WDM-FSO EXPERIMENTAL SETUP

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This paper presents some theoretical aspects of a FSO (Free Space Optics) model and an experimental WDM (Wavelength Division Multiplexing) over FSO duplex line-of-sight optical communications system. The link quality and availability are evaluated using statistical tools and atmospheric turbulence models. The transmission bitrate, the transmission length, the BER (Bit Error Rate) performance and the latency of the link are measured and discussed.

Keywords: Free Space Optics, Wavelength Division Multiplexing, LASER.

1. Introduction

WDM-FSO technology is an optical wireless high speed line-of-sight wavelength multiplexing transmission. Broadband applications, such as multimedia and TVHD, FHD, UHD and interactive, online games and social networks are some of the most targeted services that WDM-FSO is able to fully support at appropriate capacity and signal quality performances. WDM-FSO technology provides the communications system with massive data transfer capability.

The FSO communications main features are: full-duplex optical channel, point-to-point services, transmission bitrate of up to 10 Gbps, BER performing within 10^{-16}-10^{-9} range (for wavelengths between 850 nm and 1550 nm), transmission lengths of up to tens of kilometers, analogue / digital modulation schemes allowed, transparency to any kind of data format. FSO equipment can be deployed within short time (12-24 hours), the maintenance costs are reasonably low, the security is far better than a 802.11 wireless system. Optical connections developed for military applications were able to transmit data at 100 Mbps over longer than 20 km, with optical transceivers mounted on ships in motion [1].

A comprehensive description of the FSO terrestrial systems performances, including mitigation techniques for link survivability, is accomplished in [2]. In [3], an all-optical gigabit FSO LAN link is presented. A full photonic receiver and a large diameter laser beam – based transmitter are used in [4] to measure the loss budget and system performances. A full optic FSO system, with no optical-electric/electric-optical conversion is described in [5]. An all-optical approach results in cost-efficient FSO system. Today, the industrial FSO systems use

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separate channels for a duplex transmission. The model in this paper approaches a duplex WDM-based single optical beam transmission system.

2. Theoretical aspects

The diameter of the beam at the receiver depends on the beam divergence and the transmission length. The shape of the gaussian optical beam for a generic free-space optical connection is shown in Fig. 1.

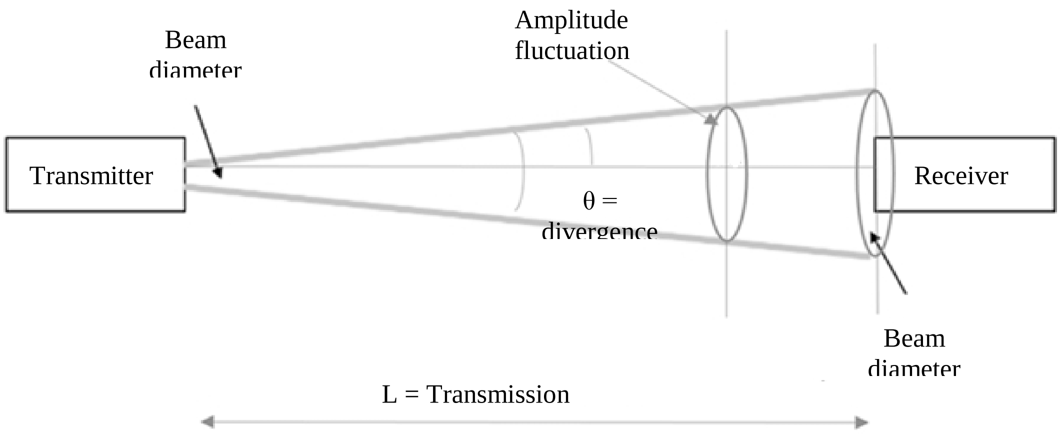

Fig. 1 The shape of the gaussian optical beam for a generic free-space optical connection

Fig. 2 shows a FSO channel transport model using WDM [6].

