology to POF systems. In fact, RoF technique is used to enlarge the coverage of the radio signal itself employing the optical link as a passive analogue repeater [7]. In this way it becomes possible to build distributed antenna systems [8]. Additionally, the transport of radio signals in their native format provides the advantages of remote antenna simplification (no need for digital signal processing), and
transparency to radio layer protocols. A first example of the possibility to exploit 1 mm core diameter POF for radio signals distribution was proposed in [9].

In this paper, we propose and demonstrate the possibility for the coexistence of a multi-gigabit baseband signal and a high capacity radio signal on a single POF link. The baseband signal is based on Discrete Multitone Modulation (DMT) format, due to its ability to achieve high spectral efficiency over a frequency selective channel with simple equalisation techniques. The radio signal is a multi-band orthogonal frequency division multiplexing (MB-OFDM) ultra wideband signal (UWB) [10]. This choice of signal constitutes only an example of a possible wireless service for home environment. In particular, MB-OFDM UWB is proposed for wireless USB, and is able to provide high speed (up to 480 Mbps) short-range (max 10 m) communications between multiple devices with low power emission in the regulated frequency bands.

After the introduction, a brief overview on different types of 1 mm core diameter POF will be given. Then, DMT and MB-OFDM UWB formats will be introduced and the experimental setup used for our demonstration will be shown. Finally, results and discussions will be presented and conclusions will be drawn.

II. LARGE CORE DIAMETER POF

Plastic or polymer optical fibre differs from standard glass fibre because it consists of a highly transparent polymer. Among different kinds of POF, polymer methyl metacrylate (PMMA) 1 mm diameter POF represents the most common solution. In particular, it has found applications in the automotive industry, for sensors, in-car video or gaming entertainment services and additionally for data communication, of the order of 100 Mbps Ethernet. In all these different applications, the maximum transmission distances achieved are below 100 m, since PMMA material presents a minimum optical loss between 100 and 150 dB/km in the visible light region.

For these applications, a low bandwidth (100 MHz after 50 m transmission) step-index optical fibre, with a core diameter of 980 μm and cladding diameter of 1 mm, is used.
Transmission speeds up to 1 Gbps were demonstrated involving pulse amplitude modulation and strong equalisation techniques [4]. However, for next generation data communication system, solutions using this type of POF will not be adequate. For this reason, new types of POF, always based on PMMA materials, were proposed to obtain larger bandwidth−distance products [2].

The most interesting proposed solutions are the graded−index (GI) and the multi−core (MC) step−index POFs, and are summarized in Fig. 2. Graded−index POF is made of a PMMA−based material with the property to have a radial decreasing refractive index profile. Hence, the intermodal dispersion is minimized and it is therefore possible to achieve bandwidths larger than 1.5 GHz at 50 m. Multi−core POF is constituted of several parallel step−index small cores (usually 19 or 37) with similar propagation properties. Light is distributed and propagates through small cores, and therefore experiences less multimodal dispersion. As shown in Fig. 3, the obtained 3 dB bandwidth of MC−POF is much larger than single core SI−POF but smaller than GI−POF. Note that the most important property of MC−POF is the high tolerance to bending, because of an acceptable bending radius down to 2 mm, much smaller than the 20−25 mm of SI or GI POFs. Ultimately, both MC−POF and GI−POF are promising candidates to substitute SI−POF.

In this work we use GI−POF in our experiment to overcome any bandwidth limitation due to the optical fibre, since we transmit broadband baseband and radio signals (bandwidth larger than 500 MHz).

III. DISCRETE MULTITONE MODULATION (DMT)

Derived from the more general orthogonal frequency division multiplexing, DMT is widely applied in large scale to digital subscriber copper lines [11]. The idea is to divide a high−speed serial data stream into multiple lower−speed streams in parallel and modulated onto subcarriers of different frequencies for transmission. An important advantage of DMT is the possibility to allocate an arbitrary number of bits per subcarrier according to the corresponding signal−to−noise ratio (SNR) profile of the channel. This is typically known as bit−loading. In the present study, a Chow bit−loading algorithm [12] is used to achieve the maximum transmission speed of the channel with a desired bit−error rate.

