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Review

A contemporary survey on free space optical communication: Potentials, technical challenges, recent advances and research direction

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ABSTRACT

Due to the unprecedented growth of high speed multimedia services and diversified applications initiated from the massive connectivity of IoT devices, 5G and beyond 5G (B5G) cellular communications, the existing electromagnetic spectrum under RF ranges is incapable to tackle the enormous future data rate demands. Free space optical (FSO) communication systems covering an ultra-wide range of unlicensed spectrum have emerged as a promising solution to mitigate conventional RF spectrum scarcity ranging of communication distances from nm to several kilometers. The implication of hybrid FSO, radio over FSO (RoFSO), MIMO FSO systems support ultra high speed 5G/B5G demand by eliminating the limitations of individual technology. FSO offers a broad range of applications both in outdoor and indoor services, for instance, wireless video surveillance, data centers, terrestrial transmission, LAN connectivity, mobile cellular networks, last mile solution, space communications, radio astronomy, remote sensing, and so on. Despite the potential benefits of FSO technology, its link reliability deteriorates due to atmospheric turbulence, cloud induced fading, some other environmental factors such as fog, aerosol, temperature variations, storms, heavy rain, pointing error, and scintillation. This survey presents the overview of several key technologies, significance, demonstration, recent development, and implications of state-of-the-art criteria in terms of spectrum reuse, classification, architecture, physical layer security, and future applications for understanding FSO system among different appealing optical wireless technologies. In addition, the adaptive modulation, channel modeling schemes, relay-aided transmission, cooperative diversity, potential challenges, numerous mitigation techniques, and opportunities in the near future are also outlined to realize the successful deployment of FSO systems.

1. Introduction

In recent years, diverse types of multimedia applications are expanding enormously, generating a mass volume of mobile data together with high data-rate wireless connectivity. The forthcoming 5G technology offers various attractive services such as massive system capacity, huge device connectivity, high-level security, ultra-low latency, extremely low power consumption with a tremendous quality of experience (QoE) (Ijaz et al., 2016; Jaber et al., 2016; Shafi et al., 2017; Chowdhury et al., 2020). Notably, 5G communication is contemplated with ultra-dense heterogeneous networks allowing hundred times additional wireless device connectivity as well as transmission rate compared to existing wireless networks (Chowdhury et al., 2018). Therefore, 5G and beyond networks require high-capacity backhaul connectivity in order to support hyper-dense fast access network, minimal power consumption, and little end-to-end delays (Olwal et al., 2016; Mustafa et al., 2016). It becomes challenging to handle the unprecedented high volume of information for the 5G connectivity and hence, robust technical solutions are required in order to guaranteed quality of service (QoS) for the end users. It is widely accepted that radio frequency (RF) is commonly used in wireless communications which are more limited due to the shortage of spectrum resources (Ghassemlooy et al., 2015; Obeed et al., 2018). Envisioning the concept of IoT, it enables real-time communications, sensing, monitoring and resource sharing in huge smart device connectivity ranging from social, industrial and business purpose.

With the rapid growth of the Internet of Things (IoT)/Internet of Everything (IoE) technologies, a massive number of physical smart devices are connected to the networks is accelerating exponentially (Palattella et al., 2016; Hassan et al., 2017; Schulz et al., 2017). Consequently, IoT devices generate a huge volume of data. To meet the ever-increasing demand of 5G networks and serving the huge demands of the IoT

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paradigm, it is predicted that the currently available electromagnetic frequency band is insufficient. Meanwhile, this RF frequency band suffers a small spectrum range, also has limitations related to regulation based spectrum use and intense level of interference from the surrounded RF access points. In many cases, RF sub-bands are entirely allocated to mobile cellular operators, TV broadcasting, and end-to-end microwave links. From the indication of RF based wireless network drawbacks, researchers are looking for alternative approach millimeter and nanometer waves for wireless communication. Likewise FSO technology, mmWave (operated in 30–300 GHz) supports high speed transmission over few kilometers (less than FSO coverage distance) but mmWave can achieves date rate up to 10 Gbps either operating in V-band (57–64 GHz) or E-band (81–86 GHz), whereas FSO systems provides about 100 Gbps range (Ismail et al., 2017). In addition, mmWave operating in E-band is a licensed spectrum which consume high transmit power and requires a large antenna gain. As a consequence, academia and industries are currently interested in license free optical spectrum covering 1 mm–10 nm as an emerging alternative to RF for future ultra-density and ultra-capacity networks in perspective of optical wireless communication (OWC) (Koonen, 2018; Cruz et al., 2018).

In contrary to RF-enabled networks, OWC technology offers some remarkable advantages like ultra-high data rate transmission capacity ranging from nanometers to several kilometers both for indoor and outdoor applications. In addition, OWC provides broad spectrum, very low latency, low cost, and lower power consumption, addressing the massive demand requirements of 5G/B5G communications. Moreover, OWC technology has the potential to provide some outstanding communication features such as reliable security, electromagnetic interference free transmission, and high system efficiency due to using a broad optical spectrum (Aguiar-Castillo et al., 2021). The term OWC is referred to wireless connectivity using optical spectrum. Ref. Tsonev et al. (2015) demonstrates that OWC technology can attain 100 Gb/s at standard indoor illuminations and is capable to provide energy efficient communication. The most important feature of OWC technologies is that it do not require a comprehensive infrastructure and thereby reducing the installation cost maintaining all the green agenda for high speed communication (Zhang et al., 2017; Khreishah et al., 2018; Arienzo, 2019). Visible light communication (VLC) and light fidelity (Li-Fi) techniques under OWC technology uses the existing illumination structure to realize wireless data transfer (Haas et al., 2016; Ghassemlooy et al., 2016; Wang et al., 2017b). OWC provides a greater level of data security since the light waves do not penetrate the enclosed walls. Typically, visible light (VL), infrared (IR), or ultraviolet (UV) spectra are used as propagation media. Most promising wireless systems in OWC such as VLC, LiFi, optical camera communication (OCC), and free space optical (FSO) communication are being developed based on those three optical bands. However, VLC, LiFi, OCC, and FSO technologies have some similarities and disparities by means of communication protocol, propagation media, architecture, and applications. On the other hand, the aggregate option of OWC and RF referred as hybrid RF/OWC systems may establish an effective solution for tremendous upcoming user demands.

The use of RF spectrum across existing wireless applications has almost been exhausted. However, RF-based communication is highly sensitive to interference but provides better performance under non-LOS (NLOS) conditions. This key feature of RF systems is capable to overcome some weaknesses of OWC schemes particularly for the end users. Due to the complementary characteristics of RF and OWC technologies, researchers have proposed some hybrid RF/OWC approaches to support IoT/IoE, 5G/B5G communications systems (Pan et al., 2017; Kafafy et al., 2018; Liang et al., 2017; Büyükçorak and Kurt, 2017; Kashef et al., 2018; Sharma et al., 2018; Rahaim et al., 2017; Li et al., 2016b; Wang et al., 2018a; Nguyen et al., 2019b; Mufutau et al., 2020; Tonini et al., 2019; Esmail et al., 2019). The co-deployment of RF/optical wireless hybrid system solves the last mile problem where end users can be benefited from RF coverage. The hybrid approach incorporates two or more different related technologies (e.g., RF/FSO, WiFi/LiFi/, VLC/FSO, LiFi,/OCC, acoustic/optical for underwater communication) that can enhance the system performance in terms of throughput, bit error rate (BER), reliability, and energy efficiency providing the combined benefits of both technologies. Hybrid networks can be deployed in many applications for instance seamless movement, load balancing, high speed wireless connectivity in remote areas, and link performance improvement (Aldalbahi et al., 2017; Basnayaka and Haas, 2017; Feng et al., 2016; Baig et al., 2018; Rakia et al., 2017; Zhou et al., 2017; Hasan et al., 2019; Tsai et al., 2019).

FSO is a line of sight (LOS) technology uses eye-safe laser beams that provide optical data communication wirelessly in the free space medium. FSO receivers are comprised of telescopic lenses that are able to collect light streams and transmit digital information to the destination at the speed of Gbps range (Zafar and Khalid, 2021). The availability of a broad optical spectrum extends the opportunity to tackle a massive volume of data capacity. FSO is a promising alternative to radio relay link as the light travels faster through the air than glass. FSO systems typically use very narrow spectrum laser beams as carrier signals that provide high speed data communication between two fixed nodes over distances up to few kilometers, inherent security (i.e., light is confined within a certain defined zone), large reuse factor, and immunity to electromagnetic interference with other communication network or electronic equipment. Unlike radio waves, the optical beam cannot penetrate walls, free from inter-cell interference, and do not require frequency coordination. Hence, the same optical beam can be reused for different purposes. Despite the multiple advantages of FSO systems over a wide range of applications, the performance of FSO link suffers of link reliability and high sensitivity to some limiting factors, for example, outdoor weather conditions (e.g., heavy rain, fog, smoke, storms, deep clouds, snow, and scintillation), atmospheric turbulence and physical obstructions. This survey preliminary discuss the comparative overview of OWC technologies competitive with the FSO technique. Thereafter, an extensive analysis of FSO technology illustrating the potential applications including recently developed intriguing features, a wide range of deployment challenges and possible mitigation methods, reliability analysis, and research directions.

