Survey of short area networks based on optical wired and wireless media

Nikolaos D. Raptis[*]

National and Kapodistrian University of Athens,
Department of Informatics and Telecommunications
raptis@di.uoa.gr

Abstract. In the present dissertation, the main target was to implement short area networks with range of tens of meters using optical media. The work was separated in two large sections. The first one concerned the implementation of indoor wired transmissions covering distances between 50 m and 100 m using Large Core Step-Index Plastic Optical Fibers (SI-POFs) made of polymethyl methacrylate (PMMA). The motivation was the necessity to deal with the rather large power losses and the low bandwidth of such fibers. The bandwidth of several SI-POF segments of different manufacturers increased by about 40% and the losses slightly decreased after passing them through a specific thermal treatment. The only limitation was the direct connection of the source with the SI-POF. The behavior of the SI-POFs remained improved to the same extent during an interval larger than a year. In the second part, diffused optical wireless transmissions at 265 nm were investigated. The target ranges were a few tens of meters. The bit rates that were applied were of kilobit per second order. The motivation was the necessity to deal with (i) the inability to deploy Non-Line-Of-Sight (NLOS) optical wireless links under several atmospheric conditions and (ii) the ambient noise that may have severe impact on such links. Both requirements were satisfied using the solar-blind part in the C-band of the Ultraviolet (UV-C) spectrum. It was proven theoretically and experimentally that the power losses of such links after applying transmissions at 265 nm are large but can be reduced significantly under harsh atmospheric conditions of artificial fog appearance. The lower losses under thick atmosphere conditions ensured the better performance of the low-rate signals that were transmitted, as well.

Keywords: thermal treatment of plastic optical fibers, bandwidth, bit error rate, pulse position modulation, solar-blind UV-C band, optical wireless communications, scattering, absorption.

1 Introduction

In this survey, two sections were covered that concerned the investigation of the potential deployment of links for short distances that are based on optical technologies. The first section concerns wired transmissions. Provided that data rates in the access

[*] Dissertation Advisor: Dimitris Syvridis, Professor.

network segment are expected to increase in the near future, the adoption of optical fibers becomes necessary. In an environment where optical cabling dominates, an issue that emerges is the type of fiber that will be selected for covering tens of meters in indoor areas. A cost-effective choice is the SI-POFs with 980 μm core diameter manufactured using PMMA. Despite their advantages, they have significant limitations that would prohibit their massive installation. The limitations are the increased power losses and the limited bandwidth. The question that was answered was how feasible is the direct intervention in the POF, in order its attributes to be modified. The results were a bandwidth increase of almost 40% and a slight decrease of the losses of the POFs that went through a specific heating procedure. For each 50 m POF segment that was thermally treated, a respective reference fiber of equal length from the same manufacturer was used for the comparisons. The profitable results appeared under the condition of direct connection of the laser with the POF, with the narrow optical beam launched focused in the center of the fiber core. However, under overfilled launching conditions, the thermally treated POFs gave similar results to those of the respective reference POFs in terms of bandwidth, whereas a slight decrease of the losses of the thermally treated fibers was measured again. During a longer than a year interval of occasional measurements, the improvement of the thermally treated fibers was preserved. The explanation of the phenomena was confirmed through simulations and the theoretical results were compatible with the respective experimental results.