IV. MB−OFDM UWB TECHNOLOGY

Ultra wideband is an emerging technology that offers great promises to satisfy the growing demand for high speed and low−cost short−range wireless networks. Regulated by the Federal Communication Commission in February 2002, the UWB technology should use a minimum bandwidth of 500 MHz and operates in the frequency range between 3.1 and 10.6 GHz, where other services are licensed. For this reason, the power spectral density measured in 1 MHz bandwidth must not exceed −41.25dBm. UWB systems support two kinds of modulation techniques: the direct sequence and MB−OFDM UWB technologies. MB−OFDM is preferred over other UWB implementations, like impulse−radio UWB, or proprietary UWB solution, due to the widely commercial availability of low−cost OFDM−based UWB solutions.

According to standard ECMA−368 [10], the available spectrum for UWB technology is divided in 14 bands, each with a bandwidth of 528 MHz. The radio signal is based on an OFDM format with 128 subcarriers, spaced by 4.125 MHz. A total 110 subcarriers (100 data carriers and 10 guard carriers) are used per band. In addition, 12 subcarriers, which allow for coherent detection, are used as pilot tones.

In this work we use a single−band MB−OFDM UWB signal, occupying the frequency range between 3.696 and 4.224 MHz.

V. EXPERIMENTAL SETUP

The experimental setup used in our study is depicted in Fig. 4. An arbitrary waveform generator (AWG) is used to
Figure 5. Frequency response of the POF system

Figure 6. Transmitted (a) and received (b) electrical signal with the combined transmission of a wired and a wireless signals.

generate the DMT signal, while a real–time MB–OFDM UWB signal is generated in real–time from a Wisair development board. The UWB signal has a bandwidth of 528 MHz and a centre frequency of 3.96 GHz, operating at 200 Mbps. This bit–rate is imposed by the limitation of this particular UWB device, but the concept is scalable to the full UWB data rate of 480 Mbps.

We chose to transport the two types of signals in POF link splitting the available bandwidth into two parts, DC to f1 for DMT and f1 to f2 for UWB, as summarized in the inset in Fig. 4. Since, as shown in Fig. 5, the bandwidth of the overall POF link is limited to 1.4 GHz, we need to down–convert the UWB signal to an intermediate frequency to fit into the limited bandwidth. In particular, we down–convert the UWB signal to a centre frequency of 1.1 GHz using an electrical mixer, and then combine it with a low–pass DMT signal occupying the bandwidth below 0.8 GHz.

The combined signal modulated directly in intensity the laser source, which is a vertical–cavity surface–emitting laser (VCSEL) at a red wavelength of 667 nm. The emitted optical power is coupled, without the use of a lens system, into a 1 mm core size PMMA GI–POF of 50 m length. After POF transmission, the optical light is coupled directly to a photo–receiver based on a silicon avalanche photo–detector (Si–APD), with an active area of 230 μm diameter, followed by a two–stage electrical amplifier. The obtained electrical signal is connected to a digital phosphor oscilloscope (DPO), used to analyze alternatively the DMT and the UWB signals.

The quality of the UWB signal is expressed in terms of error vector magnitude (EVM) of the received constellation, while for the DMT signal we consider the maximum bit–rate achievable with a bit–error rate less than 10–3. This bit–error rate target is chosen to ensure error free performance when an enhanced forward error correction overhead is used [13]. All the results shown in this paper were obtained as a statistical average of several experimental results.

VI. RESULTS AND DISCUSSION

In Fig. 6, we show the power spectral density (PSD) of the transmitted and received electrical signal. Note that both signals are not strongly distorted by the POF link, but only a SNR reduction of 10 dB can be evinced.

Therefore, the main limiting factor of our system is not the frequency selectiveness of the channel or the noise, but the non linear distortion and cross–talk between the two signals induced by the VCSEL, which is directly modulated by both signals.

To study this non–linear effect, we consider the changes of EVM and maximum data rate of the two signals induced by changing the transmitted powers of the two signals. In Fig. 7(a) and (b) we show the variation of the EVM of the UWB signal and the maximum achievable bit–rate of the DMT signal.