2. Overview of OWC

The wide range of electromagnetic (EM) frequency spectrum allows extending the use of frequency band for optical wireless communication purpose to tackle the congested spectrum of RF. Based on the related optical bands properties (e.g., near IR, VL, and UV), different OWC technologies are being developed. For example, the infrared spectrum can be used for applications where illumination is not required. On the other hand, UV frequency bands support high speed data rate for LOS and NLOS communication over short and distances. The OWC technologies offer excellent features of high data rate communication link that can be used in a broad range of applications ranging from ultra-short to long distance communications. Another important key features include unregulated high optical bandwidth, low-energy consumption, a greater level of data security, low deployment cost, immune of interference from RF based networks, low bit error rate (BER), and ease of integration with existing infrastructure. In contrast, the OWC performance degraded due to blocking obstacles along with the communication link including several other limiting factors. For ease of reference, notations used in this paper are summarized in Table 1.

2.1. OWC technologies

Optical carrier transmission in the form of infrared (IR), visible light (VL), or ultra-violet (UV) spectrum have distinctive properties enabling different key communications (Ghassemlooy et al., 2015; Maier and

Table 1
Nomenclature.

5G	5th Generation	OOC	Optical Orthogonal Codes
AMC	Adaptive Modulation and Coding	OFDMA	Orthogonal Frequency-Division Multiple Access
AP	Access Point	OOK	On–Off Keying
AWGN	Additive White Gaussian Noise	OPPM	Optical Pulse Position Modulation
B5G	Beyond 5G	OSTBC	Orthogonal Space–Time Block Code
BER	Bit Error Rate	OSSK	Optical Space Shift Keying
BCHB	Bose–Chaudhuri–Hocquenghem Block	OWC	Optical Wireless Communication
BICM	Bit Interleaved Coded Modulation	P2P	Point-to-Point
BMST	Block Markov Superposition Transmission	P2mP	Point-to-multi Point
BPSK	Binary Phase Shift Keying	EE	Energy Efficiency
CAP	Carrierless Amplitude and Phase	PAPR	Peak-to-Average Power Ratio
CBFSK	Coherent Frequency Shift Keying	PAM	Pulse Amplitude Modulation
CBPSK	Coherent BPSK	PAT	Pointing Acquisition Tracking
CN	Core Network	PD	Photodetector
CSI	Channel State Information	SM	Spatial Modulation
CSK	Color Shift Keying	PDF	Probability Density Function
CSMA	Carrier Sense Multiple Access	PEP	Pairwise Error Probability
D2D	Device-to-Device	PLC	Power-Line Communication
DCO	DC-biased Optical	PLNC	Physical Layer Network Coding
DBPSK	Differential BPSK	PM	Pulse Modulation
DPIWM	Digital Pulse Interval and Width Modulation	PPM	Pulse Position Modulation
DPPM	Differential Pulse Position Modulation	PWM	Pulse Width Modulation
E2E	End-to-End	QAM	Quadrature Amplitude Modulation
EO	Electro Optic	QPSK	Quadrature Phase Shift Keying
FEC	Forward Error Correction	QoE	Quality of Experience
FTTH	Fiber to the Home	QoS	Quality of Service
GPS	Global Positioning System	RADAR	Radio Detection And Ranging
HetNets	Heterogeneous Networks	RC	Repetition Coding
ICI	Inter-cell Interference	RCPC	Rate Compatible Punctured Convolutional
IMC	Inverted Manchester Code	RF	Radio Frequency
IM/DD	Intensity Modulation/Direct Detection	RoFSO	Radio Over FSO
IoE	Internet of Everything	ROV	Remotely Operated Vehicle
IoT	Internet of Things	RS	Reed–Solomon
IR	Infrared Radiation	SDN	Software Defined Networking
ISI	Inter Symbol Interference	SE	Spectral Efficiency
LD	Laser Diode	SER	Symbol Error Rate
LDPC	Low Density Parity Check	SIM	Subcarrier Intensity Modulation
LED	Light Emitting Diode	SINR	Signal-to-Interference-Plus-Noise Ratio
LiDAR	Light Detection And Ranging	ST	Space–Time
LiFi	Light Fidelity	STTC	Space–Time Trellis Code
LOS	Line-of-Sight	UAV	Unmanned Area Vehicle
LT	Lubry Transform	UE	User Equipment
M2M	Machine-to-Machine	UV	Ultraviolet
MAI	Multi Access Interference	UWC	Underwater Communication
MBS	Macrocellular Base Station	UWOC	Underwater Wireless Optical Communication
mmWave	Millimeter-Wave	V2X	Vehicle-to-Vehicle, Vehicle-to-Infrastructure
MIMO	Multiple-Input and Multiple-Output	VANET	Vehicular Ad-hoc Network
MPPM	Multi-pulse Pulse Position Modulation	VCSEL	Vertical-Cavity Surface Emitting Laser
MZM	Mach Zehnder Modulator	VHO	Vertical Handover
NIR	Near Infrared	VLC	Visible Light Communication
NLOS	Non-Line-of-Sight	WDM	Wavelength Division Multiplexing
NOMA	Non-Orthogonal Multiple Access	WiFi	Wireless Fidelity
OCC	Optical Camera Communication	WLAN	Wireless Local Area Network
OCDMA	Optical Code Division Multiple Access	WSN	Wireless Sensor Networks

Ebrahimzadeh, 2019). Terrestrial free space optical communication systems (FSO) are operated at IR and VL frequency bands. Whereas UV spectrum supports high speed non line-of-sight (NLOS) and LOS optical communications (Ghassemlooy et al., 2015). Several OWC technologies such as VLC, light fidelity (LiFi), optical camera communication (OCC), light detection and ranging (LiDAR), and free space optical (FSO) communication are developed to meet the widespread wireless demand. LiFi is a relatively new technology complementing WiFi that provides high data rate transmission in the speed of light illumination aiming the same purposes to be served (Haas et al., 2016, 2020; Ullah et al., 2021). Light emitting diode (LED) or laser diode (LD) with an optical diffuser can be used as transmitters and photodetector (PD) as receiver. However, VLC and LiFi technologies can provide extreme transmission speed for indoor applications which are not effective for outdoor services due to the obstacle of light. Moreover, they cannot cover long range of communication distance. On the other hand, LEDs are used as transmitters and camera or image sensors used as a receiver in OCC subsystem under OWC (Goto et al., 2016; Zheng et al., 2017). OCC achieves a high SNR performance cancels out associated interference even under the outdoor environments. Besides, it exhibits stable performance for longer link coverage whether the communication takes place in indoor or outdoor (Zheng et al., 2017). LiDAR (Jin and Huang, 2020; Zhang et al., 2019) is a remote sensing 3D laser scanning method of a target with high-resolution maps. A LiDAR device comprises an LD, a scanner, and a specialized global positioning system (GPS) receiver. It captures information about a landscape and measures things using high resolution sensors for analyzing conditions and characteristics. Recently, free space optical (FSO) communication has emerged as a promising solution for next generation lightwave networking regardless of indoor or outdoor environments, despite the system is severely suffered by the channel impairments such as atmospheric turbulence and pointing error effect between the optical transmitter and receiver (Li et al., 2019c; Sharma et al., 2019). A substantial comparison among different OWC technologies and RF systems is demonstrated in Fig. 1.

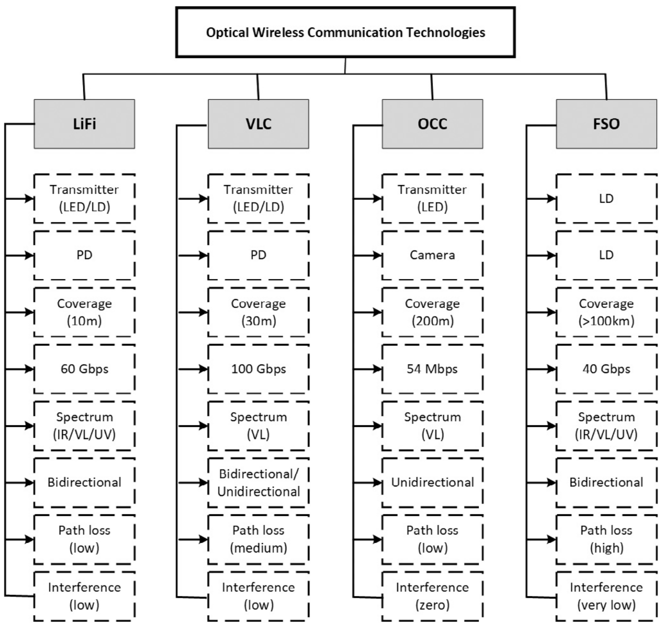

Fig. 1. Taxonomy of different optical wireless communication systems.

