Performance Evaluation of MB-OFDM UWB over GI-POF

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This paper presents a study on multiband-orthogonal frequency division multiplexing (MB-OFDM) ultra-wideband (UWB) signal transmission over graded-index polymer optical fiber (GI-POF). MB-OFDM UWB signals are generated using a development kit by WisAir (DV9110M). Measurements of packet error rate (PER) and minimum transmitted powers to achieve the maximum allowed PER are carried out for different wireless/optical channel lengths and optical channels using time frequency code (TFC) 5 (3.168 – 3.696 GHz). It is demonstrated that GI-POF is a viable solution for the transport of MB-OFDM UWB signals.

1. Introduction

Since 2002, the Federal Communications Commission (FCC) authorized the use of ultra-wideband (UWB) signal transmissions in the range from 3.1 to 10.6 GHz for unlicensed use, leading to a revive interest in research activities and the opportunity for companies to explore and develop new broadband indoor and outdoor applications [1]. Moreover, UWB is seen as a promise technology for Personal Area Networks (PAN), targeting short-range communications with data rates exceeding 1 Gb/s.

UWB signals are characterized by their huge bandwidth occupancy, high data rates and very weak intensity (-41.3 dBm/MHz), which gives them a noise-like signal characteristic, leading also to a mitigation on interference with other wireless signals and also a very low power consumption. On the other hand, its very low intensity and high data rates limit the distance of coverage to a few meters. Thus, by using radio-over-fiber (RoF) as a transparent transportation medium, it is possible to provide a significant range extension of UWB communications.

Nowadays, the majority of the building networks are based on MMF. In fact, in-building networks employing MMF topologies for high speed short-range (10 Gb/s; < 300 m) represent circa 90% of all in-building networks [1]. Therefore, the use of MMF in RoF networks has attracted much attention in the last years. Presently, it is predicted that the fastest growing part of the optical communications market will be targeting legacy MMF for installed lengths up to 300 meters [Gomes 2006]. In particular, polymer optical fibers (POF) are currently being used in small range high data rate networks, due to their low cost components, maintenance, easy installation and connectorization, as a result of its large core diameter and its high mechanical flexibility. State-of-the-art perfluorinated (PF) GI-POF offers bandwidth length products of around 1 GHz.Km and losses of 10 dB/Km (for 1320 nm).

In this paper we experimentally demonstrate a range extension of the uplink of MB-OFDM UWB (ECMA-368 standard [3]) over GI-POF using a low-cost optical transceiver. Packet error rate (PER) curves as a function of UWB transmitted power are obtained and analyzed. Unlike previous works [1], our setup is mainly focused on the low cost concept, using significantly cheaper components.

2. Emergence of Polymer Optical Fiber

Plastic optical fiber is an emerging medium for very short reach links. The popularity of polymer optical fiber is due to the advantages brought by its large core diameter and mechanical properties. These include connectorization simplicity due to the large numerical aperture, low bending loss that eases installation and low maintenance costs due to its robustness.

Common polymer optical fibers are based on polymethyl methacrylate (PMMA-POF). These fibers exhibit low bandwidth to multimodal dispersion and high attenuation (200 dB/km) hence are not suitable for today's high data rates or radio-over-fiber systems, at least when considering low cost simple transport systems.

Newer perfluorinated graded index polymer optical fiber (PF-GI-POF) from companies such as Sekisui Chemical, Chromis Fiber or Asahi Glass, solve this issue by combining a low attenuation material (about 50 dB/km @ 850 nm) with a graded index profile in their fiber construction.

Bandwidth is very high for graded-index multimode fibers. In practical terms, for short links (<100m), it is limited by capabilities of directly modulate a laser devices [5].

Comparing to common silica multimode fiber (SI-MMF) with respect to data transmission, POF has the potential of high bandwidth and less problems of modal dispersion. Moreover, PF-GI-POF offers lower material dispersion and higher bandwidth than standard MMF [6][7] with 40 Gb/s data transmission capability for 100 m links [5].

Considering the silica-based fibres, the attenuation is not an issue for short link lengths. But for the case of POF the attenuation can be as high as 20 dB for the PMMA-POF or about 5 dB for the state of the art PF-GI-POF when considering a 100 m length link. Large-core glass fiber shows lower attenuation than POF, however their core size is restricted to 200 µm due to the inherently inflexibility of glass. In this situation, POF offers again advantages concerning easy handling and termination, tolerance to misalignments and high mechanical strength [8].

