UWB Radio over Perfluorinated GI-POF for Low-Cost In-Building Networks

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Abstract— **This paper presents a performance evaluation of a multiband-orthogonal frequency division multiplexing (MB-OFDM) ultra-wideband (UWB) signal transmission over two types of perfluorinated graded-index polymer optical fibers (PF-GI-POFs) with diameters of 62.5 µm and 120 µm, using a low-cost optical transceiver. Experimental measurements of packet error rate (PER) and minimum transmitted powers to achieve the maximum allowed PER show that it is possible to have a viable transmission at data rates of 480 Mbps, 200 Mbps and 53.3Mbps over 100, 150 and 200 meters of PF-GI-POF, respectively, preceded by a 1 meter wireless link.**

I. INTRODUCTION

Since 2002, the Federal Communications Commission (FCC) authorized the use of ultra-wideband (UWB) signal transmissions for unlicensed use, in the range from 3.1 to 10.6 GHz, leading to a revived interest in research activities and to new opportunities for companies to explore and develop new broadband indoor and outdoor applications [1]. Moreover, UWB is seen as a promising technology for short range high speed wireless networks.

UWB signals are characterized by their huge bandwidth occupancy, high data rates, and very weak power density (-41.3 dBm/MHz), which gives them a noise-like signal characteristic, facilitating both interference mitigation and very low device power consumption. On the other hand, its very low intensity and high data rates limit the coverage to a few meters distance. However, by using radio-over-fiber (RoF) as a transparent signal transportation technique, it is possible to deliver UWB signals over an in-building low cost fiber network.

The use of multimode fibers (MMF) in RoF short span networks has attracted much attention in recent years. In particular, POFs are currently being used in small high data rate networks, due to their low cost components low maintenance, and easy installation. In fact, the popularity of polymer optical fibers is due to the advantages brought by its large core diameter and mechanical properties. These include connectorisation simplicity, and higher tolerance to both misalignments and vibrations, simpler installation procedures due to low bending loss, and lower maintenance costs due to improved robustness. These properties make POFs suitable for short span fiber deployments in the home environment, or even for critical applications in both the car and avionics industries.

Common POFs are based on polymethyl methacrylate (PMMA), and exhibit high attenuation (200 dB/km), and low bandwidth due to multimodal dispersion, making them unsuitable for transporting wideband signals with high frequency carriers over more than 50 meters [2]. Moreover, due to their relatively low bandwidth, a down-conversion of the signal to an intermediate frequency must be performed, which introduces additional complexity and raises base stations cost. State-of-the-art PF-GI-POFs solve these issues by combining a low attenuation material (about 50 dB/km @ 850 nm) with a graded index core profile, which provides a significantly higher bandwidth [3]. Current PF-GI-POFs have bandwidth length products of around 1 GHz.Km, and 10 dB/Km @ 1310 nm attenuation [4].

This work describes a significant extension of an earlier published work [5], where improvements were made to the RoF conversion boards, and a new large core plastic fiber was tested.

We experimentally demonstrate the uplink of a MB-OFDM UWB signal (ECMA-368 standard [6]) over two different PF-GI-POFs from Chromis Fiberoptics, using a low-cost VCSEL and 850 nm PIN optical transceiver.

Unlike earlier work ([7]), we were able to transmit 480 Mbps over large core diameter (120µm) PF-GI-POF using commercial UWB transceivers and cheap COTS. Moreover, the wireless link channel is also considered.

II. LOW-COST DIRECTLY MODULATED ROF SYSTEM

VCSELs are characterised by a vertical low divergence, circular beam patterns, low threshold currents (a few mA) and high bandwidths (several GHz). Their vertical wafer growth process enables in-wafer testing, and is well suited for large scale production. Their output light beam pattern enables

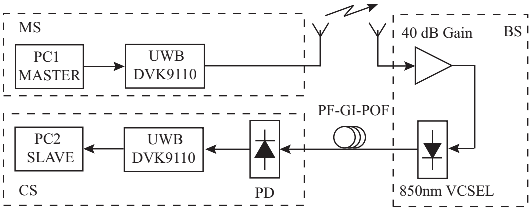

Figure 1. Schematic illustrating the RoF setup used.

efficient coupling to large diameter polymer optical fibers. Hence, simple plastic injection molded packages are sufficient as fiber coupling devices. These are reasons that make VCSELs desirable for low cost directly modulated systems in these types of widespread commercial applications.