2.2. OWC technologies using IR/VL/UV spectrum

According to the transmission spectrum allocation (Khalighi and Uysal, 2014), OWC can be classified into three categories, namely infrared, visible light, and ultraviolet. Near IR (NIR) band is widely operated for point-to-point FSO communication including ultra-short (750 nm to 1450 nm), short (1400 nm to 3000 nm), medium (3000 nm to 8000 nm), long (8000 nm to 15 000 mm), and ultra-long distances (15 000 nm to 1 mm). However, ultra-short IR and short IR optical spectrum are used for long distance FSO communications. Whereas, medium IR and long IR spectrum can be used in military applications and thermal imaging purposes respectively. Besides, IR is also commonly used in LiFi and OCC for short and medium transmission distances; covers long distances for LiDAR technologies. The operating wavelength of NIR is 760 nm–1 mm and particularly suitable for LOS communication where no illumination is needed. However, it is not always safe for humans and limited application for NLOS communication. Secondly, visible light (VL) is commonly used for VLC, LiFi, and OCC covering short and medium distances. In some limited cases, VL spectrum (operating wavelength of 360–760 nm) is also used for FSO and LiDAR over the various broadcasting ranges (Chowdhury et al., 2018). The benefit of VL spectrum are: safe for human and can be exploited for illumination and communication prospects simultaneously. Likewise NIR, VL is perfect for LOS communication and exhibit poor data rate for NLOS transmission through a reflection of light. Finally, a considerable amount of interest in UV communication found for providing high speed NLOS/LOS communication links. UV spectrum (operating wavelength of 10–400 nm) is pertinent for short and medium ranges in LiFi, ultra-short, short, medium, long, and ultra-long coverage distance in FSO systems (Chowdhury et al., 2020).

2.3. Radio frequency technologies

Table 2 presents the key comparison among different RF techniques in terms of various design parameters.

WiFi. Roy et al. (2018), Shen et al. (2019), Poularakis et al. (2019) and Meng et al. (2020) technology enables wireless area networking using radio frequency under a particular range based on IEEE 802.11 standard. WiFi provides very high data rate communication up to 8 Gbps with mobility support under both LOS and NLOS environments. The prime benefits are an unlicensed free spectrum and lower deployment cost. Conversely, the lower level security issue and interference effect limited its performance.

Microwave link networks. Li et al. (2016a), Feng et al. (2019) and Wang et al. (2019b) supports point-to-point communication with a beam of radio signals to transmit information in the microwave frequency range. Microwave communication is a promising alternative to optical fiber links with a high data rate particularly for remote areas. It can cover over 100 km link distance and bit rate of 12.6 Gbps is demonstrated in Li et al. (2016a). The performance of microwave communication is suffered by electromagnetic interference, fog, rain, and other atmospheric turbulence.

Cellular networks. Liang et al. (2019), Shnaiwer et al. (2019) and Yu et al. (2019) comprised of macrocell and small cells called heterogeneous networks (HetNets) are widely deployed to provide a high bit rate to users. A macrocell base station (BS) provides a wide range of coverage and user mobility and supports a large number of user equipments (UEs). On the other hand, small cells network (e.g., microcell, picocell, femtocell) extend the cellular connectivity at the cell edge and filled up the coverage holes especially where the access is unavailable. However, macrocell deployment is expensive and offers low data rate whereas a limited RF spectrum is allocated for small cell networks.

Bluetooth. Collotta et al. (2018), Hussain et al. (2018), Rondón et al. (2020) and Elhence et al. (2020) an RF-based wireless technology provides data rate up to 2 Mbps using short wavelength radio signal in the 2.4 GHz unlicensed frequency band. Bluetooth devices consume low energy and support LOS/NLOS communications in a single hop topology. However, the performance of bluetooth communication suffers from low level security, short operational coverage, and high interference effect.

Underwater communication (UWC). Kaushal and Kaddoum (2016), Zeng et al. (2017), Jouhari et al. (2019) and Sun et al. (2020) an acoustic and RF based technology to transfer data underwater up to 20 km long range link distance and support both LOS/NLOS communications. However, the performance of UWC is limited by low data rate, large propagation delay and high sensitivity to the conditions of water.

2.4. Related works

A number of curiosity driven research works are conducting on OWC based networks worldwide in order to address the aforementioned issues. The use of optical frequency spectrum complementary to RF based wireless system provides some advantages, for instance, low spectrum availability, secure transmission, and low power consumption. Researchers across worldwide conducted essential literature reviews (Sarigiannidis et al., 2014; Shaddad et al., 2014; Mohsan and Amjad, 2021; Malik and Singh, 2015) in several aspects of OWC field. Ref. Chowdhury et al. (2018) presents an overview of OWC focusing on the operational principles of VLC, LiFi, LiDAR, FSO technologies highlighting the advantages and range of application areas. Ref. Tsonev et al. (2015) reported a survey emphasizing various modulation schemes, dimming functions, filtering, equalization, and beamforming for indoor VLC applications. Author in Sarigiannidis et al. (2014) presents the research direction toward optical-wireless convergence pointing out the issues of the conjunction of two different wireless and optical networks under dynamic bandwidth allocation. The fundamental access technologies and related progress advancements are comprehensively discussed of wireless access and optical broadband technologies (Shaddad et al., 2014). Sevincer et al. (2013) discuss the key challenges of jointly performing the lighting and networking functions in the area of integrated FSO and VLC technologies.

Ref. Islam and Majumder (2019b) demonstrated BER evaluation considering multi access interference (MAI) and crosstalk at the SIK

Table 2
Key features of different RF technologies.

Technology	WiFi	mmWave/Microwave	UWC	Heterogeneous network	Bluetooth
Merits	Free spectrum, low installation, mobility support, enable NLOS communications	High bandwidth & high data rate, Reduced antenna size at higher frequencies	Wide range of coverage, support LOS/NLOS communications	Mobility support, high level of QoS support LOS/NLOS communications	Unlicensed spectrum, support LOS/NLOS communications
Demerits	Low-level security & high interference	Suffer electromagnetic and other interference	Poor bit rate, high propagation delay	Limited spectrum	Limited coverage, high interference, low security

receiver to assess SINR accompanied by BER varying system parameters such as code length, number of simultaneous user. Results revealed that multi-wavelength OCDMA (MW-OCDMA) attains superior BER performance oven single wavelength OCDMA FSO scheme. However, the power penalty (PP) is more significant for higher values of jitter standard deviation and simultaneous users at a given BER of 10^{-9}. Note that PP can be considerably reduced with the increment of code length and number of wavelength for a given number of concurrent users. An analytical model of multi-wavelength OCDMA wavelength division multiplexing (MW-OCDMA-WDM) FSO communication systems is conducted to evaluate BER functionality and link capacity in the presence of aforementioned limiting factors for free space applications (Islam and Majumder, 2016). Authors decompose the evaluation of BER into two categories; Q-ary Optical PPM (Q-OPPM) with intensity modulation–direct detection (IM/DD) receiver considering the impact of refractive index variation of the optical channel link without encoding. Secondly, an extensive assessment of optical direct sequence (DS) CDMA encoder and shift inverse keying (SIK) dual optical decoder IM/DD based FSO communication is further investigated taking into consideration of strong and weak atmospheric turbulence. Furthermore, the OCDMA FSO system performance in terms of signal to interference plus noise ratio (SINR) as well as BER is carried out including the combined effect of distinctive atmospheric turbulences, multi-access interference (MAI), cross talk, and pointing error varying link length, transmission rate, cloud thickness, channel parameters, code length, and a number of simultaneous users. In addition, numerous transmitter and receiver diversity like SIMO, MISO and MIMO configurations over the turbulent channel with OOK direct detection based Rake receivers are also contemplated in order to evaluate power penalty sufferings, receiver sensitivity and capacity improvement for a given BER of 10^{-9}. To the end, simulation results validate the effectiveness of MW-OCDM-WDM hybrid scheme analytical model with a promising candidate for future terrestrial wireless optical communication networks. Ref. Khalighi and Uysal (2014) describes the theoretical limiting factors of FSO channels, algorithmic-level of system design approach integrating diverse channel coding, adaptive modulation schemes, spatial diversity, and hybrid RF/FSO systems.

This article comprehensively covers the implications, practical deployment scenarios, associated challenges, opportunities, and the research roadmap in the context of free space optical communications. Although a considerable number of research works have been published on related OWC technologies, but these papers focus only on particular areas such as BER improvement, ergodic capacity, throughput enhancement, efficient resource allocation, outage probability, etc. In this survey, we particularly discussed different forms of FSO communication systems, for example, multi user FSO, radio over FSO, MIMO FSO, hybrid FSO, coherent FSO, subcarrier multiplexing FSO, and so on. Table 3 summarizes the key contributions of numerous research works conducted on different wireless optical schemes in the context of OWC.

3. Contributions

In this paper, we present a brief overview and extensive comparison of different optical wireless technologies over RF based systems. The comprehensive analysis of different OWC technologies is not the prime objective of this study. This article substantially covers the area of free space optical communication (FSO) pertaining to different issues including the effective solution for the successful deployment of FSO systems addressing related challenges. The application scenarios, principle of operations, transmitters, receivers, channel characterization, modulation techniques, network architecture of FSO, and hybrid FSO systems highlighting the key advantages and disadvantages are clearly presented. For better illustration of FSO schemes, comparative surveys among other OWC technologies are demonstrated by means of communication distance, data rate, and modulation techniques. In addition, different important hybrid schemes for instance RF/FSO, mmWave/FSO, acoustic/FSO, OCC/FSO, and the research trends are clearly manifested in this paper. To our best knowledge, there is no survey article is carried out in the FSO context comprising all the aforementioned aspects altogether in an extensive manner. For better illustration, Table 4 presents the related surveys/reviews of FSO with a concise description of their major contributions. The key contributions of this survey paper can be summarized as follows.