In the second section, which concerns the optical wireless transmissions in an outdoor environment, the target was the coverage of short distances under the regime of diffuse transmissions with low data rates. The requirements that were defined were the absence of Line-Of-Sight (LOS) components in the link and the insignificant degradation of the link operation due to the ambient noise, especially by the sun. The NLOS regime imposes the existence of a mechanism that will enable the diffused transmissions. This mechanism is the scattering due to the molecules and the aerosols in the atmosphere. Wavelengths of conventional optical wireless communication systems do not scatter intensely, whereas the noise level of the sun that reaches the earth surface in such wavelengths is not negligible. A band that allows the realization of transmissions in a diffused way with a particularly low power level from the sun on the earth's surface lies between 200 nm and 280 nm and is called solar-blind UV-C band. Initially, the survey included the channel modeling of point-to-point links applying single and multi-scattering schemes at 265 nm. Moreover, transmissions of pulsed and multicarrier signals were considered and the operation of a simple network infrastructure was modeled, as well. In the network scenario, the access to the medium was regulated by a Code Division Multiple Access (CDMA) scheme. Apart from the transmission under clear atmosphere conditions, the issue of the operation under a thicker atmosphere regime was also investigated. According to the results, a significant decrease of the power losses and an amelioration of the bandwidth appeared. The deviation from the initial results obtained under clear sky conditions was a function of the atmosphere density and the size of the scattering centers' radii that were taken into account in the more complex version of the models that were regarded for some geometric configurations. In terms of the theoretical transmissions of signals, the propagation through a medium with larger density resulted in the reduction of the required power levels for the operation of the links in specific performance boundaries and the limitation of the intersymbol interference in cases where the bandwidth was low under the clear atmosphere regime. Furthermore, in the networking scenario, when multiple nodes transmitted simultaneously according to a probability, the lower optical power levels required in order to achieve specific Bit Error Rate (BER) values under a thick atmosphere case compared to the case of clear atmosphere were verified. The simulation results indicated that NLOS links at 265 nm could be implemented and operate successfully. Therefore, the next step would be the experimental measurements. In this part, point-to-point links were deployed. In the optical part, the transmitter consisted of Light Emitting Diodes (LEDs) at 265 nm and at the receiving side an optical filter was followed by a Photo-Multiplier Tube (PMT). The first stage included the measurement of the power losses in clear atmosphere up to 20 m range, for a large set of transmitter and receiver elevation angles. When artificial fog appeared in the medium using a fog machine, a clear decrease of the losses was measured, which was different for several link distances and several elevation angle pairs when deploying NLOS configurations. For some links that were tested, the reduction of the losses was over 7 dB during a large number of successive samples of the received signals. The lowest values of the measured losses for some configurations were more than 10 dB lower than in clear atmosphere. The second stage of the experimental measurements included the performance evaluation of links in terms of BER for transmissions of a fourth order Pulse Position Modulated (4-PPM) signal [1] and a Flip-Orthogonal Frequency Division Multiplexed (Flip-OFDM) signal [2] for kbit/s rates. The BER for 10 kbit/s was measured for the largest number of elevation angle pairs that could be settled and for the same distances as in the losses measurements set. The optimum demodulation of 4-PPM was the reason of its superiority. Then, the fog machine was used for the evaluation of the impact of the medium thickening on the performance of the links under investigation. When artificial fog appeared, the expected decrease of BER at 10 kbit/s rate for 4-PPM and Flip-OFDM and at 4 kbit/s for Flip-OFDM was verified for several NLOS configurations. The amelioration was over 2 orders of magnitude for some link cases than the respective measurements under clear sky conditions. Finally, the impact of fog on LOS links was investigated, where the filter and the PMT were replaced by a proper lens and a pin photodiode. The appearance of fog had a devastating impact on performance, as a significant increase of the losses and deterioration of the BER appeared.

2 Optical Communication Systems Using SI-POFs

In the near future, the data rates will increase even in households. A cable that can support the increasing rates will be required in indoor environments for covering short ranges. A possible solution could be the Large Core PMMA SI-POFs, SI-POFs in short, due to their low cost and easy handling. Nevertheless, the SI-POFs suffer from rather large attenuation, whereas severe constraints are imposed on the transmission rate due to their increased modal dispersion. Intensive theoretical and experimental efforts have been made in order to mitigate the effect of limited bandwidth of SI-

POFs for distances between 50 and 100 m [3]-[9]. However, the bandwidth limitation is still present. It was examined if the power losses and the bandwidth could be improved by intervening directly in the channel. It was shown experimentally and verified theoretically that an increase in bandwidth and a slight decrease of the attenuation can be achieved by treating thermally an SI-POF following a specific procedure.

2.1 Theoretical Explanation of the Bandwidth Limitation of SI-POFs

Supposing that a narrow and well collimated beam is launched at the central part of the POF core, exciting only lower order modes, the origins of higher order modes activation are the inhomogeneities and impurities in the core material, which act as scattering centers for the incident beam, resulting in coupling of optical energy to higher order modes. The outcome is the lower bandwidth due to higher accumulated modal dispersion. If a mechanism existed that could "eliminate" as many as possible scattering centers along a POF, then the coupling length of the POF [10] would increase and the higher order modes would not be activated at short lengths. Additionally, the irregularities at the core-cladding boundaries may have critical effect on the accumulated modal dispersion, as well. The desired mechanism should deal with the two scattering "areas". The power coupling between modes and the influence of the non-ideal core-cladding boundaries can be visualized by the Gloge's time-dependent power flow equation given below [10] that outlines the light propagation along a POF

$$\frac{\partial p(\theta,z,t)}{\partial z} = -a(\theta)\times p(\theta,z,t) - \tau_{tr,rel}(\theta)\times\frac{\partial p(\theta,z,t)}{\partial t} + \frac{1}{\theta}\times\frac{\partial}{\partial\theta}\left[\theta\times D\times\frac{\partial p(\theta,z,t)}{\partial\theta}\right] \quad (1)$$