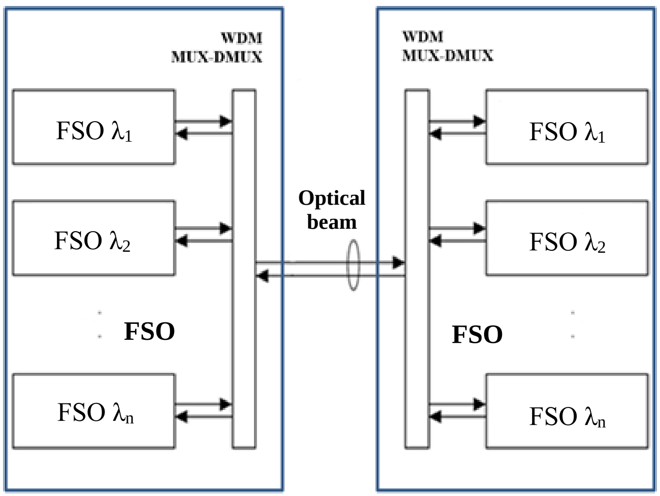

Fig. 2 FSO channel transport using WDM [6]

The standard deviation for the amplitude fluctuations of the optical beam σ_X^2 can be obtained from [7]:

$$\sigma_X^2 = 0,30545\left(\frac{2\pi}{\lambda}\right)^{7/6} \cdot C_n^2\left(L\right) Z^{11/6} \approx \frac{\sigma_R^2}{4} \quad (1)$$

where λ is the wavelength in nm, C_n^2 (L) is the structure parameter of the refractive index at the constant altitude L in $m^{-2/3}$, Z represents the transmission distance, in meters, and σ_R^2 is the Rytov variance given by [7]:

$$\sigma_R^2 = 1,23 \cdot C_n^2\left(L\right) \cdot \left(\frac{2\pi}{\lambda\left(L\right)}\right)^{7/6} \cdot Z^{11/6} \quad (2)$$

These amplitude fluctuations may affect the optical beam over its entire propagation distance, as can be seen in Fig. 1.

The atmospheric models that can be implemented for calculating the structure parameter of the refractive index are empirical models [8]:

- Hufnagel-Valley (HV) model (low turbulence):

$$C_n^2\left(h\right) = 0,00594\left(\frac{v}{27}\right)^2\left(10^{-5}h\right)^{10}\exp\left(-\frac{h}{1000}\right) + 2,7\times10^{-16}\exp\left(-\frac{h}{1500}\right) + A\exp\left(-\frac{h}{100}\right) \quad (3)$$

- Modified Hufnagel-Valley (HV) model (medium-high turbulence):

$$C_n^2\left(h\right) = 8,16\times10^{-54}h^{10}\exp\left(-\frac{h}{1000}\right) + 3,02\times10^{-17}\exp\left(-\frac{h}{1500}\right) + 1,90\times10^{-15}\exp\left(-\frac{h}{100}\right) \quad (4)$$

In these empirical relationships, v is the wind speed in m/s and h is the height at which the equipment is mounted. The typical value of parameter *A*, which describes the "intensity" of ground turbulence has the typical value of $1.7\text{x}10^{-14}\text{m}^{-2/3}$.

For L < 20 m, C_n^2 varies between 10^{-13} $m^{-2/3}$ și 10^{-17} $m^{-2/3}$ for strong or weak turbulence. The value usually used is 10^{-15} $m^{-2/3}$.

The availability of the line-of-sight optical connection is [9], [10]:

$$
\begin{aligned}
D_{conex} &= P\left(I \geq I_{th}\right) = \int_{I_{th}}^{\infty} \frac{1}{2\sigma_X I} \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{\left(\ln(I)-\ln(I_0)\right)^2}{8\sigma_X^2}\right\} dI = \\
&= \frac{1}{2} - \frac{1}{2}\operatorname{erf}\left(\frac{\ln(I_{th})-\ln(I_0)}{2\sigma_X\sqrt{2}}\right) = \frac{1}{2} - \frac{1}{2}\operatorname{erf}\left(\frac{\ln(I_{th}/I_0)}{2\sigma_X\sqrt{2}}\right)
\end{aligned} \tag{5}
$$

Equation (5) is depicted in Fig. 3, where the availability of the optical connection versus the length of the connection, for different transmit values, is plotted.

