Trends in Increasing the Channel Capacity of FSO Systems

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Abstract – **In this paper we present an overview of different methods for increasing the channel capacity of FSO systems. We have proposed an in-depth analysis of each method for increasing C_I. Also possible integration of the enhanced FSO systems and clues for future development are proposed.**

This paper could be used to educate the reader (students or engineers) about the capabilities of FSO systems and help them choose the most appropriate solution, when developing a high-speed, broadband, free-space optical system.

Keywords – **FSO, FSO-OFDM, FSO-CDMA, POLLMUX, Channel Capacity, C_I.**

I. Introduction

The free-space optical (FSO) systems are fairly new and attractive technology for delivering broadband communication services. They are easily deployed in urban areas, like the wireless microwave communication systems. At the same time they achieve data transmission speeds equal to the ones in fiber optical links. FSO systems are also very flexible in terms of network topology. Having no need for licensing the frequency bandwidth used by FSO systems, we can say that they are also very cost effective technology for broadband communications.

However there is a constant search of means to additionally increase the channel capacity (C_I) of FSO systems. For example the very high frequencies of laser beams (f ∈ [10^{14}, 10^{15}] Hz) allow the multiplexing of very large bandwidths – wavelength division multiplexing (WDM) [1, 2]. Other technologies for increasing the channel capacity of a transmission lines, like OFDM (orthogonal frequency division multiplexing) [6, 7] and CDMA (code division multiple access) [4, 5], are employed in FSO as well. Although developed for microwave communication systems, recent studies show that these technologies can also be integrated in FSO systems. Another effective method for increasing the channel capacity of wireless optical systems is to multiplex optical beams with different polarization (POLLMUX) [8, 9].

Besides reaching very high bit rates in the data transmission, the above technologies are also showing a tendency in keeping the availability of FSO systems at respected levels. The data transmission in WDM, OFDM, CDMA and POLLMUX FSOs is achieved at very low bit-error rates, BER ∈ [10^{-12}, 10^{-6}] [1-10].

In the presented paper we have reviewed the means for increasing the channel capacity of optical systems. We have summarized the techniques for implementing those methods in FSO systems. Our analysis and conclusions may be used to help and guide students in the field of optical communications to choose and fully develop a master's thesis on high-speed free-space optical systems.

II. Methods for Increasing the Channel Capacity of FSO Systems

1. *Wavelength division multiplexing in FSO systems*

Currently the most efficient method for increasing C_I of optical communication systems is the wavelength division multiplexing. Originally developed for optical fiber communications, WDM can be fully integrated in FSO systems, as well [1, 2]. There are two kinds of wavelength division multiplexing: coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (WDM).

CWDM uses wavelengths in the range of [1270nm, 1610nm]. The channels spacing is 20nm, which allows multiplexing of up to 16 optical channels.

In DWDM systems spacing between carrier beams is [0.2nm, 0.8nm]. DWDM systems use wavelengths in C (λ ∈ [15250nm, 1565nm]) and L (λ ∈ [15570nm, 1610nm]) bands; optical beams with these wavelengths are often used in FSO systems, because they belong to wavelength windows, in which the atmospheric extinction is minimal. Theoretically DWDM can multiplex 160 optical channels. However most of the dense wavelength division multiplexing optical systems combine up to 32 channels.

An example block diagram of FSO system, using DWDM is presented in Fig. 1:

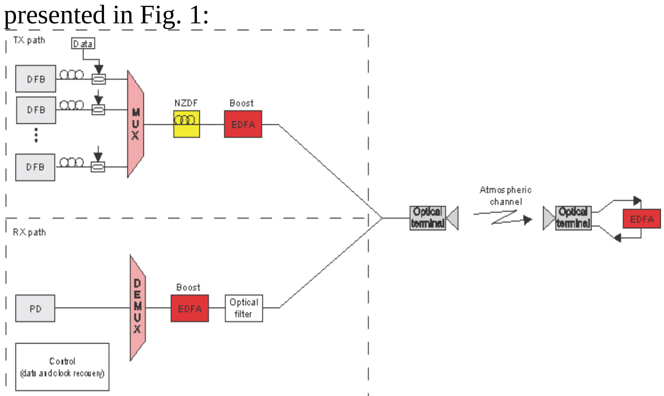

Fig. 1 Block diagram of DWDM FSO system

The WDM used in FSO is standard multiplexing scheme, same as the one used in optical fiber systems. The light emitted from the lasers (DFB: distributed feedback lasers) is modulated by a 40Gbps data streams (for test purposes pseudo

