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A Review of Modern High-Speed Optical Communication Systems and their Spectral Efficiency

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Abstract: *Recent developments in social networking, cloud computing, and smart gadgets are driving up data traffic needs that are quickly beyond the capacity of the optical fibre infrastructure. Recent projections indicate that annual internet traffic growth of around 30% is anticipated, rapidly overloading optical networks. The installed optical fibre network's total capacity has to be enhanced in order to prevent this capacity crisis. There has been constant effort to use different multiplexing technologies to enhance the capacity & data rate beyond Terabit/second. This study reviews the latest developments in wired and wireless technologies, such as OFDM, WDM, SDM, and Li-Fi, that are being employed in optical communication to improve bandwidth, spectral efficiency, data rate, and other aspects.*

Keywords: High-speed systems, Spectral efficiency, Fiber optics.

I. INTRODUCTION

Information exchange has played a major role in the development of human civilisation. Communication technologies have advanced significantly, moving from wired to wireless systems. Internet use has grown significantly in recent years; 40% of people worldwide now have an internet connection, compared to fewer than 1% a decade ago. 1995. The volume of data that these networks will transport will grow significantly and steadily, as shown by recent history. The only technology that can meet this need for fast speed and wide capacity is optical fibre communication (wired & wireless). In theory, optical fibres have an enormous amount of potential transmission capacity or bandwidth. They are being used for many different purposes, including fiber-to-the-home cable television, and long-distance data transfer. New, improved fibre designs and communication methods are needed to maximise transmission capacity. These have been created over the last several decades in a series of phases, starting with higher bit rates in telecom applications.

Despite the fact that there are many communication methods and that they cover a wide spectrum of radio frequencies, these technologies are nonetheless limited because of the attenuation that occurs when waves pass through them. The advancement of guided/wireless optical communication helped to lessen this issue. When compared to other communication mediums, the light wave travelling from an optical fibre experiences far less attenuation. This enables extremely long range communication at very high speeds using low power devices as inputs, such as LEDs and lasers. This is why optical communication transformed the state-of-the-art in communication technology. In order to get the required data rates across these channels, it also prompted the development of high speed modulation methods.

Various Multiplexing Techniques

The world of fibre optic communication will see a capacity crisis; thus, creative plans for capacity augmentation must be created. Several multiplexing approaches have been investigated periodically, each having merits and downsides of their own. This is a quick summary of the several multiplexing methods for optical communication that are available.

Orthogonal Frequency Division Multiplexing (Ofdm)

Orthogonal frequency division multiplexing, or OFDM, has become one of the most widely used modulation schemes for optical communication. The frequency division multiplexing variant is called OFDM. In wireless communications, OFDM has become a significant physical-layer signal transmission technique within the last ten years. Digital audio and video broadcasts, as well as mobile communications, have made extensive use of OFDM-based signal modulation.

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This may be ascribed to its superior speed compared to other communication technologies, as well as its much lower attenuation and resistance to frequency selective fading. The modern world still longs for more speed and data rate with the least amount of data loss, even with such sophisticated features. Rapid advancements have been made in the fields of optical communication and modulation as a result of this ongoing requirement. This is accomplished using Orthogonal-FDM which sends many symbols over a group of subcarriers. Each symbol is modulated using a different mix of in-phase and quadrature components to guarantee orthogonality across a bit-period. These components are distributed so as to minimise fading and guarantee optimal spectral efficiency throughout a symbol period.

Design And Implementation Of Ofdm System

The serial to parallel converter was the first step in the creation of the OFDM signal. The QAM module needs parallel input, hence the serial data must be converted to a parallel format. The proper symbol is transferred to such parallel data. The IFFT module is used to convert the parallel symbols from the frequency domain into the time domain. To be sent, the data is transformed into a serial format.

Optical OFDM

Electrical OFDM signals are often complicated valued data signals. A complex electrical I/Q mixer may be used to modulate a complex valued data signal after it has been electronically up-converted using an electrical intermediate frequency carrier . A modern amplitude modulator may be used to transform the up-converted electrical OFDM data stream into an electro-optic format. As an alternative, the complex electrical OFDM signal may be used to directly drive a complex electro-optic I/Q modulator, converting it into the optical domain. Simple photodiodes that use the square law detection method are often used in optical receivers. Considering The optical OFDM signal cannot be immediately transferred into the electrical domain. An optical carrier must be given either by the transmitter or by a local oscillator in the receiver via a heterodyne or intradyne technique, in place of direct detection of the pure optical OFDM signal.