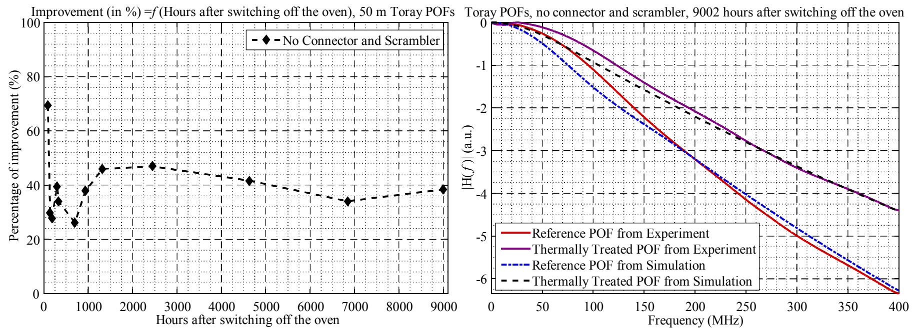
where z represents the length dimension, t is the time variable, θ is the propagation angle with respect to the fiber axis, $p(\theta, z, t)$ is the power distribution over angle, space and time, $a(\theta)$ is the mode dependent attenuation, $\tau_{tr,rel}(\theta)$ is the relative mode delay and D is the coupling coefficient.

Three terms are added to give $a(\theta)$. One of them appears due to reflections of modes at the core-cladding interface and is proportional to $-ln(R_{refl})$, where R_{refl} is the reflection factor with $0 \leq R_{refl} \leq 1$ [4]. By decreasing R_{refl} and considering more irregular core-cladding boundaries, the reflected power into the POF is severely decreased during light propagation and the activated higher order modes will appear intensely attenuated at the end of the POF compared to a POF with higher R_{refl}, leading to bandwidth increase. Therefore, the R_{refl} decrease would have a favorable impact on bandwidth. The coupling coefficient D is related to all the scattering sources in the core [10]. If D is decreased, the core is considered more homogeneous, and assuming central launching of a focused laser beam, a lower number of higher order modes will appear at fiber end, resulting in larger bandwidth for a fiber with a length shorter than its coupling length. Therefore, a contradiction would appear between the improved core homogeneity and the improved irregularities at the core-cladding boundaries in terms of bandwidth of a properly manufactured fiber. We decided to proceed to a thermal curing of SI-POF specimens of 50 m and 100 m length, targeting at increasing their homogeneity. Such a procedure decreased D and increased slightly R_{refl}.

2.2 Heating Procedure and Experimental Results

Focusing on 50 m segments, two types of commercially available SI-POFs have been used: those having Numerical Aperture (NA) of 0.46, provided by Luceat and those having NA of 0.5, provided by Toray. For both types, the core and cladding diameters were 0.980 and 1 mm, respectively. For each POF type, a pair has been used in all the experiments; one serving as a reference and the other to be treated thermally. Both POFs of the same pair were wrapped in loose loops of equal diameters and were kept in the loop state before, during and after the heating procedure. It was experimentally confirmed that the POFs of the same pair had the same bandwidth and attenuation, before the procedure begun. For the thermal treatment, an oven with adjustable temperature was used. About 1.0 m of each end of the POFs to be heated was kept outside the oven. The heating process consisted of increasing the temperature of the oven by 5^{o}C every 20 minutes up to 75^{o}C. After 20 minutes at 75^{o}C, the temperature was reduced to 65^{o}C and kept at that level for 1 hour. Finally, the POFs were left to cool slowly, reaching the ambient temperature (25^{o}C) after approximately 1 hour. This process decreased the scattering centers and the ameliorated core homogeneity surpassed the impact of the improved core-cladding irregularities, resulting in larger bandwidth after the thermal treatment [11]. The requirement is the direct connection of the source with the POF. The source was a laser and the beam with a waist much smaller than the POF's diameter was launched in each POF sample aligned with the core. The disadvantages were a slight deformation of the thermally treated POFs and the inability to generate exactly the same improvement after repeating this procedure for different POF samples of the same length even from the same reel.