Moreover, the typical large core of polymer fiber allows for large tolerance on misalignments that results in the possibility of using cheaper connectors. For comparison, consider the case of the power loss due to lateral (axial) misalignment of connecting two graded index (parabolic case) MMF with different core diameters. Comparing the power loss, assuming uniformly modal power distributions, for a misalignment of 25 µm, yields a loss of 1.76 dB for a 62.5 µm core diameter MMF whereas for the case of POF with a core diameter of 200 µm, the 25 µm displacement results only in 0.48 dB loss [9]. New PF-GI-POF fibers being developed are able to withstand large temperature variation (-65º to 125º) and so may be suitable for applications in harsh critical environments. The ease of installation, tolerance to alignment and vibration and large temperature variation operation makes these fibers suitable for short-range applications in deployment of fiber in the home environment or in critical applications such as car and avionics industry.

3. Directly modulated Radio-over-Fiber systems

VCSELs are characterized by a vertical low divergent, circular beam patterns, exceedingly low threshold currents (few mA) and high bandwidths (several GHz). Their vertical wafer growth fabrications process enables in-wafer test and so are

well suited for large production series. Due to their output light beam pattern they enable efficient coupling to large numerical aperture polymer optical fibers and so simple plastic injection molded packages are sufficient as fiber coupling devices. These are the reasons that make the use of VCSEL desired for low cost directly modulated systems in these types of commercial widespread applications.

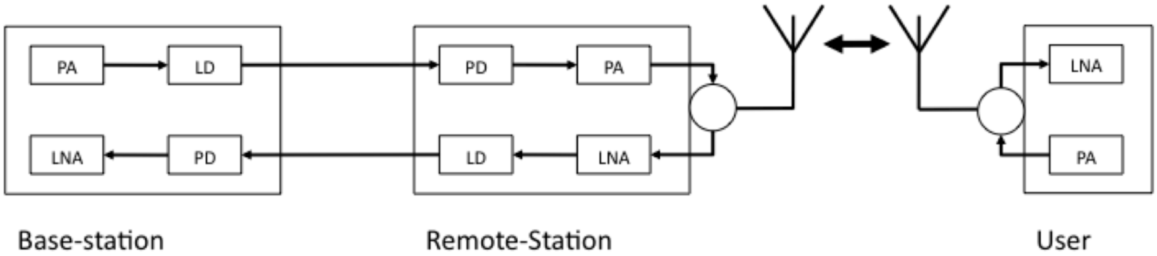


Figure 1: Schematic illustrating the optical and radio link.

The proposed system is based on today's commercially available low cost VCSELs and photodiodes not optimized for radio-over-fiber applications.

Figure 1 represents a schematic of the optical and radio link. In the down-stream direction (base-station to user), the radio signal directly modulates a laser device (LD) through an amplifier (PA). The optical signal is transported through the fiber reaching the remote-station where a photo-diode (PD) converts the optical signal to an electric signal, which is amplified (PA) and fed to the antenna. The user picks up this signal and amplifies it with a low noise amplifier (LNA).

The output optical signal power (P_{OPT} in dBm) at the laser is given, with P_{RF} in dBm, by [10][11][12]:

$$P_{OPT} = \frac{G_{TX} + P_{RF}}{2} + 10\log_{10}\left(G_m \sqrt{1000/Z_{in}}\right) \tag{1}$$

G_{TX} is the PA gain, G_m is the VCSEL modulation gain in mW/mA and Z_{in} the laser input impedance value (assumed constant within the band of interest).

The received electrical power ($P_{RF,USER}$) is on the other turn given by:

$$P_{RF,USER} = G_{RX} + 10\log10\left(R^2 Z_{out}/1000\right) + 2P_{OPT} - 2OL \tag{2}$$

Here G_{RX} is the LNA gain, R is the photodiode responsivity in mA/mW, Z_{out} the photodiode output impedance (also assumed constant within the band of interest) and OL is the optical power loss due to the fiber attenuation and connector 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. This means that any reduction on the transmitted optical power will have a strong impact in the link budget.