We can determine that CO-OFDM has the highest resilience against chromatic dispersion and polarisation mode dispersion by comparing CO-OFDM with DD-OFDM.This is a result of the coherent detection technique's linear impact, which raises receiver sensitivity. Conversely, the nonlinear direct detection in DD-OFDM limits the dispersion tolerance. Furthermore, because of the costly and sophisticated equipment required for the E/O and O/E conversion, CO-OFDM is mostly used in long-haul applications. However, for applications where cost is a factor, including local area networks and metropolitan area networks DD-OFDM is a more affordable option.

Division Multiplexing of Wavelengths Weakness-division multiplexing With the use of several laser light wavelengths, WDM [9]is a technique that multiplexes many optical carrier messages onto a single optical fibre. Through the use of this approach, bidirectional communications via a single fibre stand are made possible, along with capacity multiplication where a distinct channel is carried by each wavelength. WDM splits the optical spectrum into smaller channels so that data may be sent and received at the same time. The optical WDM networks are shown in the figure, where each transmitter broadcasts a distinct wavelength, i, where i = 1, 2, 3,... N. Wavelength replaces frequency in these networks.

Dense Wavelength Division Multiplexing and Coarse Wavelength Division Multiplexing are the two kinds of WDM systems. The enormous demand for data in communications networks may be met via DWDM. More bandwidth is available when customers connect their devices directly to the router using DWDM. By reducing wavelength gap, DWDM increases both transmission capacity and distance. Cost-effective CWDM is another kind of WDM. Since CWDM is more economical than DWDM, it is used for short transmission lengths of less than 50 km.

Space Division Multiplexing (SDM)

While multiple parallel fibre systems were once described using the same terminology, the term SDM now refers to multiplexing techniques that create multiple spatially distinguishable data pathways through the same fibre. This represents the benchmark that must be surpassed in terms of cost per bit if any of the SDM approaches currently being researched are ever to be commercially deployed. Multiplicity of space channels is used in space-division multiplexing to boost optical communication capacity. It may be used for guided waves and free space optical communication.

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Space-multiplexers, which couple light from various cores or modes into SDM fibres, SDM optical amplifiers, which enhance SDM signals, spaced de-multiplexers, and optical connectors are the main new components for SDM.

Polarization-Diversity Multiplexing (PDM)

A physical layer technique called polarization-division multiplexing uses the polarisation of electromagnetic waves to separate distinct orthogonal signals when multiplexing signals carried on those waves. When combined with optical QAM or phase modulation, polarization-division multiplexing enables transmission rates of up to 100 Gbit/s across a single wavelength.

Mode Division Multiplexing (MDM)

Mode-division multiplexing is a rapidly growing multiplexing method among many others. In a different sense, with increased capacity requirement over signals per fibre core, it is becoming more concentrated due to the maturity of digital signal processing. Mode-division multiplexing is another name for the technique whereby numerous independent modes are employed as an independent channel.Since 2011, there has been significant advancement in MDM transmission experiments using coupled MCFs or well-designed FMFs with or without multiple-input multiple-output processing for large capacity and long-haul applications. Many signals may be sent on any certain wavelength and core using different propagation modes. For high-speed communication, researchers have also looked at MDM-WDM transmission using LP01 and two degenerate LP11 modes.