A schematic of the MB-OFDM UWB over GI-POF system used is shown in Figure 1, representing a RoF communication uplink between a Mobile Station (MS) and a Central Station (CS), via a Base Station (BS). In order to generate MB-OFDM UWB signals compliant with the ECMA-368 standard, a commercially available UWB transceiver module from WisAir (DVK9110M) was used. The proposed system is based on today's commercially available low cost VCSELs and photodiodes that are not optimized for radio-over-fiber applications.

At the BS, a power amplifier (PA) amplifies the driver signal. The optical signal power (P_{OPT} in dBm) at the laser output is given by [8][9]

$$P_{OPT} = \frac{G_{TX} + P_{RF,BS} - L}{2} + 10\log_{10}\left(G_M\sqrt{\frac{1000}{Z_{in}}}\right) \qquad (1)$$

where G_{TX} is the PA gain in dB, $P_{RF,BS}$ is the received electrical power, in dBm, at the BS, G_M is the VCSEL modulation gain in mW/mA and Z_{in} (~50 Ω) is the laser input impedance assumed constant within the band of interest.

The received electrical power at the CS, $P_{RF,CS}$, is given by [5]

$$P_{RF,CS} = 20\log_{10}(RG_M) + 10\log_{10}\left(\frac{Z_{out}}{Z_{in}}\right) - \\ - 2OL + G_{TX} + P_{RF,BS} - L \qquad (2)$$

where R is the photodiode responsivity in mA/mW, Z_{out} (~50 Ω) is the photodiode output impedance (also assumed constant within the band of interest), OL is the optical power loss due to both the fiber attenuation and connector loss and L is the wireless link loss. Note the factor of 2 multiplying the optical power term which results from the quadratic optical power to electrical power conversion in the photodiode meaning that reduction on the transmitted optical power has a significant impact on the link budget.

The electrical to optical and optical to electrical conversion (whose efficiency is given by RG_m) jointly with the attenuation of POFs is the dominant factor reducing the link power budget of these systems.

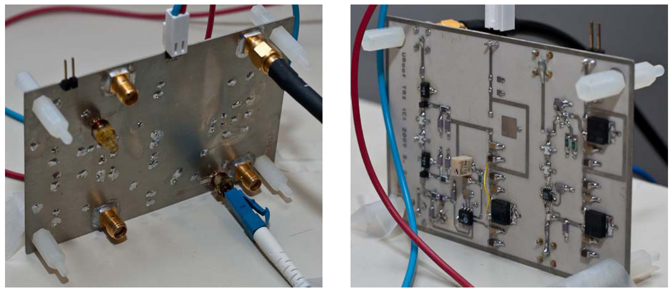

Figure 2. RoF conversion board.

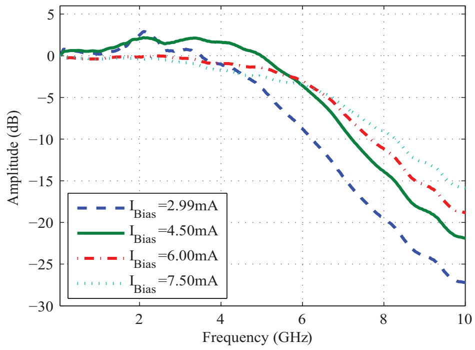

Figure 3. Laser transfer function vs bias current.

The relatively high POF attenuation can be partially overcome by post detection amplification, at the expense of some SNR degradation due to amplifier noise. In our experiments, an extra LNA was not included because the UWB DVK provides enough sensitivity.

MB-OFDM UWB radio applications make extensive use of multiple subcarriers and, hence require large dynamic range and highly linear devices. The signal transmission is mainly impaired by the laser nonlinearity, the optical loss due to the fiber, the free space loss and noise added by the system.

III. Experimental Demonstration of Concept

A. Radio-over-Fiber conversion board

Figure 2 depicts the RoF conversion board based on low-cost electrical and optical components. An amplifiers cascade and a polarizing circuit makes up the laser driver for the E/O conversion circuit and a photodiode with an integrated transimpedance amplifier was used for the O/E conversion circuit.

The amplifiers were chosen among devices with both high IP3 (3rd Order Intercept) and low noise figure. High IP3 is essential for guaranteeing the integrity of multiple carrier ultra wideband signals. The VCSEL (HFD3180-203) and photodiode (HFE4192-581) operate at 850 nm, and have a combined 3 dB bandwidth of about 5 GHz. The laser modulation efficiency, and photodiode (PD) responsivity are 0.07 mW/mA and 12.5 mA/mW, including transimpedance amplifier gain, respectively. It was also experimentally verified that the receiver noise is much larger than the laser RIN, even with short POF lengths.