A set of bandwidth values obtained after occasional measurements in an interval of thousands hours for both SI-POF pairs gave a clear indication of the performance improvement. In the experimental setup, a Fabry-Perot Laser Diode at 653 nm was connected directly with the POF. The POF was directly connected to the photodiode, as well. After reception, the frequency response of the electrical signal was measured. Before each measurement, the whole system was calibrated using a 0.3 m piece of SI-POF in order to isolate exclusively the optical frequency response of the fiber. The evolution of the fiber bandwidth enhancement with time appears in Fig. 1(a) for the 50 m POF pair of Toray. The horizontal axis corresponds to the hours that have passed after the end of the treatment. The vertical axis corresponds to the bandwidth improvement of the treated POF relative to the reference one. A sequence of ten bandwidth measurements has been performed for both the thermally treated and the reference POFs and the difference of their mean bandwidths has been drawn as a percentage value. As it can be observed in Fig. 1(a), after some fluctuations during the first few hundreds of hours, the bandwidth of the thermally treated fiber stabilized at more than 30% higher values than those of the reference fiber. Even 9002 hours after the end of the treatment, the improvement was close to 38.40%. The mean bandwidth enhancement was close to 39.28% from all the measurements. Concerning the optical losses of the thermally treated POF, a decrease between 0.35 dB and 0.64 dB appeared during the respective measurements in the 9002 hours interval. A similar behavior appeared for the thermally treated POF of Luceat. More specifically, the mean bandwidth increase of the treated POF compared to the one of the reference POF was around 42.78% and the losses were decreased in a range between 0.5 and 0.95 dB in an interval of 11900 hours after switching off the oven.



(a) (b)

Fig. 1. (a) Optical bandwidth improvement for the thermally treated Toray POF as a function of time for direct connection of the source with the fiber. (b) Experimental snapshots of the amplitude of the frequency response of the two Toray POFs, 9002 hours after switching off the oven and the respective frequency response amplitudes after numerical solution of (1).

Two snapshots of the magnitude of the frequency response of the thermally treated and the reference Toray POFs, captured 9002 hours after switching off the oven, are depicted in Fig. 1(b) as solid curves. The optical bandwidth at 3 dB of the snapshot of the treated POF is almost 267.47 MHz. About 189.03 MHz was the measured bandwidth of the reference POF. It was crucial to confirm if the impact of the reduction of D and the slight increase of R_{refl} achieved after the thermal treatment agreed with the experimental results. For this reason, (1) was solved numerically. The central launching of a Gaussian beam at 650 nm with $\sigma = 3^{o}$ (inside the POF) was considered. NA = 0.50 and core refractive index n_{core} = 1.492 were set for both POFs. $D = 3.18\times10^{-4}$ rad^2/m and R_{refl} = 0.99982 for the reference and $D = 1.51\times10^{-4}$ rad^2/m and R_{refl} = 0.99991 for the thermally treated POF were defined. In Fig. 1(b), the dashed-dotted and the dashed curves represent the amplitudes of the theoretical frequency response of the fibers that correspond to the reference and the treated POFs, respectively. These curves both follow quite well the respective experimental curves. The theoretically obtained optical bandwidths were 188.16 MHz and 267.52 MHz, for the reference and the treated POFs, respectively, verifying further the explanations of the improvement.

An issue that appeared was the behavior of each POF under overfilled launching conditions. With all modes present from the beginning of the span, the contention between the two mechanisms, i.e. the attenuation of higher order modes due to the irregularities at the core-cladding boundaries and the (re)activation of higher order modes due to the core impurities, is expected to result in no bandwidth improvement for the treated POFs. The experimental frequency responses of both Toray POFs verified the expectation when overfilled launching was applied 9002 hours after switching off the oven, as 96.72 MHz and 99.71 MHz were the bandwidths of the reference and the thermally treated POF, respectively. Theoretical bandwidths close to the experimental values were estimated for both POFs. In terms of the losses, a decrease between 0.50 dB and 0.85 dB was obtained for the treated POF from all the measurement sets under this launching regime. A similar behavior to that of the Toray POFs appeared for the Luceat POFs under overfilled launching conditions, as well.

For direct connection of the laser with each POF, the bandwidth superiority of the heated POFs remained constant up to the moment of the last measurements. The bandwidth increase of the thermally treated POFs disappeared under overfilled launching conditions, though. A slight decrease of the losses appeared for the thermally treated POFs under both launching conditions. The assumptions that after the thermal treating the scattering centers in the POF core diminished (decrease of D) and the irregularities at the core-cladding boundaries are reduced (slight increase of R_{refl}), are realistic producing compatible theoretical results to the experimental ones.

3 Communication Systems Using Diffuse Light

Conventional communication systems may fail in environments with intentional jamming or interference, combined with dense atmosphere and/or complex configurations due to obstacles. A solution can be the solar-blind UV-C band, whose tempting features are the significantly reduced solar irradiance on earth's ground, the intense scattering [12] which offers the way to set up NLOS links and its combination with strong absorption which ensures covertness [13]. In the present section, apart from investigating theoretically and experimentally the losses and the BER performance of low rate short-range NLOS links at 265 nm under clear atmospheric conditions, a second crucial target was to examine how strong scattering in a denser medium affects the performance of such links.