Figure 7. DMT maximum bit–rate (red line) and UWB EVM (blue line) varying the input power of DMT (a) or UWB (b) signals in the combined transmission experiment.
In Fig. 7(a), the UWB power is fixed to −1 dBm, and DMT power varies from −7.2 to +2.8 dBm. For values of the DMT power below 0.8 dBm, the UWB EVM performance is compliant with the transmitter standard EVM limit of 15.5%. Note that at 0.8 dBm, the maximum data rate of DMT starts to decrease. The recommended operating region is where the difference between the two curves is the largest, i.e. between −4 and 0 dBm. We choose the value of −3.2 dBm as our optimum DMT input power in order to achieve 2.2 Gbit/s of DMT transmission while maintaining a UWB EVM below 13%.

In Fig. 7(b), we repeat the previous experiment by varying the UWB power, while keeping the DMT power constant at −3.2 dBm. Notice that the minimum UWB EVM value can be achieved with a UWB power of −1 dBm. The recommended region of operation is between the UWB input power of −5 and 0 dBm. In the following figures more details about the two signals used are shown for the DMT input power of −3.2 dBm and the UWB input power of −1 dBm.

In Fig. 8 the characteristics of the DMT signal are pointed out. We used 128 subcarriers in a bandwidth of 0.8 GHz, obtained with an AWG sampling speed of 1.6 Gsamples/s. The bit-loading algorithm starts from the evaluation of the SNR, as shown in Fig. 8(a), sending a DMT signal with a 4 quadrature amplitude modulation (QAM) in every subcarrier with a uniform power level. Based on this SNR, the algorithm determines the number of bits (constellation size) to associate to every subcarrier, as in Fig. 8(b). To support an exact integer number of bits, the algorithm assigned the right amount of power to every subcarrier, as in Fig. 8(c). Due to this power allocation, the resulting SNR, coming from the evaluation after the bit-loading process, assumes a step-like shape, as shown in

Figure 8. (a): signal-to-noise ratio before bit-loading, (b): bits allocated to the subcarriers of the DMT signals after bit-loading, (c): power allocated to the subcarriers after bit-loading, (d): signal-to-noise ratio after bit-loading versus the DMT input power and the UWB input power, respectively.

In Fig. 9, 4-QAM (left) and 8-QAM (right) constellation diagrams of the subcarriers with 2 and 3 bits allocated, respectively, of DMT signal after simultaneous transmission over 50m POF.

Figure 10. Spectrum and constellation diagram of the UWB received signal, off-line up-converted, after simultaneous transmission over 50m POF.
Fig. 8(d). Figure 9 shows the constellations for the subcarriers with 2 bits (4−QAM) and 3 bits (8−QAM) allocated.

Finally, in Fig. 10 the UWB signal analysis, obtained by the DPO is shown. Figure 10(a) presents the spectrum of the UWB signal, up–converted by the off–line analysis process, while Fig. 10(b) shows the received quadrature phase–shift keying constellation.

VII. CONCLUSIONS

This work presents the idea of a converged in–home network based on plastic optical fibre. Due to the potential “do–it–yourself” installation, the small cable size and the low sensitivity to bending and heating, plastic optical fibre represents an interesting solutions for home environment.

To prove the versatility of POF–based systems in delivering any kind of services, a converged transmission of wired and wireless signals over a single plastic optical fibre link has been successfully demonstrated. A DMT signal occupying the bandwidth below 0.8 GHz, with a bit–rate of 2.2 Gbps, and a UWB signal with a bandwidth of 528 MHz, transporting 200 Mbps, were successfully transported over 1 mm core 50 m PMMA graded–index POF. For this purpose, a detailed study on the main system limitations, including the non–linearity of the laser source and optimum signal power values have been presented.

The obtained results of this paper shows that the achieved high data rates can support present and near–future home services, giving the user greater freedom in the choice of the type of information delivery, i.e. wired or wireless.

We believe that the proposed scenario is a promising solution for mass–deployment broadband next–generation in–home networks, where cost, simplicity of installation and functional upgradability are important features.

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