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random sequence may be used) through March-Zender (MZM) modulators. After that the laser beams are multiplexed, using array waveguide grating. Five kilometers long, non-zero dispersion fiber (NZDF) is used to de-correlate the 32 multiplexed beams. The beam is then amplified and passed to the optical unit. The fiber-to-free space method is used in DWDM-FSO systems, that is the light is transmitted from the end of the single mode fiber to the optical aperture.

Using a conventional optical unit (aperture) we can transmit 32x10Gbps data streams. But if we use an optical terminal with integrated system for precision tracking, acquisition and pointing (Fig. 2) we can achieve 32x40Gbps, error free (BER ~ 10^{-9}), data transmission [3].

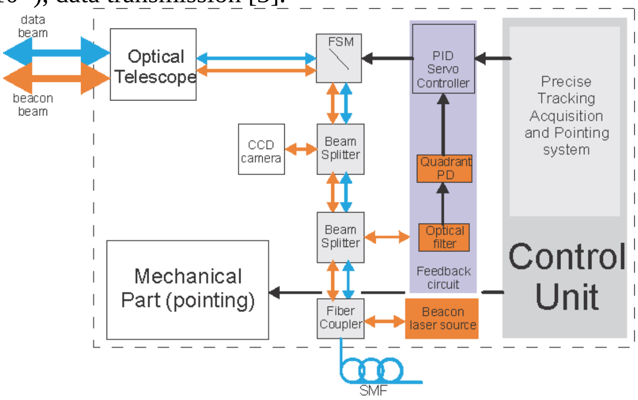

Fig. 2 Block diagram of the optical unit

Fig. 2 is a block diagram of the optical unit used in the DWDM system shown in Fig. 1. With the use of beacon beam and CCD camera it is possible to track the receiver's position and very precisely point both terminals to each other. The fast steering mirror (FSM) in combination with the PID unit assure that maximum power of the received laser beam is directed to the single-mode fiber (SMF) coupler, thus the SMF itself. The feedback, which the control unit uses to operate the fast steering mirror, is composed of beam splitter, an optical filter and a quadrant photo detector.

Using such optical transceiver (Fig. 2), the data transmission speed is increased to 1,28 Tb/ps (or 32x40Gbps), and at the same time BER is kept minimal (BER~ 10^{-9}) [2].

2. Using CDMA in FSO systems

Using code division multiple access (CDMA) in free space optical systems (Fig. 3) is fairly new trend in the methods for increasing FSO's channel capacity.

A typical CDMA scheme is used to modulate the data stream. The incoming digital data flow is divided into *n* serial data streams. Each of them is coded with a pseudo random sequence (code). The signal is then modulated; QAM or PSK may be used. At the final stage the manipulated data stream is passed to an optical transmitter. Optical terminal with integrated tracking and acquisition scheme (Fig. 2) is advised to be used for transmitting the laser beam.

Fig. 3 depicts the code division multiplexing process, that is used in free-space optics.

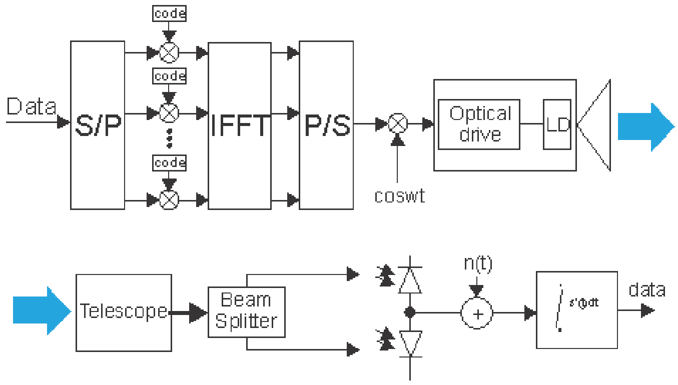

Fig. 3 Block diagram of CDMA used in FSO systems

The same codes, developed for microwave communication systems, like Kasami, Gold, Alamounti, PN-codes etc., are also used to encode the digital signal (before electro-optic transformation) in FSO systems [4, 5].