II. LITERATURE REVIEW: RECENT DEVELOPMENT IN OPTICAL COMMUNICATION

Since OFDM was first brought to the optical realm in 2005, the rate at which signals are sent has increased dramatically. 2009 saw the successful demonstration of transmission over 80 km of single-mode fibre without dispersion correction by Takayuki et al. [14], who disclosed a unique electro-optic subcarrier multiplexing approach to create an over 100 Gb/s high speed optical OFDM signal with a limited number of subcarriers. As stated in coherent optical frequency-division multiplexing transmission is used to show 1 Tb/s per channel. In 2010, Shief et al. introduced a novel technique known as multiband DFT-spread OFDM in which 107 Gb/s transmissions over long-haul standard-single-mode-fiber are achieved by applying DFT-SOFDM to each sub-band of the multiband CO-OFDM in order to reduce the PAPR within each sub-band. A unique approach to create coherent 21 optical subcarriers with a fixed frequency of 25 GHz was developed and experimentally proven by Yu et al. in 2011. A 1.96 Tb/s polarization-multiplexing optical orthogonal frequency multiplexed signal was produced using these optical subcarriers. In a comparable year, Hillerkuss et al. presented an optical fast Fourier transform scheme that offers the processing power required to decode lower-bit-rate tributaries from fiber-transmitted OFDM data streams and encode them into 10.8 and 26.0 Tbit s^{-1} line-rate OFDM data streams. Zhu et al. announced in development of a novel multicore fibre with seven single-mode cores stacked in a hexagonal array. The MCF demonstrated minimal loss across the C and L bands as well as reduced crosstalk among the cores. Using space-division multiplexing and dense wavelength- division multiplexing we experimentally show a record transmission capacity of 112 Tb/s across a 76.8-km MCF. The same year reported the first experimental demonstration of 56-Tb/s of space-division multiplexed DWDM transmission of PDM-QPSK channels over a multicore fibre, with a record spectral efficiency of 14 b/s/Hz, and a total capacity of 56-Tb/s over a 76.8-km seven-core fibre. In Qian et al. used PDM-128QAM-OFDM modulation with pilot-based phase noise reduction to show transmission of 101.7-Tb/s across 3×55 km SSMF, achieving spectral efficiency of 11 bits/s/Hz.

According to in 2012, 64 Tb/s of capacity was successfully transmitted across 320 km of reach using 8 THz of spectrum in the C+L bands, with a nett spectral efficiency of 8 bit/s/Hz. The use of raised-cosine pulse-shaped PDM-36QAM modulation and ultra-large-area fibre, in which each 25 GHz channel was divided into four sub-bands, each carrying a 73.5 GHz OFDM signal modulated with 128-ary Quadrature Amplitude Modulation at each modulated subcarrier, allowed for the achievement of the goal. The same year, Xiang et al talked about how to use Nyquist-shaped, polarization-division-multiplexed 32-quadrature amplitude modulation and both pre- and post-transmission digital equalisation to generate and transmit 450 Gb/s wavelength- division multiplexed channels over the standard 50 GHz ITU-T grid optical network at a nett spectral efficiency of 8.4 b/s/Hz. 101.7-Tb/s transmissions over 355 km of standard single-mode fibre with a nett spectral efficiency of 11 b/s/Hz were experimentally realised by Qian et al.

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utilising 370 dense wavelength-division multiplexed channels spanning the optical C- and L-bands separated at 25 GHz. Sleiffer et al. showed that a 73.7 Tb/s DP-16QAM mode-division-multiplexed signal could be sent over a 119-kilometer few-mode fibre transmission line that included a phase plate-based mode multiplexer and an inline multi mode EDFA in the same year.

The enabling modulation, coding, and line system technologies, together with the obstacles that now exist, were suggested by Xiang et al. in 2013. It was shown that a common 50 GHz frequency can transport signals at 400 Gb/s per channel. ITU-T grid with a nett spectral efficiency of 8.4 b/ds/Hz across a useful transmission range for urban and regional applications. Using PDM-OFDM-16QAM modulation, all-Raman amplification, and coherent detection, Li et al. achieved 63-Tb/s signal across 160-km standard single mode fibre transmission in the C- and L-bands with 25-GHz channel spacing. Additionally, Foursa et al. carried 441x100Gb/s signals across 9,100 km with a bit rate-distance product of >400 Pb/s*km in 9 THz of optical bandwidth. In order to achieve high data rates of 1.050 Tb/s across 3600 km single mode fibre Fahad et al. examined the combination of wavelength division multiplexing with direct detection optical orthogonal frequency division multiplexing. Using space division multiplexing with 19 channels, Jun et al. announced record capacity data transmission of 305 Tb/s across 10.1 km in their paper. With the use of free-space optics and little extra crosstalk, they created a 19-channel SDM multiplexer/demultiplexer and a trench-assisted homogeneous 19-core fibre. A 17.6-Tb/s DWDM optical transmission system that is spectrally efficient was shown across a distance of 678 kilometres using pre-filtering analysis, as stated in reference.