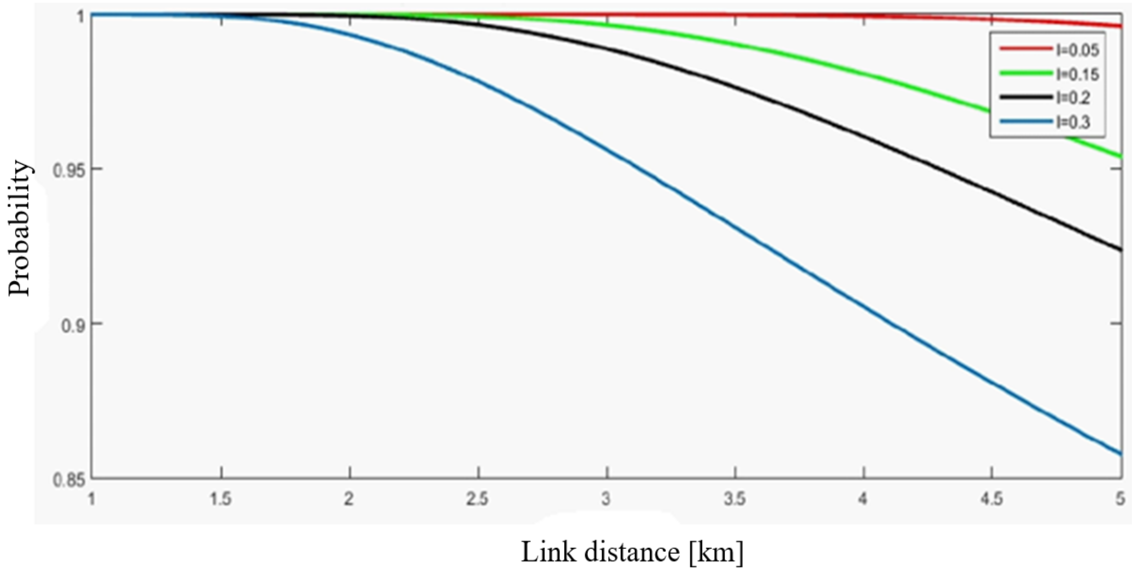

Fig.3 Availability of optical free-space connection versus distance [11]

For a certain threshold report I_{th}/I_0, the availability of the connection is given by the standard deviation σ_X, depending on atmospheric conditions and transmission length [3]. The availability of a FSO connection is significant for lengths of up to 5 km.

3. Experiment device(s)

Two gigabit-ethernet media-converters were used with two SFP (Small Form Factor) modules operating on two distinct wavelengths (up-link and down-link) as optic interfaces and using a single optical beam for full-duplex transmission. The wavelengths on which the optical transmission is performed in this experiment are λ1 = 1550 nm and λ2 = 1310 nm.

The experimental device can be seen in Figs. 4, 5 and 6 respectively:

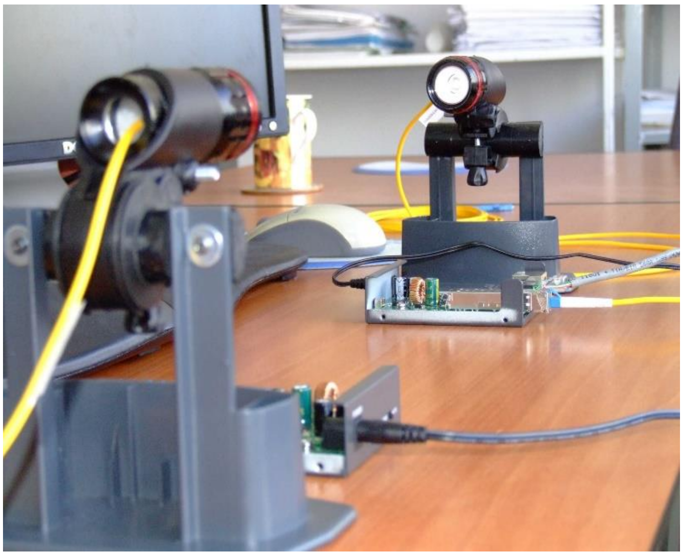

Fig. 4. WDM – FSO devices

Initial alignment of transceivers is made using LEDs with visible radiation. Following the alignment and adjustment procedure, the visible light LED will be switched off and the SFP module's LASER source is turned on.

Fig. 5. WDM - FSO Laboratory Experimental Device – Component disposal

Fig. 6. Experimental laboratory device WDM - FSO - media-converter [12]

iPerf ver.3 program and the SpeedTest platform were used to deliver 500Mbps traffic to the setup and to measure the optical connection quality.