Substituting (1) into (2) we obtain the one way link budget defined by:

$$P_{RF,USER} = 20\log_{10}(RG_m) + 10\log_{10}(Z_{out}/Z_{in}) - 2OL + G_{RX} + G_{TX} + P_{RF} - L \tag{3}$$

where L is the wireless link additional loss. The electrical to optical and optical to electrical conversion whose efficiency is given by RG_m is the most pronounced penalty in the power link budget of these systems. In the case of our system this equates to -49 dB. The total electrical gain ($G_{RX} + G_{TX}$) is 60 dB in the uplink direction.

The electrical mismatch of the laser and photodiode has a penalty expressed by $10\log_{10}(Z_{out}/Z_{in})$. Common VCSEL and photodiode devices for commercial data

transmission applications will have a mismatch penalty near 0 dB since they are built for high signal integrity and so low reflections ($Z_{out} \approx Z_{in} \approx 50\Omega$).

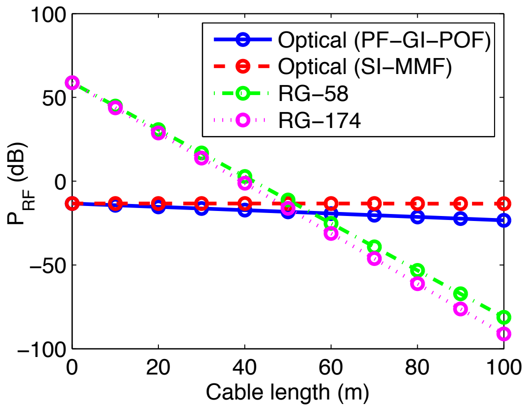


Figure 2: RF power at the remote-station as function of the optical loss.

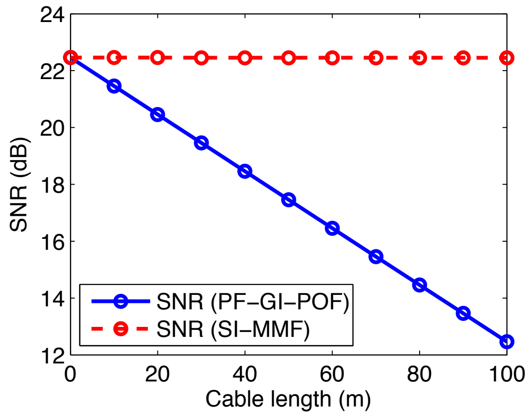


Figure 3: SNR at the remote-station as function of the optical loss.

Figure 2 shows the RF power at the remote-station as function of the optical loss. We considered in the calculations an input power of -19 dBm, which is in agreement with the capabilities of the UWB DVK used in this paper. We compare this result with the loss of common silica multimode fiber (SI-MMF) and RF electrical cables (RG-58 and RG-174 considering the same operating band and the same RF gain as applied to the E/O/E converter). Although there is a penalty by using the E/O/E conversion and optical transport, this is nonetheless very small when compared to the loss suffered by the signal when transported with electrical cable at distances of several tens of meters.

POF attenuation can be in part compensated by extra amplification in the receiver side (G_{RX}), but SNR will decrease due to added noise from the amplifiers. Amplification in the transmitter side (G_{TX}) is limited by the modulation depth and spurious free dynamic range (SFDR) of the laser device.

The relative intensity noise (RIN) of the laser sets a limit to the achievable signal-to-noise at the output of the photodiode in the E/O/E converter. Multiple optical reflections may degrade further system performance [10][11][12]:

$$SNR = P_{RF} + 10\log_{10}\left(G_m^2 / Z_{in}\right) - 2RIN - 20\log_{10} B - 2OL \quad (3)$$