Optical unit, like the one shown in Fig. 2 is used to transmit the optical signal into the atmosphere. However, if on the receiver sides, besides the tracking and acquisition, aperture averaging (AA) is used, the performance of the system would improve [5]. By using AA we can maintain a constant BER in the interval [10^{-10}, 10^{-6}]. BER rate remains in this interval even in cases of moderate and strong turbulence in the atmospheric channel.

Free space optical systems using CDMA have C_I = 10 Gb/s and BER ~[10^{-8}, 10^{-6}]. These results, by far, exceed the channel capacity of microwave systems using CDMA. For example UMTS CDMA networks, working with f =1800MHz or f = 2100MHz have C_I= 5Mb/s.

3. Using OFDM in FSO systems

This is another technology used to increase channel capacity (C_I), which was originally developed for wireless radio networks, but is showing very good results, when used in FSO systems [6, 7].

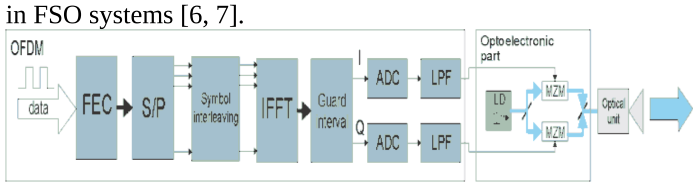

Fig. 4 Block diagram of an OFDM FSO system

Fig. 4 is a diagram showing the blocks used for constructing an FSO-OFDM system. The bits in the signal are first passed for a bit interleaving, then to forward-error correction encoding (FEC) and after that to phase manipulation (PSK or QAM); all of these operations are united in the FEC block in Fig. 4. Then the signal is divided into *n* serial data streams (S/P). After that it is passed to a symbol interleaving. Then to inverse fast furrier transformation (IFFT). After that guard intervals are added. Each of the produced I and Q components of the signal is then filtered and transmitted to the optical part of the system.

In FSO OFDM systems C_I = 10Gb/s is achieved.

These systems can be additionally optimized by using LDPC codes to encode the digital signal. This way the sensitivity of the receiver is increased by 3dB, thus bit-error rate is decreased.

By using different light polarization for the modulated (by I and Q) optical beams, the influence of turbulence induced fading on the transmitted laser signal is greatly reduced [8].

Fig. 5 is a block diagram of light polarizing optical unit used in FSO-OFDM systems.

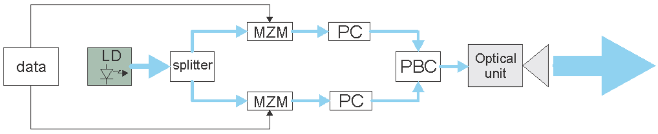

Fig. 5 Light polarizing optical terminal for FSO-OFDM systems

4. Multiplexing laser beams with different polarization (POLLMUX)

As already mentioned in the previous paragraph, combining laser beams with different polarization is advantageous for FSO systems. Light beams of such kind are far less affected by the turbulence induced fading in the atmospheric channel. In POLLMUX FSOs the errors caused by random phase fluctuations of the system are decreased; also the information's security in such system is increased [8, 9].

The achieved channel capacity is $C_I = 100$ Gb/s.