A model to transmit 49.3 Tb/s across 9,100 km utilising 282 16QAM coded modulation channels with spectral efficiency suited to the spectrum performance of the transmission system was developed and built by Cai et al. in 2014. Guifang et al. published work on SDM for few-mode or multimode fiber-optic communication in the same year. They focused in particular on the crucial issue of mode crosstalk. In order to achieve high data speeds of 1.60 Tb/s across 4500 km of single mode fibre Sinan et al. examined a coherent optical orthogonal frequency division multiplexing system with dense wavelength division multiplexing Multiplexing 16 OFDM signals at 100 Gb/s each resulted in a signal of 1.60 Tb/s. Rahman et al. covered the trade-offs at the transmitter and receiver to accomplish long-haul reach for a 1 Tb/s superchannel in the same year. A four-channel wavelength-division multiplexing 256.51 Gbps/s 16-ary quadrature amplitude modulation-OFDM signal transmission system for short-range optical amplifier free inter-connection with real-time reception based on FPGA was successfully demonstrated by Xiao et al. in 2016. A trained and pilot-aided digital coherent receiver that can identify a 1 Tb/s super channel using a single optical front end was designed and characterised by Millar et al. Over hybrid spans using quasi-single-mode fibre, Zhang et al. showed transmission capabilities of 34.9 Tb/s over 6375 km based on Gaussian-like DP-64APSK and 33.3 Tb/s over 6800 km utilising DP-32QAM. We proposed and demonstrated dense space-division multiplexing which offers the possibility of ultra-high capacity SDM transmission systems with high spatial density and spatial channel count of over 30 per fibre. Mizuno et al. described recent advances in space division multiplexed transmission. As stated in, Zhang et al. finally showed that they could transmit 34.9 Tb/s over 6375 km using DP-64APSK, which is Gaussian-like, and 33.3 Tb/s over 6800 km using DP-32QAM via hybrid spans with quasi-single-mode fibre.

Li-Fi Technology: Wireless Data Transmission Through Visible Light

Similar to Wi-Fi, Light Fidelity is a fully networked, bidirectional, high-speed wireless communication system. The phrase "visible light communication" was first used by Harald Haas. It is a subset of optical wireless communications and may be used in conjunction with RF communication or even in substitute of it when data broadcasting is involved. Li-Fi, often referred to as "Optical Wi-Fi" or "Light Fidelity," is a system that uses light waves to transport data faster than the human eye can follow. It works by utilising an LED light bulb to adjust the light's intensity. It is predicated on visible light communication a data transmission method that uses visible light with a wavelength range of 375 to 780 nm.

In 25 years, LED bulbs will have the processing capacity of contemporary mobile phones, according to Haas, who predicts that LEDs will become more than simply light sources. The Li-Fi Consortium highlights that Li-Fi technology can achieve rates higher than 10 GHz. Initially, using a standard white-light LED, researchers at the Heinrich Hertz Institute in Berlin, Germany, were able to reach over 500 gigabytes per second. The Li-Fi group demonstrated their work in integrating emitters and photodiodes to detect light using readily accessible red, green, and blue LEDs at the

IEEE Photonics Conference in October. The system could transmit and receive data at a combined rate of 110 Mbps by doing that. They designed their system to send data across a distance of ten metres at a speed of 1.1 Gbps. In a laboratory environment, researchers at the Fraunhofer Henrich Hertz Institute in Germany were able to transport data at 3Gbps in 2013.

Researchers from the Autonomous Technological Institute of Mexico and the Mexican business Sisoft claimed to have employed LED lights to simultaneously illuminate the room and transport data in a single direction at a rate of 10Gbps. Using infrared technology, researchers at the University of Oxford recently reached 224 Gbps bi-directional speed across 3 meters. With this speed, eighteen 1.5 GB movies may be downloaded in a single second. Leeds University researchers also used laser diodes to achieve 20 Gbps indoor VLC . Recently, research has been conducted in the field of solar LiFi , where light is utilised to transfer high-speed data and the solar panel is capable of receiving LiFi signals. In addition to collecting energy, the solar panel also serves as a broadband receiver and a source of energy for LiFi technology.

III. CONCLUSION

In-depth research on many multiplexing strategies for fast wired and wireless optical communication is covered in this publication. The data rate via OFDM channel has risen dramatically in the last few years, going from 100 Gb/s to 100 Tb/s. The research presented in this article indicates that a number of cutting-edge sub-band carrier modulation techniques may have helped achieve this high data rate. Furthermore, we found that the CO OFDM has emerged as an effective substitute in lessening the impacts of frequency selective fading and dispersion based on the investigation and analysis of different OFDM strategies. This increases the benefit of having a bandwidth-efficient link with a quicker reaction time. Furthermore, we've seen that obtaining such high data rates has been greatly aided by the use of very accurate and efficient equipment for the creation and detection of OFDM signals. Additionally, recent work on wireless optical communication, or Li Fi, has been discussed; this field has a tonne of room for study and innovation in the future. Through the use of natural solar energy, this technology will contribute to the creation of a cleaner, safer, greener, and more radiant future.

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