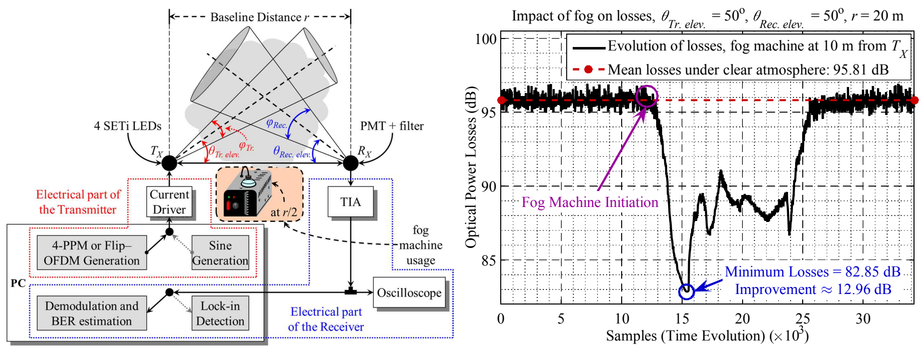
3.1 Theoretical estimations

The performance improvement of NLOS systems at 265 nm when the medium thickened was numerically demonstrated for short ranges and two scenarios; a point-to-point and a networking one. For the configurations and all the modulation formats that were investigated, the lower losses of the thicker medium imposed lower emitted power levels. For the same configurations, higher bandwidth values were estimated under thick atmospheric conditions [14], [15]. These results were evaluated using two theoretical channel models; a single-scattering channel model [15] and a Monte-Carlo approach that supports multiple scattering events per photon [16], which was more reliable in cases where higher order scattering events must be taken into account.

In a networking scenario where a few nodes transmitted to a central one at 265 nm establishing NLOS links with ranges up to 50 m in a sparse medium, the application of a CDMA protocol may cause significant limitations [15]. The enhanced bandwidth and the lower losses of the channels in a thick environment allowed the transmission of encoded signals without requiring extreme emitted power levels in order specific BER values to be achieved, making the connections to the central node feasible.

3.2 Experimental Setup for Measuring either the Losses or the BER

The setup could be used for measuring either the power losses or the BER, as shown in Fig. 2(a). The elevation angles of both the transmitter ($\theta_{Tr.\ elev.}$) and the receiver ($\theta_{Rec.\ elev.}$) and the range (r) could be adjusted. The transmitter consisted of 4 LEDs (by SETi) emitting at 265 nm. The receiver consisted of a PMT (R7154 by Hamamatsu) with an optical filter (transmittance = 0.17) in front of it. The LEDs' divergence angle ($\varphi_{Tr.}$) and the receiver's Field-of-View ($\varphi_{Rec.}$) were 10^o and 30^o, approximately. The PMT was followed by a Trans-Impedance Amplifier (TIA).



(a) (b)

Fig. 2. (a) Experimental setup. PC: Personal Computer. (b) Time evolution of the losses without and with fog in the medium, for $\theta_{Tr.\ elev.} = \theta_{Rec.\ elev.} = 50^o$, $r = 20$ m.

The LEDs intensity was directly modulated. The losses were estimated by producing a 1 KHz sine signal and applying a lock-in detection scheme [16]. The sources were biased to the same point that provided close to 1 mW mean optical power per LED. For the set of BER measurements, slightly less than 0.5 mW mean optical power was emitted by each LED. Non-linearity issues were avoided. 4-PPM and Flip-OFDM were examined [2], [17]. The same root mean square voltage was generated for both schemes for fair comparisons due to the AC coupled TIA output. For 4-PPM, maximum likelihood detection without threshold was applied after integrate-and-dump filtering in slot duration level. For each Flip-OFDM symbol, 256×2 subcarriers were used. A fog machine [17], [18] was used to increase the thickness of the medium artificially. It was set to $r/2$ in all link cases. It was examined if stronger scattering in a thicker medium would result in the reduction of the losses or BER of NLOS links.