Generalized block diagram of POLLMUX free-space optical system is presented in Fig. 6:

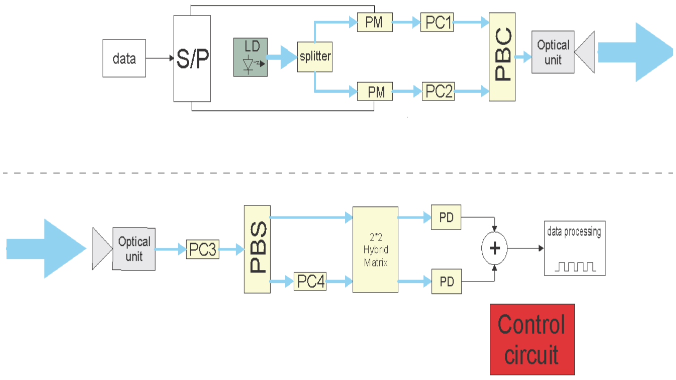

Fig. 6 Polarization Multiplexing system for FSO

The signal is divided in two data streams using serial-to-parallel converter. Then this two data streams are used to modulate the intensity of the laser beams (PM, usually MZM), which were produced by splitting the original laser beam using a beam splitter. The two optical signals are polarized. Then they are combined, using polarization beam combiner (PBC), and transmitted to the atmospheric channel. In the receiver the detected incident light signal is split (using polarization beam splitter PBS) and passed through 2*2 Hybrid. After that it is converted by two similar photo detectors and the resulting electronic signals from both PDs are combined and passed for further processing.

III. Analysis of the Proposed Methods for Increasing the Channel Capacity of FSO Systems

1. Analysis of the presented FSO systems

The results accomplished by using the presented methods for increasing C_I of FSO systems are analyzed in this section.

Table 1 summarizes the results of the presented enhanced FSO-systems:

Table 1

Method for increasing C_I	C_I, Gb/s	L, m	BER
$DWDM_{(1)}$	40	350	10^{-6}
$DWDM_{(2)}$	1280	212	10^{-9}
FSO-CDMA	10	350	$(10^{-7}, 10^{-12})$
POLLMUX	112	300	$(10^{-7}, 10^{-12})$
FSO-OFDM	12	450	$(10^{-7}, 10^{-12})$

(1) Without pointing system
(2) With pointing system (CCD camera)

The graphical representation of the data in Table 1 is Fig. 7:

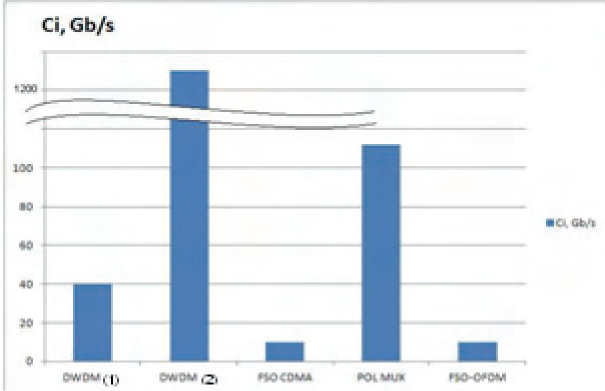

Fig. 7 C_I achieved by using different methods for increasing the channel capacity of FSO systems

The difference between the channel capacities of the two DWDM systems is because of the used optical terminal. In DWDM(1) a conventional optical terminal is used , while in DWDM(2) the used optical terminal has a precise tracking and pointing system (Fig. 2). A DWDM FSO without pointing system (DWDM (1)) can also achieve $C_I \sim 1$Tb/s, but the bit-error rate will be too high, making such FSO system unusable. By using a beacon beam and CCD camera (Fig. 2) for tracking and precise pointing of both terminals, practically error free data transmission ($BER < 10^{-8}$) can be achieved.

The typical parameters (C_I, length, BER) of commercially available FSOs are presented in Table 2:

Table 2

Vendor	C_I, Gb/s	L, km	BER
LightPointe	1.25	2.8	$(10^{-9}, 10^{-12})$
MRV	1.25	3.5	$(10^{-9}, 10^{-12})$
CableFree	1.5	1.5	$(10^{-9}, 10^{-12})$
SonaBeam	2.5	1	$(10^{-9}, 10^{-12})$

It is obvious that the conventional FSO systems (Table 2) are offering far slower data transmissions, than the wireless optical systems using CDMA, OFDM, DWDM and POLLMUX. For example CDMA and OFDM technologies integrated in an FSO system increase its channel capacity 8 to 10 times. However, commercially available FSO systems allow data transmission to greater distances (Table 1, Table 2).