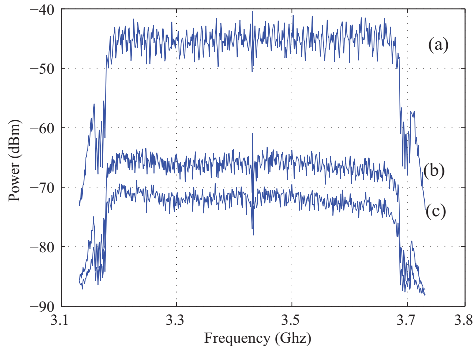

Figure 4. Spectrum of the MB-OFDM UWB signal (a) transmitted by the UWB kit and after a 1 meter wireless link and (b) 50 meters and (c) 100 meters of GigaPOF-120LD (RBW = 1 MHz).

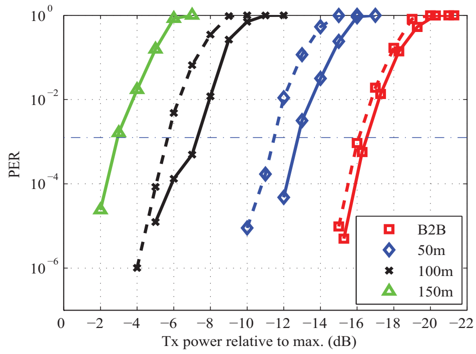

Figure 5. PER vs transmitted power, after a 1 meter wireless link for a transmission rate of 200 Mbps when using GigaPOF-62LD (dashed) and GigaPOF-120LD (solid).

The VCSEL bias current was also judiciously adjusted. It was found that the optimum bias current, in this case, is not that which provides maximum bandwidth (~7.5 mA, see Figure 3), as one might have expected. Instead, the bias current was set to a lower level of 4.5 mA, thereby increasing the output optical modulation index (the input RF intensity is fixed), without significantly compromising the bandwidth, and without significantly increasing the laser nonlinear dynamic distortion.

The total budget of this system prototype does not exceed 50 €. Large scale production of such a system would undoubtedly have an even lower price, meeting well in the requirements of a widespread commercial application for home or office use.

B. *Experimental setup*

The UWB kit operates is the band group 1 (from 3.168 GHz to 4.752 GHz) and the maximum equivalent isotropic radiated power (EIRP) is -41.3 dBm/MHz (FCC regulation limit [1]), using antennas with approximately 5 dBi of gain. This band group consists of three sub-bands, each occupying a bandwidth of 528 MHz and containing 128 subcarriers. Thus, the maximum output power corresponds to an EIRP of -14 dBm per sub-band. Consequently, the power transmitted by the UWB DVK is approximately -19 dBm, disregarding the antenna gain. Although three subbands are available for transmission, the optical transceiver design limitations (commercial VCSEL, photodiode and amplifiers available at the moment) prevented using the entire available bandwidth.

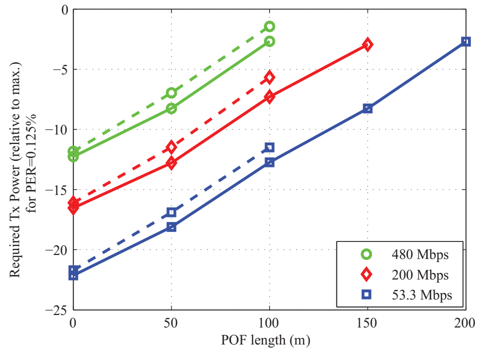

Figure 6. Required signal transmit power after 1 meter of wireless link to achieve a PER of 0.125% as a function of POF length for GigaPOF-62LD (dashed) and GigaPOF-120LD (solid).

Therefore, the time-frequency code was set to TFC 5 (3.168 GHz to 3.696 GHz).

Previous experimental demonstrations have shown that a 1 meter wireless link produces similar results to the ones obtained using a 40 dB attenuator, which corresponds to the free-space air attenuation over 1 meter distance, approximately [5]. Therefore, and for simplicity sake, the effect of the wireless link was simulated by the attenuator. In this experimental demonstration we have used two different PF-GI-POFs from Chromis Fiberoptics, namely, the GigaPOF-62LD and the GigaPOF-120LD, with core diameters of 62.5 µm, and 120 µm, respectively.

C. *Measured results*

The experimental validation was done by transmitting data with our setup at rates of 53.3 Mbps, 200 Mbps and 480 Mbps.