Fig. 7 shows the block diagram for experimental laboratory device WDM-FSO - media-converter

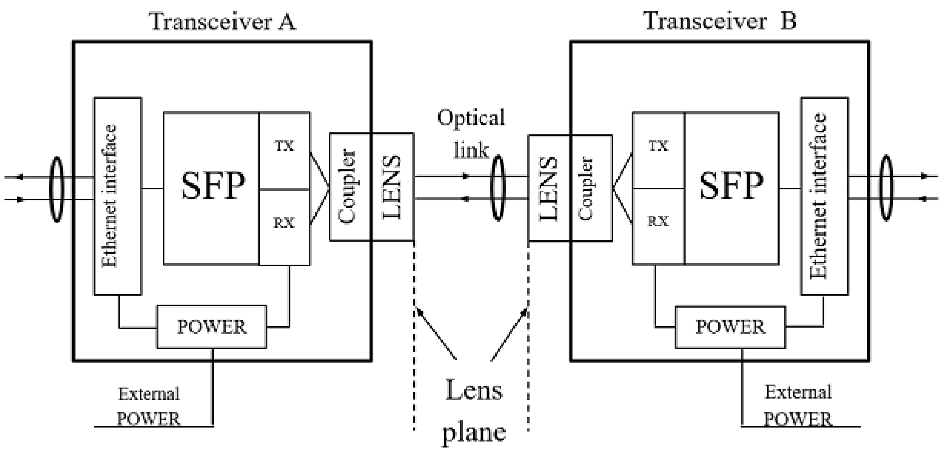

Fig. 7. Block diagram for experimental laboratory device WDM - FSO - media-converter

Fig. 8 depicts the interconnection of the devices - experimental laboratory setup using a modified TP-Link mediaconverters (FO to Ethernet and viceversa) [12].

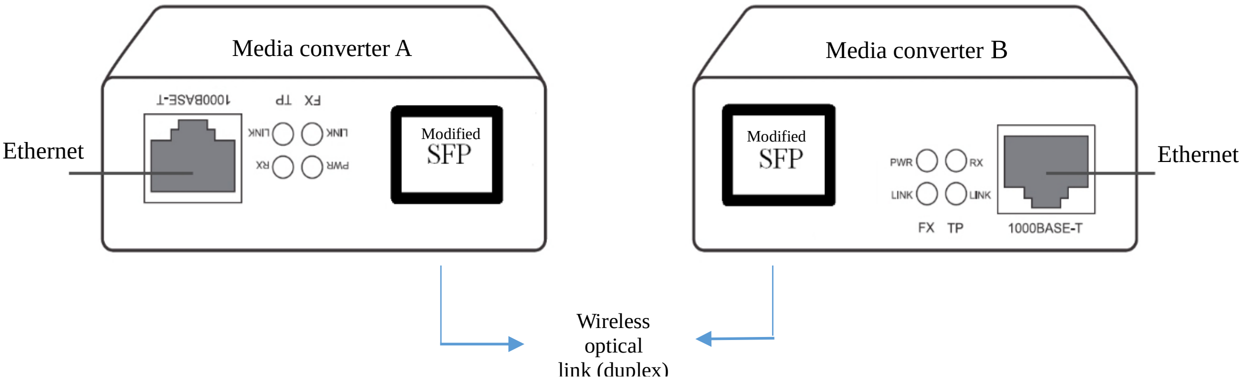

Fig. 8. Experimental laboratory – interconnection of the devices [12]

For interconnecting FSO devices with media converters, patchcords characterized by reduced reflection and attenuation are used. The SM - LWP (Low Water Peak) optical fiber used in these patch cords is ITU-T G.652.D standard compliant. The average attenuation is about 0.4 dB / km at 1310 nm and 0.25 dB / km for 1550 nm. The optical fiber is covered with PVC and stiffened with kevlar fibers. The SFP (Small Factor Plugable) [12] used in this setup could be viewed in Fig. 9.

Fig. 9. SFP view [13]

Optical fiber with LWP (Low Water Peak) technology can be used for any wavelength ranging from 1280 nm to 1650 nm. Optical system and focusing mechanism at the optical fiber (see Fig. 10) adjust the size of the optical beam to fit the optical fiber termination at the transmission length.