3.3 Experimental Measurements of the Power Losses and the BER under Clear Sky and Foggy Conditions

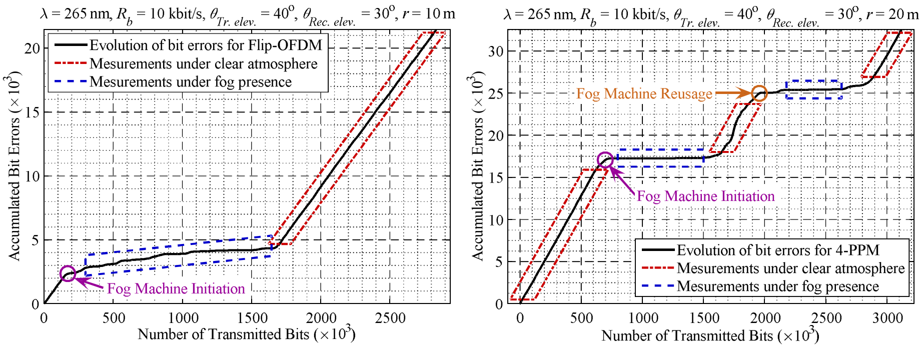
The power losses were measured for a large combination of transmitter and receiver elevation angles and 5, 10 and 20 m ranges under clear atmosphere conditions. The losses were below 60 dB only when both LOS components existed in the links and r = 5 m. The losses increase with distance was intense. When r = 10 m and $\theta_{Tr.\ elev.}$, $\theta_{Rec.}$

$_{elev.}$ were both over 40^o in order NLOS links to be established, the losses were over 80 dB. For r = 20 m and $\theta_{Tr.\ elev.}$, $\theta_{Rec.\ elev.}$ over 40^o, the losses were over 90 dB. Therefore, the NLOS links were deployed due to the dominance of scattering over absorption in a sparse medium at 265 nm. The losses were significantly high, though.

A wireless environment rich in scattering centers is expected to exhibit lower losses for short distances (r < 50 m) and transmissions at 265 nm, an expectation reinforced by the theoretical results in 3.1. The medium was thickened intentionally using the aforementioned fog machine for experimental verification. After the initial convergence of the lock-in stage, the operation of the fog machine started and during its operation, the impact of fog was observed until the machine was stopped, leaving the detector to converge again to the initial losses. This procedure was repeated for each examined configuration up to 20 m, reusing the machine in order to ensure the reappearance of the results. A representative scenario is depicted in Fig. 2(b). Time samples in thousands values are shown on the horizontal axis. The vertical axis represents the instant values of the losses. Each sample is obtained every 5 msec. After setting the elevation angles, the distance and the PMT gain to $\theta_{Tr.\ elev.} = \theta_{Rec.\ elev.} = 50^o$, r = 20 m and 4.51×10^6, respectively, the transmission of the modulated carrier with the sine signal started. The mean losses in clear atmosphere were estimated close to 95.81 dB for this set of measurements. After 12100 samples the operation of the fog machine started. The denser medium resulted in an immediate reduction of the losses. The minimum value of 82.85 dB was the lowest one than all the measured values for this configuration. The losses diminished by almost 13 dB meaning that the received optical power was 20 times higher than the level measured in clear atmosphere. Despite the instability of the medium, after the 18500th sample the losses remained lower than 90 dB for more than 5000 samples, i.e. almost 4 times higher received power than initially for more than 25 sec, before the rapid dissolution of fog. The losses of all the NLOS links at 265 nm that were examined exhibited definitely a decreasing behavior when fog appeared, even when an obstacle was placed at r/2 in some cases [16].

BER measurements were obtained for R_b = 10 kbit/s rate, whereas the ranges that were studied were 5, 10 and 20 m for many geometric configurations. For this rate, 30 subcarriers carried data Quadrature Phase Shift Keying symbols per Flip-OFDM symbol. Under clear sky conditions, the performance of 4-PPM was better compared to that of Flip-OFDM due to the optimal demodulation of the former. The superiority of 4-PPM was clear in intermediate elevation angles which ensured the NLOS operation of the links. However, for large elevation angles, the superiority of 4-PPM was rather mitigated due to the decreased received power levels and the deterioration of the Signal-to-Noise-Ratio. The limitations due to the higher losses at large elevation angles became more severe at r = 20 m. The transmissions were not bandwidth limited for the examined rates [19]. Consequently, for the tenuous medium and the emitted power levels applied here, 4-PPM outperformed Flip-OFDM, as 4-PPM fitted better to loss limited NLOS links at 265 nm up to r = 20 m, provided that the losses are not extreme due to the increased range and the large elevation angles.