We also used a 64 octet packet length for PER measurements. Figure 4 shows the MB-OFDM UWB signal spectra obtained before the wireless link and after the GigaPOF-62LD. The attenuation of these links obtained from (2) are 20.6 dB and 25.6 dB, which agrees with the measured values of 21 dB and 26 dB from Figure 4. In addition to the wireless/optical link attenuation, it can be seen that subcarriers suffer slightly different attenuations mainly due to the photodiode and amplifier frequency response. The UWB signal spectrum shows no distortion for the tested fiber lengths, which indicates that the bandwidth-distance product is not the factor limiting the transmission on the fiber.

Figure 5 depicts the experimental results of PER as a function of transmitted power (relative to the maximum allowed defined by the ECMA-368 standard [6]) for different POF lengths preceded by a 1 meter wireless link and considering a transmission rate of 200 Mbps. As expected, results show that the PER increases when the POF length is increased. The horizontal dashed line corresponds to a PER of 0.125 % which is the maximum PER allowed for a 64 octet frame body (ECMA-368 [6]).

Figure 6 shows the minimum required signal power (relative to the maximum) for achieving the maximum allowed PER, as a function of POF length, and including a 1 meter wireless channel. As expected, the PER increases for

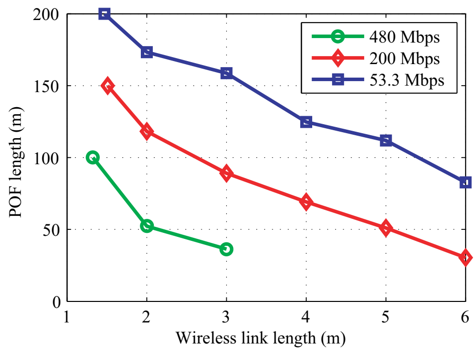

Figure 7. GigaPOF-120LD length vs wireless link length when transmitting at the maximum allowed power for a 0.125% PER.

larger data rates, and the required power for achieving a valid transmission also increases.

A linearly increasing transmitted signal power (in dB) is necessary to compensate for the linearly increasing POF loss with distance, keeping both the receiver SNR and the PER constant, as indicated in Figure 6. This shows that the overall noise level is constant at the output of the receiver board, and that intermodulation products are sufficiently bellow the receiver noise level (for the chosen link parameters). A further interesting result is that the slope of the plots depicted in Figure 6 correspond to the fiber attenuation, which is approximately 50 dB/Km in both cases, indicating that fiber attenuation (and not fiber bandwidth) is the dominant transmission penalty (see Figure 4).

Results also show that it is possible to transmit 480 Mbps up to 100 meters distance when preceded by a 1 meter wireless as well as 200 Mbps and 53.3 Mbps in 150 meters and 200 meters, respectively. The slight difference found in the back-to-back configuration shows that the large core diameter fiber has a better light coupling efficiency. This difference persists in all the lengths.

It was not possible to obtain results for fiber lengths longer than 100m, due to the unavailability of suitable GigaPOF-62LD cables at our lab. Nonetheless, by looking at the plots trends, one can also infer that valid transmissions at 200 Mbps over 150 meters of GigaPOF-62LD and at 53.3 Mbps over 200 meters of the same fiber, are likely achievable.

A generalization of the results plotted in Figure 6 is depicted in Figure 7, for the GigaPOF-120LD. In order to obtain these results, the required signal power for a 0.125% PER was obtained for up to 6 meters wireless links (with a one meter span) in a back-to-back optical configuration. All other POF length cases were extrapolated using the start point given by the back-to-back configuration and the trend indicated in Figure 6 of the transmission power increase with the POF length. Results in Figure 7 represent the maximum POF length as a function of the wireless link length when transmitting at the maximum allowed power for a 0.125% PER. At 480 Mbps, one can see that 100 meters of GigaPOF-120LD preceded by a 1.3 meters wireless link gives the same performance as 3 meter wireless link followed by approximately 35 meters of GigaPOF-120LD.

IV. Conclusions

This paper presents a radio-over-fiber system, based on low-cost components, for transporting MB-OFDM UWB signals over plastic fiber links. Results show that it is possible to transmit 480 Mbps over a 1 meter wireless link followed by 100 meters of GigaPOF-62LD and GigaPOF-120LD. We have experimentally demonstrated maximum transmission distances of 150 meters and 200 meters, respectively, using GigaPOF-120LD, with data rates of 200Mbps and 53.3 Mbps. It is also demonstrated that the PG-GI-POF attenuation, and not its bandwidth, is the dominant factor limiting the fiber link length. In conclusion, the PF-GI-POFs are a viable solution for transporting MB-OFDM UWB signals. In particular, a GI-POF with 120 μm diameter actually shows a PER advantage when compared to its smaller core version. This large core fiber may find applications in both the home and office environments where easiness of installation and handling are vital.

Acknowledgment

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