- Demonstrate the potential key features of FSO technology in perspective of different systems (e.g., 5G/B5G, IoT/IoE, underwater communications, space communications, etc.) shedding light to the research communities.
- Outline the detailed scope of FSO and hybrid FSO technologies, multi-user FSO, MIMO FSO system, coherent FSO techniques, SCM-FSO systems, including the recent research trends and research gaps are surveyed. The paramount implications and distinctions of FSO systems in comparison with other OWC technologies are clearly illustrated.
- Provide extensive surveys on FSO transceivers, channel modeling, QoS provisioning, various diversity techniques, relay transmission, FSO transmission in physical and TCP layer, link budget, reliability, high capacity backhaul networking, and next generation FSO systems.
- The challenging issues encountered and the potential mitigation techniques in light of advanced optics, as well as future research directions for FSO systems are extensively pointed out.

The rest of the paper is organized as follows. Section 4 presents the fundamentals of FSO communications, merits and demerits, wide range of application scenarios. The reliability of including link budget is demonstrated in Section 5. The potential of mitigation techniques to address the technical challenges are extensively discussed in Section 6. Subsequent sections describe some attractive features of FSO technology pointing out on multiuser FSO, MIMO FSO, and the prospect of future generation FSO technology. The research challenges, opportunities, and future research directions are outlined in Section 9. Furthermore, the summary of this survey and lessons learned is presented in Section 10. Finally, Section 11 concludes the review paper.

4. Free space optical (FSO) communication

Free space optical communication (FSO) refers to the point-to-point wireless optical transmission through the unguided propagation media using infrared (IR) and visible light bands.

Table 3
Related works of OWC technologies (Contd.).

OWC System	Major contribution	References
LiFi	Application of LiFi components to hybrid LiFi/WiFi networks and clarify how LiFi takes VLC to realize fully wireless network systems.	Haas et al. (2016)
	Introduce dynamically resource allocation scheme, management and configuration in LiFi attocell access network.	Alshaer and Haas (2018)
	Presented the downlink performance of optical attocell networks in terms of SINR, outage probability achievable throughput with OFDM technique.	Chen et al. (2016a)
	The key advantages of LiFi over WiFi is presented by means of data rate and flexibility operation.	Soni et al. (2016)
	Demonstrated LiFi based 8 Gbps transmission rate in the 5G communication.	Haas (2018)
	Described the underlying principles of high performance indoor OWC focusing on throughput maximization, energy efficiency, hardware complexity integrating OFDM-MIMO transmission and non-linearity model.	Dimitrov and Haas (2015)
	Experimented of 56 Gbps bit rate based on four level pulse amplitude modulation (PAM) LiFi in outdoor environment.	Lu et al. (2017b)
VLC	Investigated 100 Gb/s transmission capabilities using LDs at indoor level considering illumination constraints.	Tsonev et al. (2015)
	Analyzed the accuracy of VLC based indoor positioning systems based on three methods namely, mathematical, sensor-assisted and optimization.	luo et al. (2017)
	Reviewed the system design, physical layer properties of VLC channel, adaptive modulation formats, medium access control, characteristics of transceiver, various visible light sensing, robustness to noise, direction of increasing communication range, enhancement of spectral efficiency, concept of heterogeneous VLC for short range communication, parallel VLC framework, and potential applications in indoors and outdoors, deployment challenges.	Pathak et al. (2015), Khan (2017) and Khan (2017)
	Examined resource and power allocation mechanisms, access point (AP) coordination techniques, non-orthogonal multiple access VLC networks, security concerns, fairness, energy efficiency, fairness, secrecy rate, channel capacity evaluation, performance metrics, simultaneous information transmission and energy harvesting in VLC networks in the context of 5G communication.	Obeed et al. (2019), Hammouda et al. (2018b)
	Discussed optimal resource allocation, fairness, spectral efficiency, achievable throughput and interference management in a multi-user VLC system employing OFDMA technique.	Bawazir et al. (2018)
	Pointed out the point-to-point ergodic channel capacity and SNR with respect to geometrical parameters for indoor VLC applications.	Xu et al. (2017b)
	Proposed a combined optical spectral efficient mobile fronthaul integrating low cost LED in the perspectives of spatial densified LTE networks to enable multi-tier coordination.	Lu et al. (2017a)
	Proposed a priority based dynamic channel reservation model focusing on call blocking probability and channel utilization considering real-time call arrival rates provisioning QoS.	Chowdhury et al. (2014)
OCC	Presented 55 Mb/s VLC signal transmission using optical communication image (OCI) sensor and optical OFDM with achievable BER $<10^{-5}$.	Goto et al. (2016)
	Examine the channel model according to link distance between transmitter and receiver for vehicle to infrastructure varying the luminance of the central pixel projected from optical sources.	Takai et al. (2014) and Yamazato et al. (2015)
	A downlink mobile camera based short-distance VLC is designed to examined the attainable data rate incorporating camera rotation compensation for multiuser access.	Cahyadi et al. (2016)
	A vehicle localization scheme in an outdoor environment based on hybrid optical camera communication and photogrammetry technique is proposed.	Hossan et al. (2018a)
	Introduced the smartphones localization technique in an indoor environments by calculating the coordinate of receiver and distance from LED transmitters.	Hossan et al. (2018b)
OCC	Demonstrated head mounted display enabled human bond communication method of bidirectional communication among multiple users for visual applications in OCC.	Hossan et al. (2019)
LiDAR	Introduce a new approach of LiDAR waveform decomposition and a new detection scheme for occluded pedestrian based on human Doppler distribution.	Kwon et al. (2017)
	Proposed a novel speed estimation system sensing visible light variation of the vehicle's headlamps under different road scenarios.	Abuella et al. (2019)
FSO	Presented BER evaluation of a multi-wavelength OCDMA FSO system with shift inverse keying balanced direct detection receiver and optical encoder taking into consideration of pointing error.	Islam and Majumder (2019b)
	Multi access interference (MAI) and crosstalk at the SIK receiver are assumed to assess SINR accompanied by BER varying system parameters such as code length, number of simultaneous user considering atmospheric turbulence.	Islam and Majumder (2019a)
	Analyzed adaptive acquisition system that perform better for the low probability of detection based on shotgun scanning approach in FSO.	Bashir and Alouini (2020)
	A detector array based receiver is illustrated in deep space for FSO in order to minimize pointing loss and improvement of probability error under low SNR condition.	Bashir (2020)
	Examined the feasibility of vertical backhaul/fronthaul framework where the traffic transport between the access and core networks via point-to-point FSO links under different weather conditions.	Alzenad et al. (2018)

Table 4
Comparison of related Surveys/Reviews on FSO communications.

Reference	Year	Journals/Book Chapters	Major contribution
Sevincer et al. (2013)	2013	IEEE Communications Surveys & Tutorials	Explore the VLC and FSO technologies and survey the potential of combined implications in a single field of study. Present different scenarios of limiting factors on system performance and functionality of light sources.
Alkholidi and Altowij (2014)	2014	Contemporary Issues in Wireless Communications	Review the applications of FSO, optical link budget, and empirical study of BER performance in a particular city considering few constraints.
Khalighi and Uysal (2014)	2014	IEEE Communications Surveys & Tutorials	Survey FSO link modeling, modulation formats, cooperative transmission, and hybrid RF/FSO systems.
Son and Mao (2017)	2017	Digital Communications and Networks	Demonstrate the characteristics of different classified subnetwork FSO systems and several design factors including network topology design, eye safety issue.
Kaushal and Kaddoum (2017)	2017	IEEE Communications Surveys & Tutorials	Survey numerous challenges encountered in FSO uplink/downlink space communications and inter-satellite transmission.
Mansour et al. (2017)	2017	Optics and Lasers in Engineering	Overview the potential challenges in FSO communications and solutions including cooperative relay networks and aspects of three different channel coding.
Chowdhury et al. (2018)	2018	IEEE Access	Survey different wireless optical access technologies, and provide details of these technologies explicitly.
Kaymak et al. (2018)	2018	IEEE Communications Surveys & Tutorials	Review on pointing, acquisition, tracking, and (PAT) techniques used in FSO systems under line of sight (LOS) and non-LOS scenarios.
Farooq et al. (2018)	2018	Optical and Wireless Technologies	Addressing the factors related to channel impairments in FSO applications
Raj and Majumder (2019)	2019	IET Communications	Review the FSO channel limitations, temporal and spatial challenges, and possible mitigation techniques.
Hamza et al. (2019)	2019	IEEE Communications Surveys & Tutorials	Survey multi-level FSO network classifications compared to existing ones.
Kumar and Singh (2020)	2020	Intelligent Communication, Control and Devices	Overview of challenges and possible mitigation techniques in FSO communications briefly.
This Paper			Comprehensive survey dedicated to FSO wireless systems in comparison with other optical wireless systems, discusses all of the relevant FSO technologies, address various issues related to a wide range of FSO challenges, mitigation methods, reliability and link design aspects, extensive application scenarios incorporating next-generation functionality and heterogeneous FSO networks. The research roadmap and opportunities are also demonstrated.

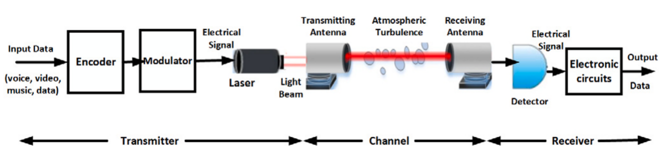

Fig. 2. A basic FSO communication system.