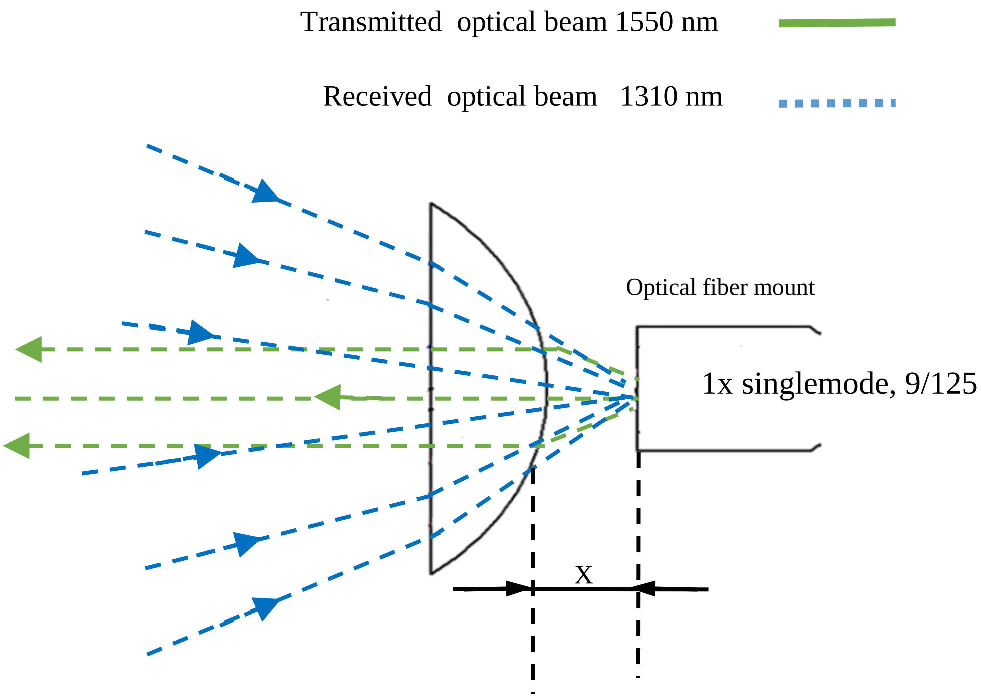

Fig. 10 Optical system and focusing mechanism on the optical fiber termination

The variable length X, which can reach up to 1.5 cm, adjusts the focus of the transmitted / received beam at the fiber optic termination. Some advantages of SFP's are: easy tunning of the wavelengths, external powering, separate optical beams for transmission/reception.

The SFP module supports 20 km single-mode fibers and/or FSO connections at transmission speeds of up to 1.25 Gb/s. The LC connector can be replaced with lens so as wireless optical connections are allowed.

The main SFP features are:

- bidirectional single channel communication (WDM-FO/FSO/LiFi),
- compliant to FO/FSO/LiFi networks,
- speed up to 1.25 Gbps (IEEE 802.3z 1000Base-FX),
- maximum transmission range of 20 km (FO) or 2 km FSO,
- optical interface: LC connector.

The optical signal is transmitted in transmission window II (1310 nm) and received in window III (1550 nm). The complementary module with the 203/5G LC is the SFP-205/3G L1417 module that transmits data in window III and receives in window II.

The SFP Gigabit Module (GbE) can be used with transmission media converters and with most IEEE 802.3z 1000Base-FX standard SFP switches and routers. The use of media converters with the possibility of changing SFP modules is particularly advantageous when it is necessary to make changes to the network configuration. Instead of replacing the entire unit, it is enough to change the SFP transceiver.

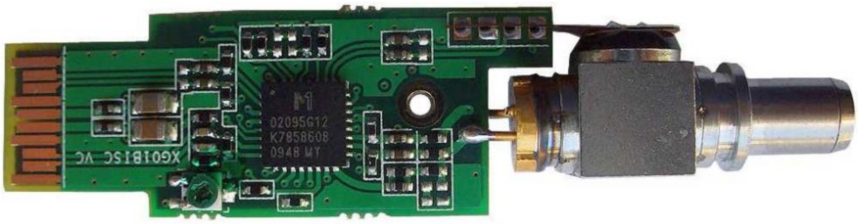

Fig. 11. SFP module - (interior view) [13]

Fig. 11 shows the SFP-WDM circuit, the transmitter and the receiver being coupled through a passive optical combiner. The SFP modules tested in this experiment were originally designed for fiber optic communication.
If the devices are installed in urban areas, safety warinesses should be taken in order to avoid eye damages.

4. Results

The experimental setup was plugged into a 500 Mbps Gigabit-Ethernet network card. Transmission length, transmission bitrate, BER and latency have been measured under different weather conditions. The experimental results are presented in Table 1.