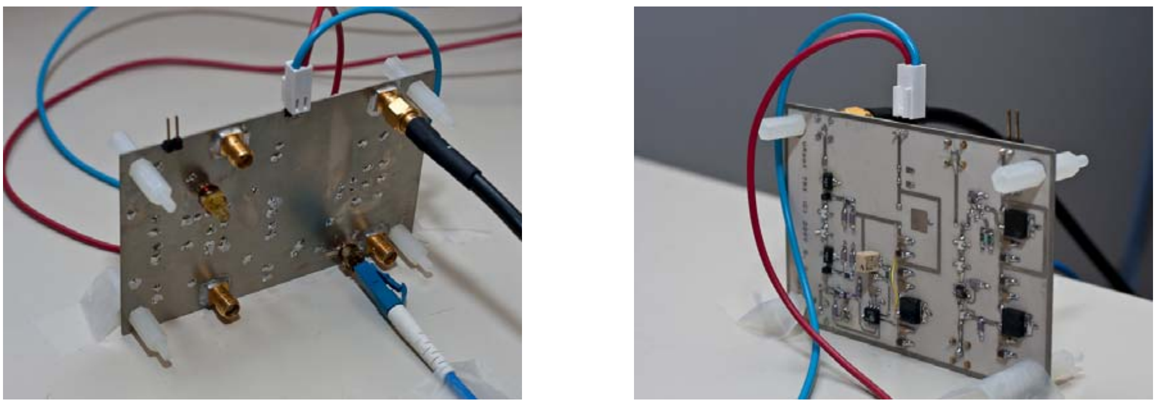


Figure 4: ROF conversion board.

Figure 3 shows the SNR at the remote-station as a function of the cable length for the case of PF-GI-POF and, for comparison, SI-MMF considering a typical $RIN = -130 dB/Hz$ and a bandwidth of $B = 528 MHz$. The SNR will decrease with $P_{RF,USER}$ due to fiber attenuation. And so, in the case of a PF-GI-POF system, the length of fiber that can be used is limited by attenuation and not by dispersion (bandwidth-length product) [5].

MB-OFDM UWB radio applications make extensive use of multiple subcarriers and so require large dynamic range and high linearity devices. The signal transmission is mainly impaired by the nonlinearity of the laser device (LD), the optical loss due to the fiber, the free space loss and noise at the user receiver.

4. Radio-over-Fiber conversion board

Each board (as the one depicted in Figure 4) contains one electrical to optical (E/O) conversion circuit and one optical to electrical (O/E) conversion circuit. A cascade of amplifiers and a polarizing circuit makes up the laser driver for the E/O conversion circuit. A photodiode with integrated amplifier was used for the O/E conversion circuit but an additional amplifier was used to raise the signal to a level suitable for transmission through the antenna.

The amplifiers were chosen between devices with high IP3 (3rd Order Intercept) and low noise figure. High IP3 is essential as to guarantee signal integrity in the case of multiple carrier ultra wide band signals. The VCSELs and photodiode used operate at 850 nm and have a combined bandwidth of about 5 GHz at -3 dB). The modulation gain of the laser and photodiode responsivity are low (0.07 mW/mA and 0.05 mA/mW respectively) hence not optimized for radio-over-fiber. The main system limitations are indeed the combined modulation gain of the laser and photodiode responsivities that together with the high optical losses in the fiber (higher than with silica fiber) limit the system SNR.

The total budget of this system prototype does not exceed 50 €. Considering large scale production of a system like this would easily have a lower price and thus fitting well in the requirements of a widespread commercial application for home or office use.

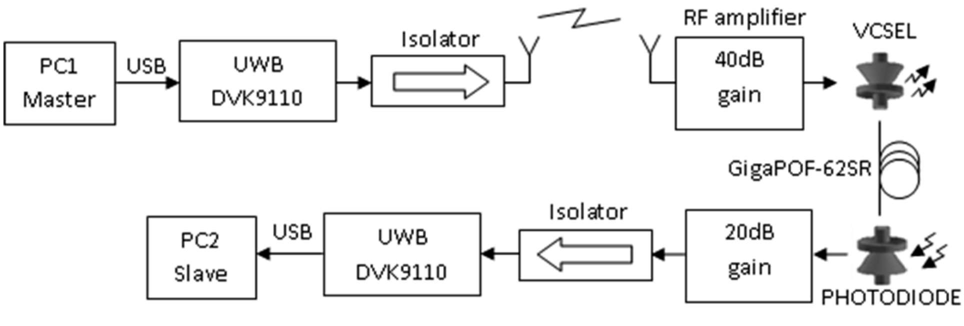


Figure 5: Measurement setup.