The decreasing behavior of the losses under fog presence was exploited in order to increase the received optical power and decrease the BER in NLOS links for the distances and the bit rate examined so far. The impact of fog on BER is presented on curves where the horizontal axis depicts the transmitted bits and the vertical axis depicts the respective accumulated bit errors [17], [18]. The slope of such curves is the BER. If any change in the medium affects the losses, such as the number of the scattering centers, then the slope will be modified locally. Therefore, the behavior of BER for a specific configuration due to the absence and then the presence of fog can be evaluated experimentally. In order to do so for Flip-OFDM, the following parameters were set: r = 10 m, $\theta_{Tr.\ elev.}$ = 40°, $\theta_{Rec.\ elev.}$ = 30° and the PMT gain close to 7×10^5. All measurements were carried out in real-time. The respective curve appears in Fig. 3(a). The values in both axes of both curves in Fig. 3 are in thousands bits. The fog machine was initiated after roughly 1.72×10^5 transmitted bits. The blue dashed parallelogram indicates an interval of 1529 accumulated bit errors for almost 1.345×10^6 received bits giving BER ≈ 1.14×10^{-3} locally. Then, the machine was stopped and the fog dissolved rapidly. For the rest of the curve covered by the red dashed-dotted parallelogram, the slope was 1.48×10^{-2} (16553 bit errors for 1.118×10^6 received bits).



(a) (b)

Fig. 3. Evolution of bit error accumulation for $\theta_{Tr.\ elev.}$ = 40°, $\theta_{Rec.\ elev.}$ = 30°, R_b = 10 kbit/s and (a) Flip-OFDM at r = 10 m and (b) 4-PPM at r = 20 m.

Keeping $\theta_{Tr.\ elev.}$ = 40°, $\theta_{Rec.\ elev.}$ = 30° and setting r = 20 m and the gain of the PMT close to 2.00×10^6, a 4-PPM signal was transmitted at the same rate. The impact of fog on BER is displayed in Fig. 3(b). Initially, under clear atmosphere, for 6×10^5 transmitted bits, 15393 errors occurred and BER ≈ 2.57×10^{-2} was measured. This part is highlighted by the first red dashed-dotted parallelogram. Just before the transmission of 7×10^5 bits, the operation of the machine initiated. During fog production which is pointed by the blue dashed parallelogram, only 20 errors appeared for a 7×10^5 transmitted bits, and the BER became 2.86×10^{-5}, that is 3 orders of magnitude lower than the initial BER. After fog dissolution, according to the second red dashed-dotted parallelogram, the BER was restored to 2.60×10^{-2}. Just after 1.95×10^6 bits, the machine was reused. For 4.5×10^5 received bits (noted by the second blue dashed parallelogram) the BER changed to 1.91×10^{-4}, almost one order of magnitude higher than the previous measurement with fog present, due to the more inhomogeneous coverage with fog than previously. The improvement is not canceled, though. The BER became 2.43×10^{-2} for the last part of the curve. It is evident that when fog appeared, the performance was enhanced for both configurations that were presented and for many others that were investigated under the presence of fog for distances up to 20 m.

4 Final Conclusions

The main target of this work was separated in two branches. The first one was to cover distances of tens of meters in indoor environments using SI-POFs, while trying to deal with the disadvantages of the channel. The second one was the coverage of tens of meters distances in outdoor environments using the scattering of atmosphere as the mean to deploy optical wireless NLOS links. The wavelength range between 200 and 280 nm has some favorable attributes that can be exploited in order to deploy such links. A simultaneous task was the investigation of the impact of the atmosphere thickness on the performance of NLOS links.

In the wired transmissions, when SI-POFs from different manufacturers were treated thermally following a specific procedure, a mean 35-40% bandwidth increase appeared in more than a year interval compared to the bandwidth of the respective reference SI-POFs of the same manufacturers. The requirement was the direct connection of the laser with the POF. Otherwise, under overfilled launching conditions, both the thermally treated and the respective reference SI-POFs presented similar bandwidths. A slight decrease of the losses appeared in all treated POFs. An open issue is the optimization of the treating procedure is crucial in order to achieve the highest possible improvement. The systematic investigation of the impact of a similar thermal procedure on Graded-Index POFs (GI-POFs) could be an interesting issue, as well.

In the wireless part, the experimental results for transmissions at 265 nm showed the feasibility to establish functional outdoor wireless NLOS links in the solar-blind part of the UV-C band under clear atmosphere. The main attributes were the increased but not prohibitive power losses and the low bit rates that could be supported. A clear dominance of scattering over absorption was proven experimentally and validated by theoretical results when the atmosphere became thicker. This was verified for several NLOS links by measuring not only the losses but also the BER when artificial fog was inserted in the medium. Therefore, it was confirmed that the part of the UV-C band between 200 and 280 nm is a strong candidate in applications where the operation of short range and low bit rate NLOS optical wireless links is required under harsh atmospheric conditions and covertness. A further step can be the optimization of the emitted power levels in order to deploy as distant as possible NLOS links, in accepted limits in terms of eye safety, though. Other critical issues are the deployment of functional network clusters and the implementation of multiple access protocols that suit better to the nature of the power-limited NLOS channels. In terms of other applications, the underlying technology can be used as a supplementary choice to conventional technologies when the latter fail. For instance, combined with the 802.15.7 standard [20], the concept of intelligent transport can be enhanced. Finally, the immediate and intense change of the losses in NLOS links at 265 nm when the thickness of the medium altered is an attribute that can be exploited in local weather prediction systems as a supplementary alternative to other mature technologies.