Table 1

Internet traffic speed for the WDM-FSO experimental setup

Transmission channel	Transmission length [m]	Weather conditions	Transmission speed [Mbps]		BER	Latency [ms]
			Download	Upload		
Fiber optic	2m (patch-cord)	-	520	470	10^{-16}	2
FSO	0,5m (indoor)	-	490	445	10^{-14}	14
	20m (indoor)	-	410	380	10^{-13}	16
	300m (outdoor)	Clear sky	280	246	10^{-12}	16
	300m (outdoor)	Light rain	260	220	10^{-9}	24
	300m (outdoor)	Heavy rain	210	186	10^{-8}	26
	300m (outdoor)	Fog	12	9.6	10^{-6}	>30
WiFi	5m (indoor)	-	120	95	10^{-9}	18
	15m (indoor)	-	76	62	10^{-7}	24

A ***LanTEKIII network tester*** has been used to measure BER, latency and optical connection quality.

5. Interpretation of results. Applicability. Benefits

The WDM-FSO setup delivered experimental results for different turbulence intensities of the atmospheric channel, from the no air turbulence of a clear sky to low turbulence value of the light rain to high turbulence of the heavy rain and fog. For the sake of comparison, the setup has been used to produce experimental results for a 2 meter fiber patchcord channel which simulated a linear time invariant filter for the optical signal.

The indoor results show out that the average performance slightly decreases as the transmission length gets longer. The main reason for that shrinking is the missalignment between the transmitter and the optical receiver, which results in higher optical power loss at the receiver lens as the link length gets longer. A larger lens is improving the reception quality up to the fiber channel excellence.

The outdoor experimental results demonstrate that the average performance significantly downgrades due to optical power loss in the air channel. All of the system parameters are strongly decaying, the worse the weather conditions the higher the falling. The bitrate is decreasing sharply from 280 Mbps for clear sky conditions down to 12 Mbps for fog conditions, while the latency gets almost twice longer, from 16 ms up to 30 ms.

The comparison we made with fiber optic, using as a reference the 2m section was made only to remain in the optical domain due to the basic function of the two media converters. In Table 1, however, we have also introduced the standard Wi-Fi transmission speeds for indoor transmissions. The advantages of radio transmission are given by wide area propagation through different environments (eg concrete walls), which do not necessarily require direct visibility. The propagation distance for which a certain transmission speed is guaranteed depends on the sensitivity of the receiver, the transmit power and the type of antenna used. In the case of urban agglomerations where the density of radio transmitters is very high, the occurrence of interferences is imminent; from this point of view, free space optical communication has a great advantage.

6. Conclusions

The experimental setup is an one lens single optical beam WDM-FSO system. The link quality is described by using BER and latency. The link availability is assessed using statistical tools and atmospheric empirical turbulence models.

The proposed experimental model was chosen because it combines the simplicity of practical realization (it was realized using common, easy to find and cheap components) with good performances compared to some industrial devices. Such a communication system (the laboratory setup), meaning the two converters and optical devices (optical fiber and focusing devices), is firstly cheap - costs about 100 euros. By realizing monoblock, weatherproof housing and high-quality treated lenses, the cost price will increase substantially but will not exceed 1000 euro/system. Industrial achievements, with complicated localization/focusing systems and multiple lenses, cost between 4,000 and 12,000 euros. For these communication systems, as well as professional photo cameras, the cost price is dictated mainly by the lens system and not by the electronic subsystem. Optical devices used for long distance communications (km or tens of kilometers) should form a very narrow and precise optical beam, not to be affected by temperature variations, requiring effective reception filters to allow only the wavelengths of the useful wave. The automatic alignment system also have a large weight in the total cost of free space optical systems.

The major advantage of this device is the use of a single optical beam that leads to a relatively simple alignment process. Also, multiple wavelengths could be transmitted on the same beam, meaning different communication channels, or may be conveniently multiplexed to increase the overall bitrate of the entire system. Another advantage of this setup is its versatility. By changing the SFP module from the media converter we can return to the classic version, used in most industrial designs, which involves sending two different optical beams through the atmosphere, for the two channels of transmission (transmission/reception). This also results in higher cost by doubling the number of lenses. Or, it can simply go back to the basic function of the two media converters, with minimal cost of fiber optic transmission between two points.

The FSO setup demonstrates an easy way to establish quickly and reliable, secured optical link, using on-the-shelf devices. The hundreds of meters link length is enough in most cases to connect buildings in a LAN.

Fast establishing last mile networks, extending metropolitan networks, enhancing enterprise connectivity, establishing FSO fiber-optic back-up, or rescaling the heterogeneous wireless networks are some benefits of the presented system.

The better the line-of-sight one lens transmitter – receiver alignment the higher the system overall performances.

High turbulence conditions claim for spatial diversity techniques in order to improve the signal acquiring.

Future research will approach multicolor spatial diversity FSO system at Gbps rates.

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