5. Experimental setup

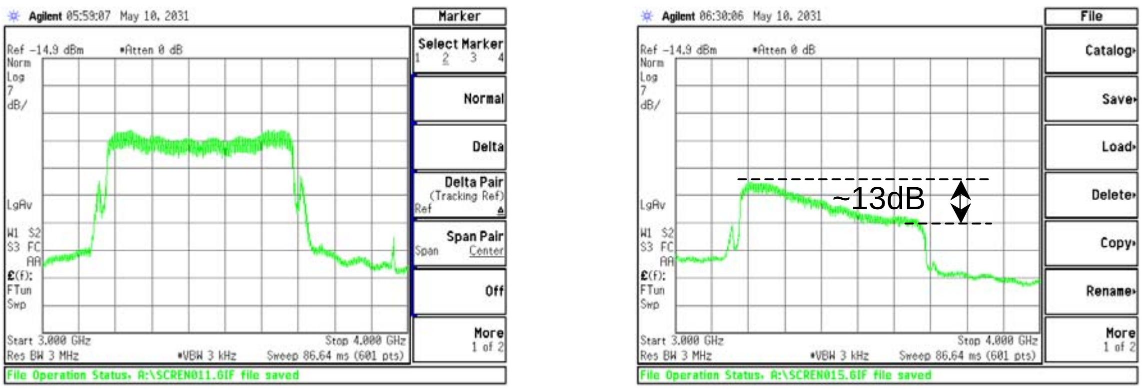
The MB-OFDM UWB over GI-POF system used is shown in Figure 5 and corresponds to a RoF uplink communication. In order to generate MB-OFDM UWB signals complied with the ECMA-368 standard, we have used the commercially available UWB transceiver modules from WisAir (DVK9110M).

The operation band of the kit is band group 1 from 3.168GHz 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. The band group has three sub-bands. Each sub-band has 528 MHz and contains 128 subcarriers.

Although three sub-bands are available for transmission, limitations on the O/E transceiver design (commercial VCSEL, photodiode and amplifiers available at the moment) prevented the usage of the full bandwidth.

The time-frequency code used corresponds to TFC 5 (3.168 GHz to 3.696 GHz). The maximum output power corresponds to EIRP of -14 dBm when using only sub-band one. Therefore, when the gain from the antennas is not considered, the power transmitted by the MB-OFDM UWB DVK is approximately -19 dBm.

In the most part of our experiment we replaced the wireless link by a fixed 40 dB attenuator, which corresponds to the free-space air attenuation of approximately 1 meter. The offered data rate ranges from 53.3 to 480 Mbps. In our measurement, we considered these two extreme cases as well as an intermediate of 200 Mbps.



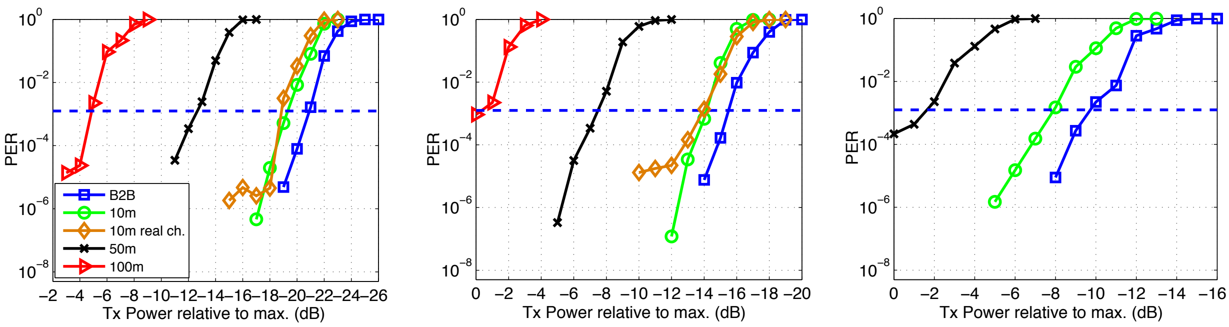
(a) Output of UWB Tx (b) After a 1 meter wireless link and 50 meters of GI-POF

Figure 6: MB-OFDM UWB signal spectra.

6. Measured results

In this section we present and discuss the measured results.

Figure 6 shows the MB-OFDM UWB signal spectra obtained at the (a) UWB DVK output and (b) after a 1 meter wireless link and 50 meters of GI-POF. In addition to the attenuation imposed by the wireless/optical link, it can be seen that subcarriers have different attenuation levels. In fact, a difference of 13 dB between the first and last subcarriers is observed due to the frequency response of the E/O transceiver.



(a) 53.3 Mbps (b) 200 Mbps (c) 480 Mbps

Figure 7: Packet Error Rate vs transmitted power, after a 1 meter wireless link.