References

1. He, Q., Sadler, B. M., Xu, Z.: Modulation and coding tradeoffs for non-line-of-sight ultraviolet communications. In Proceedings of SPIE, 7464, San Diego, CA, USA, (2009).
2. Fernando, N., Hong, Y., Viterbo, E.: Flip-OFDM for unipolar communication systems. IEEE Transactions on Communications 60(12), 3726–3733 (2012).
3. Lee, S. C. J. et al.: Discrete multitone modulation for maximizing transmission rate in step-index plastic optical fibers. Journal of Lightwave Technology 27(11), 1503–1513 (2009).
4. Breyer, F.: Multilevel transmission and equalization for polymer optical fiber systems. Ph.D. Dissertation, Dept. Tecnhische Universität München, München, Germany, 2010.
5. Grivas, E., Raptis, N., Syvridis, D.: An optical mode filtering technique for the improvement of the large core SI-POF link performance. Journal of Lightwave Technology 28(12), 1796–1801 (2010).
6. Raptis, N. et al.: Space-time block code based MIMO encoding for large core step index plastic optical fiber transmission systems, Optics Express 19(11), 10336–10350 (2011).
7. Raptis, N. et al.: Space-time block codes application in large core step-index plastic optical fibers. In Proceedings of POF 2011, pp. 31–36, Bilbao, Spain (2011).
8. Pikasis, E. et al.: A space-frequency block encoded OFDM scheme for short area POF networks. In Proceedings of POF 2011, pp. 537–541, Bilbao, Spain (2011).
9. Pikasis, E. et al.: Performance evaluation of CDMA-DMT for 1-mm SI-POF short-range transmission links, IEEE Photonics Technology Letters 24(22), 2042–2045 (2012).
10. Drljača, B., Djordjevich, A., Savović, S.: Frequency response in step-index plastic optical fibers obtained by numerical solution of the time-dependent power flow equation. Optics and Laser Technology 44(6), 1808–1812 (2012).
11. Raptis, N., Syvridis, D.: Bandwidth enhancement of step index plastic optical fibers through a thermal treatment. IEEE Photonics Technology Letters 25(16), 1642–1645 (2013).
12. Xu, Z., Sadler, B. M.: Ultraviolet communications: potential and state-of-the-art. IEEE Communications Magazine 48(5), 67–73 (2008).
13. Junge, D. M.: Non-line-of-sight electro-optic laser computations in the middle ultraviolet. M.S. thesis, Naval Postgraduate School, Monterey, CA, USA (1977).
14. Raptis, N., Roditi, E., Syvridis, D.: Power-spectrum requirements in ultraviolet optical wireless networks. In Proceedings of SPIE, 9354-2, San Francisco, CA, US (2015).
15. Raptis, N., Pikasis, E., Syvridis, D.: Performance evaluation of modulation and multiple access schemes in ultraviolet optical wireless connections for two atmosphere thickness cases. Journal of Optical Society of America A 33(8), 1628–1640 (2016).
16. Raptis, N., Pikasis, E., Syvridis, D.: Power losses in diffuse ultraviolet optical communications channels. Optics Letters 41(18), 4421–4424 (2016).
17. Raptis, N., Pikasis, E., Syvridis, D.: Performance evaluation of non-line-of-sight optical communication system operating in the solar-blind ultraviolet spectrum. In Proceedings of SPIE, 9991-3, Edinburgh, UK (2016).
18. Raptis, N. et al.: Experimental evaluation of modulation formats' performance in diffuse UV channels. IEEE Photonics Technology Letters 29(11), 887–900 (2017).
19. Chen, G., Xu, Z., Sadler, B. M.: Experimental demonstration of ultraviolet pulse broadening in short-range non-line-of-sight communication channels. Optics Express 18(10), 10500–10509 (2010).
20. Rajagopal, S., Roberts, R. D., Lim, S.-K.: IEEE 802.15.7 visible light communication: modulation schemes and dimming support. IEEE Communications Magazine 50(3), 72–82 (2012).