Generally, outdoor FSO links operate in the VL and UV bands, near IR and VL bands are used in indoor and underwater FSO communication (Hamza et al., 2019). FSO operating at extremely high frequencies (i.e. short wavelength) make the photodetectors immune to multipath signal fluctuations whereas RF networks are highly susceptible to multipath fading. Multiple digital signals such as internet data, voice, image/video, computer files, etc. are first converted to light signals using an optical transmitter, then modulated by a suitable scheme, traveling multiplexed signal through the FSO channel in the optical domain, received the incoming signal using optical photodetector and finally transmitted demultiplexed signals toward the destination after necessary electronic switching. Fig. 2 demonstrates the typical free space optical communication system depicting light sources, transmission medium, optical receiver, electrical to optical conversion and vice-versa.

4.1. Applications of FSO

FSO systems have primarily attracted as it provides efficient solution of the bottlenecks of last mile problem filled up the gap between optical fiber infrastructure and the destination users. To fully utilize the existing setup, telecom operators are investing considerable investments to fiber backbone and expansion of FSO links as well accompanied by the tremendous growth at the network boundary where end subscribers easily get access with high speed systems. FSO schemes can be a promising alternative in cases where buried optical fiber connectivity is costly and/or infeasible. A few applications of FSO systems are illustrated in Fig. 3. Some attractive applications of FSO systems are briefly described in the following.

- *Inter-building (e.g., Campus/Enterprise/Residential) connectivity*:
  Buildings in different infrastructures (i.e., school campus, office, corporations) are experiencing heterogeneous traffic demand (e.g., voice, internet data, fax, and multimedia services) overwhelmingly. FSO technology can setup a path among multiple buildings in certain areas supporting extreme levels of data speed in a cheaper way without installing dedicated fiber links. FSO can be used as high speed data interconnection bridge among geographically separated buildings (i.e. enterprise connectivity) for example, ship-to-ship, and community to community communications.
- *Video surveillance and disaster monitoring*:
  Wireless video monitoring is widely employed in military applications, commercial and public safety which provides high throughput than conventional ones. FSO systems exhibit a good choice of alternative to allow ultra-quality of video transmission. On the other hand, temporary FSO links can be readily installed in disaster situations to monitor terrorist attacks, emergency situations, and natural disasters. Besides, FSO links can be readily deployed in the area where no wireline connections are not feasible.
- *Backhaul for cellular networks*:
  A communication among cellular base stations (i.e., base transceiver station, controller section, and mobile switching center) involves wireline connections by means of T1/E1 lines and microwave communications for the wireless link. The deployment of FSO technology offers a backup path for extended bandwidth-intensive high speed cellular services. As a consequence, FSO can

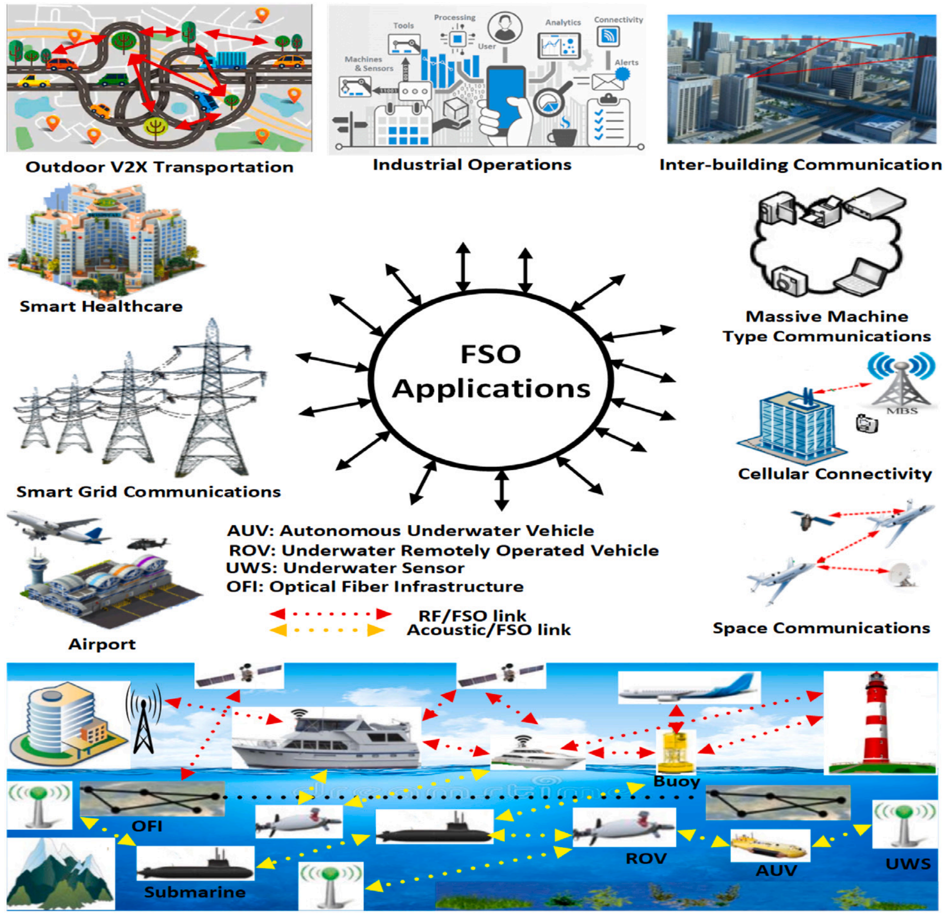

Fig. 3. A few applications of FSO systems.

be deployed for SONET rings connectivity and core infrastructure in the metropolitan area.

- *Video Broadcasting*:
  Nowadays live events broadcasting such as sports, high definition (HD) services, television crime, and ceremonies reports, covering critical news in remote zones, signals from cameras are needed to be sent a central node. FSO system is capable of satisfying the high quality of transmission (throughput demand) among different nodes to end users.
- *Security:*
  Cyber security and computational security under the realization of quantum computers world attaining deep attention, for example, transfer secure electronic money transfer. Quantum cryptography provides unconditional security which is generally connected with fiber optic infrastructure. Unwanted users cannot hack the information, since FSO signal cannot penetrate an obstacle.
- *Last mile solution:*
  Nowadays, a majority of the buildings are connected via coaxial cable and fiber optic cable, there are still many end-users who do not have access to the optical fiber infrastructure (FTTH). FSO communication can be considered as a paramount solution for remote end users (e.g., users in rural areas) with high speed connection of Gbps range over a large link distance. FSO can provide instant service to fiber optic users during laid off their existing fiber connectivity. Moreover, broadband internet services can be readily provided in isolated areas via FSO link where it is very hard to achieve conventional access technologies.
- *IoT and 5G:*
  IoT extends the widespread internet connectivity beyond conventional multimedia devices enabling to exchange information between themselves and the external environment. The dense deployment of IoT devices demands high bandwidth, high bit rate, security, low latency, and electromagnetic interference free data transmission. The implementation of 5G technology in IoT, high speed FSO links extends the coverage area and the overall system performance by means of spectral efficiency and robust data transmission capability (Dhasarathan et al., 2020). In other words, the integration of FSO technology with IoT over 5G connectivity can satisfy the requirement to realize global IoT.
- *Satellite communications:*
  FSO technology can be effectively deployed in space applications together with radio astronomy and remote sensing. FSO transmission scheme provides power efficient large distance inter-satellite orbital links with better receive sensitivity. Orbital angular momentum (OAM) beams have an intense level of data carrying capability providing an enhanced system capacity and spectral efficiency. Therefore, FSO is a preferred choice for attaining ultra information carrying capacity using OAM beams in deep space communications.
- *High-capacity backhaul network:*
  A backhaul network establishes a bridge between the access network and core network. A high-speed backhaul connectivity is a compelling part while exchanging a large volume of data information between access network (AN) and core network (CN) in 5G/B5G or IoT perspectives. Densification of cellular networks by means of mass deployment of small cells to increase frequency utilization as well as system capacity. The deployment of additional infrastructure in the access networks is considered in

densely populated areas where an intensive level of traffic volume is generated. Furthermore, the shorter user-base station distance ensures the greater level of attainable throughput due to lower multipath fading in 5G/B5G networks. To address the network densification issue, the facility of high-speed FSO connectivity guarantees backhaul constraints. In addition, a high capacity backhaul is essential for long-range applications such as inter-building communications, inter-city connectivity, and satellite-to-satellite links. Unless the high capacity backhaul network, the entire communication will be worthless even though the AN or CN supports the Gbps communication equipment, hence, leads to a bottleneck in the system. Current backhaul networks are equipped with dedicated fiber optic infrastructure, coaxial cable, copper, microwave, and mmWave links, and sometimes satellite paths (Jaber et al., 2016; Artiga et al., 2018). Together with the wired optical fiber networks, FSO system offers excellent features to solve the low-capacity backhauling issues effectively especially in long distance outdoor backhaul links. FSO enabled high speed backhaul networks provides the connectivity in far distance areas, for example, underwater, space communication, isolated island, etc. Moreover, the latency is less than one millisecond and achievable data rate of 40 Gbps for FSO point-to-point communication technology. In summary, FSO systems have the potential to handle high traffic volume, allowing massive telecommunications and IoT devices, least power consumption, cost effectiveness, and greater spectral efficiency in the backhaul network platform.
It is widely accepted that the throughput of optical fiber cable is the maximum among all other related technologies till now. Since both fiber optic technology and FSO systems use a similar type of optical transmitter and receiver, so attaining similar throughput performance will be possible in the forthcoming future. Unlike NLOS link, FSO LOS link achieves higher system capacity because of the absence of multipath propagation delays and effective power link budget. On the other hand, a diffused light sources are used for the NLOS links to disperse a light beam for multipath propagation caused by the reflections of different obstacles. Thus, NLOS links are more robust when dealing with objects along communication paths. However, increasing the FSO backhaul capacity is a challenging task with the enormous growth of traffic volume.