As said before the free-space optical systems allow transmitting of information at higher bit rates, than the microwave communication systems (Fig. 8):

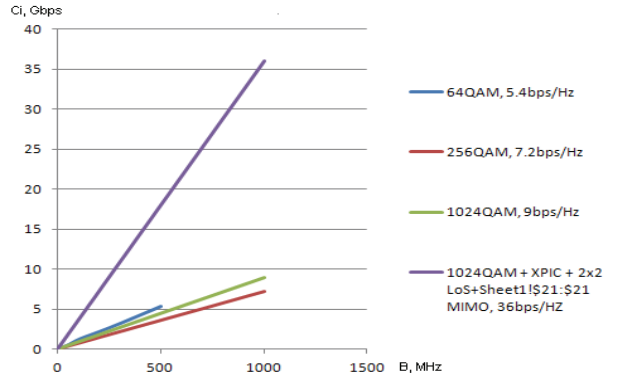

Fig. 8 Channel capacity achieved by microwave communication systems

Fig. 8 represents the latest technologies for increasing C_I in microwave radio-communication systems. Fig. 8 shows that transmitting data at bit-rates of 5Gbps would require at least 100MHz bandwidth. Such bandwidth could not be obtained by using microwave frequencies.

From the analysis of the presented FSO systems, can be concluded that FSO systems achieve channel capacity equal to the one in fiber-optics communication systems. This makes FSO systems a competitive technology. They can be used in hybrid (fiber-to-free-space) links for: enterprise connectivity, last-mile access network, backup lines etc.

FSO systems, using WDM, OFDM, CDMA, POLLMUX, practically eliminate the “bottleneck” effect in telecommunication networks. They can also be used to realize the concept of next generation network, which delivers high-speed broadband services to the end user (Fig. 9):

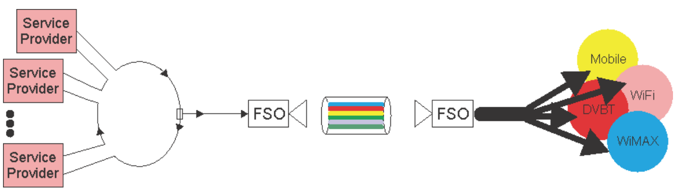

Fig. 9 Next generation network, using FSO system

2. *Possibilities for further enhancement of FSO*

Despite the achieved results, in terms of channel capacity (C_I), we think that there are more means to enhance the FSO systems.

In the process of analyzing DWDM integration in FSO systems, we concluded that using system for precise tracking acquisition and pointing improves the system’s performance. Same method could be used to increase C_I of OFDM and POLLMUX FSO.

Different polarization circuits, with decreased number of splitters and combiners, could be used in order to avoid losses in the optical system. This way a faster optical data streams could be transmitted.

Another way to enhance FSO systems is by improving their availability. For example: by using different channel codes; or by using different methods for detecting the received optical signals. By improving the system availability, decreasing BER, data streams with higher bit-rates can be transmitted, in other words decreasing BER, allows the increasing of C_I.

It is also possible to develop a relay-assisted free-space optical link, which can transmit data to longer distances.

IV. Conclusion

In this paper we have reviewed different methods for increasing the channel capacity of FSO systems, some of which could also be used for improving the availability (decreasing BER). WDM, OFDM, CDMA and polarization multiplexing/POLLMUX were analyzed as possible means for increasing C_I of wireless optical systems. Generalized block diagrams of each of the technologies were presented. The advantages of each technology were summarized. Possible future enhancements of the FSO systems were proposed.

This paper could be used by master students, studying Telecommunications, at Technical University of Sofia, for designing high-speed broadband FSO systems.

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