In Figure 7 it is depicted the packet error rate (PER) as a function of transmitted power (relative to the maximum allowed defined by the ECMA-368 standard [3]) for different GI-POF lengths and data rates. Experimental results of PER for 53.3 and 200 Mbps using a 1 meter wireless link and 10 meters of GI-POF are shown to be in consonance with the ones using an attenuator of 40 dB instead of the wireless link. Therefore, and for simplicity, the wireless link was replaced by the attenuator. Results show that by increasing the POF length, the PER starts to increase. 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 [3]). Results show that it is possible to transmit 53.3 and 200 Mbps through up to 100 meters of GI-POF, after a 1 meter wireless link.

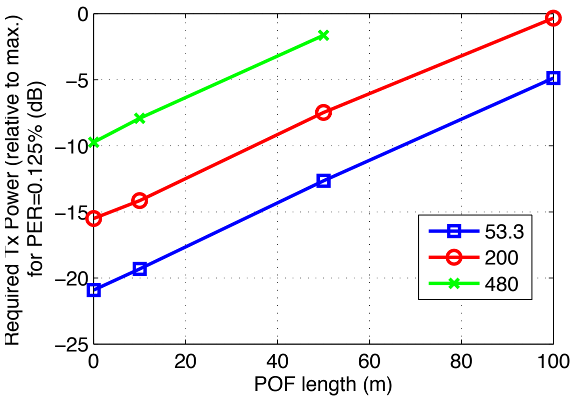


Figure 8: Required signal transmit power after 1 meter wireless to achieve a PER of 0.125% as a function of POF length.

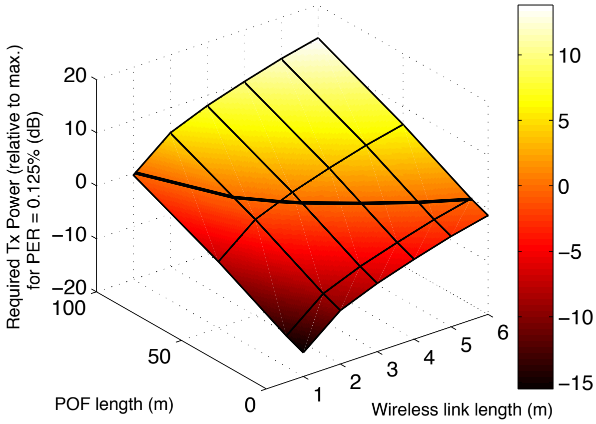


Figure 9: Required signal transmit power to achieve a PER of 0.125% as a function of POF length and wireless link length for 200 Mbps.

Figure 8 shows the minimum required signal power (relative to maximum) to achieve the maximum PER allowed as a function of the GI-POF length. As it is expected, when the data rate increases, the PER increases as well, and the required power to perform a valid transmission increases. Another interesting result is the linear characteristic of the required signal power with the increasing of the GI-POF length. This result shows that the attenuation factor of the GI-POF is the dominant penalty factor among several penalty sources of the fiber.

A generalization of the results plotted in Figure 8 is depicted in Figure 9, for the 200 Mbps data rate transmission. In order to obtain these results, the required signal power for the PER of 0.125% was obtained for wireless links up to 6 meters (with a one meter span) in a back-to-back optical configuration. For the 10, 50 and 100 meters of GI-POF cases, results were extrapolated using the start point given by the back-to-back and knowing that the transmission power increases linearly with the GI-POF length (see Figure 8). Note that the 1 meter wireless link results are the ones plotted in Figure 8 for the 200 Mbps case. The solid black line in Figure 9 indicates the intersection of the surface with the 0 dB plane, which represents the maximum transmitted power. With this result it is possible to see that a 1 meter wireless link followed by a range extension of 100 meter of GI-POF requires the same amount of transmitted power as the 6 meter wireless link with a 10 meter GI-POF link.

7. Conclusion

In this paper we present a radio-over-fiber solution to perform a range extension of a MB-OFDM UWB signal transmission, based on low cost components. Results have shown that it is possible to transmit 480 Mbps over a 1 meter wireless link followed by a 50 meters GI-POF range extension or 100 meters of GI-POF, when data rates of 53.3 and 200 Mbps are considered. It is demonstrated that GI-POF is a viable solution for the transport of MB-OFDM UWB signals, which may find applications in the home environment as well as in more demanding harsh environments such as the avionic industry.

Acknowledgements

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