- *Unmanned Area Vehicle (UAV):*
Recently, the usage of drones are increasing in many commercial and military applications include remote sensing, surveillance, downlink transmissions, monitoring, and security because of the scalability and agility nature of networked flying platforms. Driven by the merits of FSO systems, FSO-UAV enabled solutions provide efficient fronthauling/backhauling of heterogeneous networks (Fawaz et al., 2018). The data transmission between small cell base stations and core networks, and relay-aided high speed transmission via UAV platforms can be possible using FSO links (Abou-Rjeily et al., 2019). With the improvement of high resolution imaging sensors, FSO links transmit high data rate between UAVs or UAV and ground terminal, air-to-air, ground-to-air, ship-to-air at 1–3 Gbps speed (Majumdar, 2015). All the optical nodes receive command information from ground, which also updates GPS information continuously collected by the UAV GPS terminal, and then the UAV receiver provides updated GPS data to the optical nodes. The optical terminals updated information from UAV receiver and the ground stations simultaneously and send the beacon message to blind point the gumball for initiating communication (Michailidis et al., 2021).
- Device-to-device (D2D), machine-to-machine (M2M), vehicle-to-infrastructure (V2X), multipoint-to-multipoint, end-to-end communication mechanisms can be applied in healthcare, railway stations, shopping malls, and industry. Scalability limitations of RF-based networks, for instance, fairness and throughput are limited for the large hop number, can be easily overcome with high speed FSO network over existing wireless mesh connections.

4.2. FSO in IoT, 5G and B5G

5G communication offers enormous smart device connectivity, ultra-high throughput, extremely low latency, ultra-high encryption, incredibly low power consumption, and ultra-level quality of service (Ghosh et al., 2019; Habibi et al., 2019). 5G network and beyond are now widely developed including nested small cells in heterogeneous (i.e. a combination of the macrocell, microcell, picocell, and femtocell) configuration in order to increase network capacity in an effective way with desired quality of experience (QoE) (Khan et al., 2020). To ensure high QoE under an intensive data demand and wide range of large device connectivity, 5G/B5G networks are anticipated to ultra-dense HetNet deployment. 5G/B5G networks have the capability to support up to 10 Gbps downlink data rate which will be ten to 100 times bigger than 4G. The number of connected electronic devices is hundred times higher than 4G LTE networks results in thousand times volume data (Ijaz et al., 2016). 5G technology consume 90% less power compared to 4G networks and provide extremely low latency in a fraction of millisecond. B5G networks are expected to provide four times spectral efficiency over 4G networks and lower network deployment costs. Offloading a massive volume of data to indoor small cells from the macrocell is another significant characteristic of 5G/B5G networks (Khan et al., 2020). Fig. 4 demonstrates the implications of FSO transmission in 5G/B5G wireless cellular networks and Fig. 5 presents the application of FSO in massive IoT platforms.

FSO supports high speed bit rate 5G communication together with high-capacity backhauling and the massive connectivity of IoT. Energy consumption is a key concern for designing a large scale 5G cellular and IoT infrastructure in where FSO helps to curtail additional energy expenditure in comparison to traditional RF systems (Chettri and Bera, 2020). Some other demands of IoT systems are low implementation cost, high level of security, large energy efficiency, cost-effective and support a huge number of smart devices. FSO technology is capable to support massive smart device connections in the IoT paradigm through low power LED or LD technologies. A reliable connection by means of strong encryption can be assured using FSO technology (Chowdhury et al., 2019).

4.3. FSO in space communications

With the advancement of space and FSO technology, satellite communications including uplink (i.e. ground-to-satellite), downlink (i.e., satellite-to-ground), inter-satellite links, and deep space communications incorporating FSO have received considerable attention among researchers and industries (Kaushal and Kaddoum, 2017). The losses incurred through the atmosphere are much higher for FSO uplink compared to the downlink communications as the optical beams are spread and distorted at the ground-based point. The variation of temperature, concentration of aerosol particles, and encountered air pressure with altitude affect the laser beam propagation in the passage through atmosphere. These losses can be defined as absorption (i.e. absorbers may be the water molecules, CO_2 gas) and scattering loss. Note that absorption loss and scattering loss (dB/km) is a function of wavelength. The scattering loss is more noticeable when the wavelength is below 1 um especially ultraviolet or visible range for FSO communications. Thus, the selection of transmission window (e.g., ultra-short IR, short IR) is a crucial FSO design parameter. Rayleigh scattering is produced when the atmospheric particles are comparatively smaller to than the optical wavelength and Mie scattering is generated for vice-versa (Kaushal and Kaddoum, 2017). Air molecules and haze particles typically cause Rayleigh scattering, in contrary, aerosol, rain, snow, fog particles are the primary contributors for Mie scattering. The applications of FSO in space communications are explicitly presented in Fig. 6.

Under the presence of dense fog (visibility is below 50 m), the signal losses can be higher than 350 dB/km (Nadeem et al., 2010). In such conditions, high power lasers operating at the third transmission

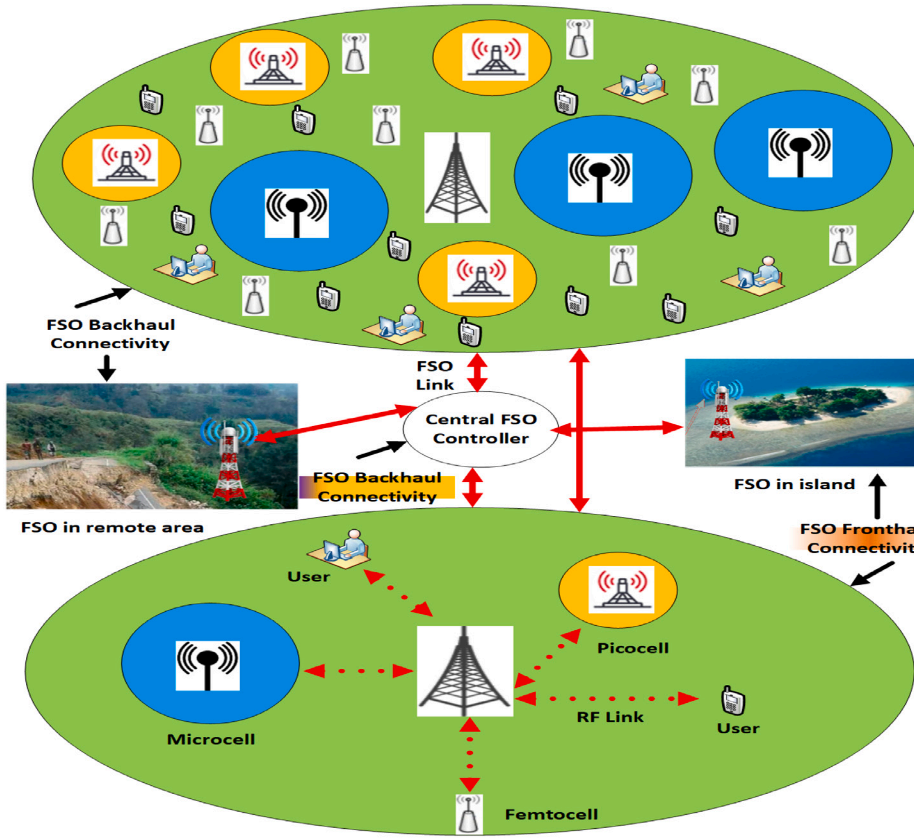

Fig. 4. FSO backhaul connectivity for cellular networks.

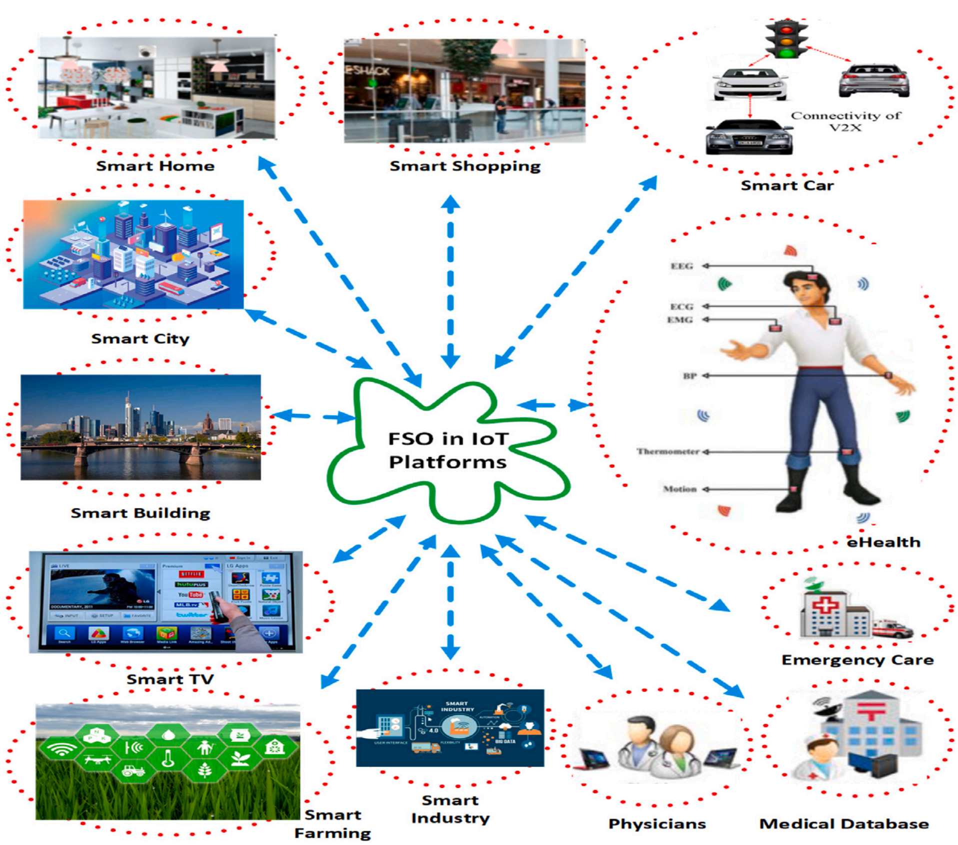

Fig. 5. FSO in IoT platform.

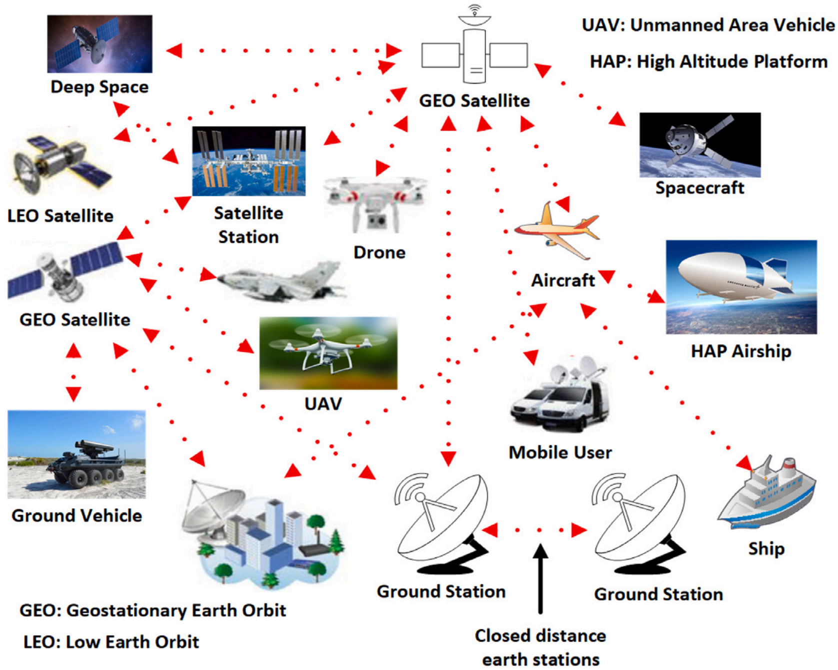

Fig. 6. FSO in space communications.

window help to uplift the link reliability. It is obvious that the heavy rain droplets lead to higher attenuation loss. According to Suriza et al. (2013), heavy rain (25 mm/h) incur attenuation ten times than the light rain droplets (2.5 mm/h) ranging from 1 dB/km to 10 dB/km for 1500 nm wavelength. The hybrid RF/FSO system is a suitable choice to enhance the link availability under this condition. On the other hand, the attenuation due to snow particles are lies between rain droplets and fog particles. Atmospheric turbulence induced particles called eddies with different size and refractive indices generated beam wandering effect when the size of eddies are greater than beam radius. In contrast, smaller eddies size in comparison to the beam dimension also resulting in tempo-spatial irradiance fluctuations of the transmitted signal at the receiver end (Kaushal et al., 2011). Turbulent cells also degrade the coherence properties of the optical beam and hence, create interference.

The beam divergence is an important factor of FSO uplink design in space communications. Beam divergence is incurred before the receiver aperture due to the diffraction of light. Some fraction of laser beams are not collected at the receiver hence, causes beam divergence loss or geometrical loss. This loss considerably increases with the transmission distance regardless of the diameter of receiver aperture. In such case, a narrow beam laser source is preferable, and receive diversity techniques can be employed. It is worth mentioning that sky radiance can be happened both daytime and night time which is driven by the altitude of the receiver, cloud thickness, atmospheric particles concentration, and solar irradiance. In particular, the magnitude of sky radiance primarily depends on the geometrical position of the sun, earth, and the FSO receiver. Pointing loss may happen due to small vibration of satellite, slight stress on mechanical or electronic devices, or jitter platform. A little misalignment between the transceivers could cause FSO link failure, thus, it is very essential to control LOS directivity with narrow beam divergence (Ma et al., 2012). In addition, the beam wandering effect may shift the transmitted beam from the propagation path that causes pointing loss. In any case, pointing errors can remarkably reduce the received optical power as well as SINR resulting in high BER and increase the chances of FSO link failure. Proper care must be taken of vibration free FSO devices installation and maintain adequate bandwidth control to compensate residual jitter. Pointing error is more apparent for lower earth orbital (LEO) satellites than GEO satellite (Ma et al., 2012). Pointing error considerably degrades the system performance in terms of BER and outage particularly at visible wavelength. Furthermore, noise in the tracking sensors and mechanical vibration of satellite causes tracking errors. A compensation technique to address pointing and tracking errors for the uplink FSO space communications is presented in the literature (Viswanath et al., 2015a).

The presence of a thick cloud disrupts the signals or occasionally completely blocks the link regardless of uplink or downlink communications. These intermediate disruptions can last from a fraction of minutes to few hours based on the geolocation and season. The opaque clouds could lead to severe attenuation as big as tens of dB. The tempo-spatial diversity deployment can combat the optical beam loss due to attenuation. Owing to the effect of atmospheric turbulence, the optical signals fluctuating at the focal plane of photodetector or lead to spot motion. This effect is known as fluctuation of arrival angle that can be mitigated by implementing a fast beam steering mirror or adaptive optics. The aforementioned limiting factors for FSO space communications can be handle by proper choice of system design parameters, for instance, operating wavelength, beam divergence, intensity of transmitted power, transceiver field of view (FOV).

Inter-satellite space FSO links are not affected by weather and atmospheric limitations as the satellite obits are far distant of atmosphere layer; however, they are restricted by other key challenges such as acquisition and tracking (AT), stability of satellite station, Doppler shift, and background radiations. The coherent detection method is more appropriate over direct detection for inter-satellite FSO communications since it covers a longer link distance. Cooperative frequency tuning between the transmitted signal and local oscillator (LO) is adopted to combat the impact of the Doppler shift. A coherent tacking scheme can be implemented to combat AT including background radiations. Coherent techniques either homodyne or heterodyne maintain the power efficiency of the link and offer good receiver sensitivity with a lower level of power penalty (Zech et al., 2015). The concept of detector arrays contemplating in deep space FSO communications helps to collect the light signals even if misalignment exists between transceivers (Bashir, 2020). Bashir (2020) pointed out that a receiver detector array outperforms a lot better in terms of probability of bit error, pointing error, and SINR than a single detector system.

5. Reliability of FSO communication systems

A reliability issue is an important characteristic for any sort of communication system. The FSO systems assure a high level of SINR both for indoor users and long-distance outdoor communications addressing associated shortcomings. Besides, FSO networks open the opportunity of provisioning additional tier network which inevitably enhances the reliability of communication systems. Several limiting factors such as scattering, absorption, poor atmospheric visibility variations interrupt the high speed data transmission through the wireless optical link that deteriorates the FSO system performance and reliability as well. Atmospheric turbulence is the key source for link reliability degradation. The installed FSO systems should retain to operate under severe weather conditions i.e., under the influence of beam diversity, multipath fading, and received signal fluctuations due to atmospheric turbulence. The tight beam propagation with a confined divergence of few mrad and the field of view at the receiving end temporarily causes poor link connectivity. As a result, narrow beam property causes link loss or misalignment issues, and thus pointing, acquisition, tracking (PAT) mechanism is essential.

Under link budget design, the received optical power can be easily estimated in a fiber optic communication, whereas, it is unpredictable, complex, and inhomogeneous in air because of the spatial distribution of FSO channel and atmospheric fluctuations. Since optical propagation through space is severely affected by atmospheric conditions, resulting in signal loss or phase shifting/fluctuations of signal intensity, thereby limiting the SINR performance and link availability as well with increased BER. Fog prominently deteriorates visible and NIR radiations and the greater level of humidity percentage in air also lessens the optical signal wavefront quality. Scintillation effect is more apparent for long transmission distances that degrades the overall reliability of the FSO system. On the other hand, atmospheric molecular absorption is a function of optical wavelength, attenuates the signal particularly in the higher wavelength region (Majumdar, 2014). As a consequence, the choice of operating optical wavelength consistent with the on-site atmospheric conditions is the key design issue for the successful deployment of FSO devices. However, FSO devices are placed in such a position where the probability of disturbance occurrence is much lower and the weather conditions are better on average. It is important to take into account point-to-point delay, packet loss, jitter and fairness while designing protocols and algorithms in FSO systems. For example, the existing congestion control mechanism in TCP could result in inferior throughput performance due to incompatibility in FSO networks, and hence more adaptive protocols should be developed.

To model the long-term reliable FSO data link design, the average visibility information should be surveyed based on the statistical behavior of atmospheric conditions at a given geometrical location. After these analyses, the link budget can be expressed as follows (Raj and Majumder, 2019).

$$R_{LM} = P_{TX} - S_{RX} - L_P \tag{1}$$

where P_{TX} represents transmit power, S_{Rx} denotes the receiver sensitivity, and propagation loss is indicated by L_P. Eq. (1) gives the basic link margin (LM) to express the reliability of optical data link. The LM can also be defined by (Katsilieris et al., 2017)

$$R_{LM} = \frac{P_{RX}}{P'_{RX}} \tag{2}$$

where P_{RX} represents the available receive power and P'_{RX} identifies the received power required to maintain a specified BER at the given transmission rate. R_{LM} defines the loss margin required to compensate the turbulence effects at a given link coverage. For telecommunication purpose, FSO networks must meet the high data rate requirements as much as possible which is equivalent to five minutes downtime per year (link reliability around 99.99%) (Majumdar, 2014). For example, if laser transmit power P_{TX} = 30 nW, photodetector sensitivity S_{RX} = 25 nW, misalignment loss L_a = 3 dB, optical loss L_o = 4 dB, then the estimated R_{LM} = 54 dB. For a particular BER value, the range of received power (P_{RX}) level defined the reliability of link functionality. The FSO system fails to attain desired BER when the minimum SINR does not meet the condition of $P_{RX} > P_{Th,r}$ or $P_{RX} < S_{Rx}$, where $P_{Th,r}$ represents the specified saturation value of P_{RX} level. However, the data link availability (T_a) can be defined when the achievable throughput exceeds the threshold limit at a specified BER. In practice, T_a is a crucial design parameter in the presence of multiple turbulences.

$$T_a = \int_0^{\alpha_a} p(\alpha_a)\, d\alpha_a \tag{3}$$

where α_a presents the atmospheric attenuation coefficient and the probability distribution function can be defined as (Uysal et al., 2016)

$$\alpha_a = \frac{17.3}{V}\left(\frac{\lambda}{550}\right)^{-q}, \quad \text{dB/km} \tag{4}$$

where V is the visibility measurement to estimate α_a, the value of q is chosen based on the V parameter.

T_a is very useful to assess FSO link performance particularly in FSO assisted access networks at a given location and coverage distance. Note that pointing errors due to jitter is not taken into account to compute T_a for the automated FSO systems. However, the link reliability can be expressed as

$$R(l) = \int_{I_{th}}^{\infty} p(I)\, dI = 0.5 - 0.5 erfc\left(\frac{ln(I_{th}/I_0)}{2\sqrt{2}\sigma}\right) \tag{5}$$

where $p(I)$ is cumulative probability irradiance and a threshold intensity (I_{th}), l is the transmission link distance in m, $erfc(.)$ is the complementary error function, I_0 is the average intensity with no turbulence and σ is the variance parameter. FSO data link reliability varies in the range between 0 to 1 that depends on the link distance, maintain an inverse relationship with $R(l)$. FSO link can be recognized as established when reliability is greater than threshold limit I_{th}.

The broadband functionality of FSO networks is key benefit due to the wide frequency range and it offers unlimited ultra-speed data services in compared to RF wireless networks. It has been reported that 1550 nm laser operating at 200 THz bandwidth exhibits 200 000 times greater data rate over a 2000 MHz microwave link (Davis et al., 2003). Notably, the FSO systems provide an attractive solution to the last-mile bottleneck, recognized as a pivotal component for the next generation broadband wireless connectivity. However, the total achievable throughput of the FSO link is determined by the aggregate traffic carrying capacity to the destination under the given constraints. FSO transceivers require an advanced level of automation allowing self-healing and self-configurations algorithms for topology control (Desai and Milner, 2005). Authors in Desai and Milner (2005) proposed a heuristic algorithm addressing congestion called the bottom-up minimum spanning policy according to the transfer matrix. Demir and Yılmaz (2020) proposed a design of an experiment based on Taguchi's optimization method to investigate the reliability of the FSO systems analyzing different parameters such as visibility, link distance, scatter particle size variations per unit volume to avoid large computational time.

6. Deployment challenges and mitigation techniques

Despite the potential advantages of FSO communication, FSO networking is not yet mature as their RF counterpart because of some limitations. The performance of FSO links are intensively deteriorating the link reliability due to atmospheric turbulence effects such as heavy rain, fog, snow, cloud, and pointing stability in wind. Some other limiting factors including beam dispersion, background light radiation (e.g., sunlight), and shadowing effect degrades the system performance pertaining to bit error rate (BER), SINR, ergodic capacity, outage probability. Uneven distribution of temperature on the earth, velocity variation of wind, and atmospheric pressure due to irregular flow of wind causes atmospheric turbulence. Such atmospheric circulation affects the optical beam propagation along with the FSO link both in the tempo-spatial domain. Atmospheric turbulence causes phase shifts of the transmitted optical beams resulting in signal distortion is referred to as optical aberrations. Scintillation is an intensity distortion of propagating light pulses caused by atmospheric turbulence (Alimi et al., 2018). A laser beam passing through scintillation experience irradiance fluctuation even in short distance communication. Moisture, aerosols, temperature, and pressure variations generate refractive index deviations in air density known as eddies. However, the refractive index change of air causes wavefront phase perturbation of propagating optical light. As a consequence, some other wave fronts having different phase causes an interference and amplitude variation. Therefore, the received optical signal fluctuating randomly and causes a distorting wavefront of the iso-phase surface. Note that the optical laser beam will bends when the dimension of turbulence eddies are bigger than the beam radius. In addition, constructive and destructive interference due to arrival time variations of multiple wavefronts resulting temporal fluctuations of the light intensity at the receiver end.

Pointing error/jitter is another noticeable parameter of FSO systems that can be defined as the digression between the expected antenna position and its actual position. In other words, mechanical misalignment of FSO transceivers and mechanical vibration causes an error in tracking systems. Owing to the strong nature of the directional beam of FSO transmitter, the problem involves in pointing, acquisition, and tracking (PAT) technique because each optical transceiver must be precisely aligned simultaneously at the point of communication. Any unwanted objects in LOS links break the communication between transmitter and receiver. Cloud is another important limiting factor which is the collection of water droplets (i.e. excess vapor condenses of tiny particles) and crystals suspended in the air. Clouds imposes the attenuation, beam scattering and absorption during the laser beam traveling through the medium. On the other hand, non-selective scattering due to rainfall and heavy fog is one of the major impairments of FSO link reliability. A larger size of rain droplets and a high dense fog causes reflection and refraction of light beam (Jahid et al., 2015).

In order to attain high link reliability, some viable approaches have been presented in literature including PAT technique (Kaymak et al., 2018; Wu et al., 2020; Kaymak et al., 2017; Yousif et al., 2019), diversity mechanisms (Aghajanzadeh and Uysal, 2012; Miglani and Malhotra, 2019; Sharda and Bhatnagar, 2020; Al-Ebraheemy et al., 2020; Jaiswal et al., 2018), hybrid RF/FSO systems (Zhou et al., 2017; El-Malek et al., 2017; Balti and Guizani, 2018; Salhab et al., 2016; Trinh et al., 2017; Enayati and Saeedi, 2016; Varshney and Jagannatham, 2017; Soleimani-Nasab and Uysal, 2016; Ai et al., 2020; Bhowal and Kshetrimayum, 2020; Hassan et al., 2020) considering atmospheric fluctuations. Optical signals can be blocked fully or partially by temporary obstacles such as drones, birds, industries smoke, unmanned area vehicles, building sway, tree limbs, etc. in the line of sight connectivity. These sorts of temporary fluctuations can be handle by adopting multi input multi output (MIMO) FSO transmit/receive diversity system (Miglani and Malhotra, 2019). Under MIMO FSO scheme, an object blocking signal either on Tx or Rx side does not cause any considerable impact on overall FSO performance. Today's commercial FSO networks are augmented with beam divergence combination, beam tracking-alignment, clock-recovery phase locked loop (CR-PLL) that have the capability to maintain beam centroid capability. It is widely recognized that high power laser beams alleviate atmospheric disturbances while maintaining the desired quality of data rate. Albeit data transmission through FSO links does not create mutual interference but extreme power laser sources beyond the threshold limit are harmful to human eyes. Therefore, safety regulations are paramount issue for FSO performance and it is important to handle the laser emission enforcement at high intensity in optical wireless communications. The adaptive control mechanism of laser sources via dynamic power adjustment in accordance with the wireless optical channel conditions offers reliable FSO data link services. It is obvious that the system requires low transmit power for clear weather conditions, whereas, a relatively high intensive laser power is needed to ensure the desired level of throughput, BER, and QoS.

The temporal diversity of the FSO channels is directly affected by the variations of temperature, geographical location, wind velocity, altitude, air pressure, humidity level, etc. (Raj et al., 2015). In order to address spatial distortion of the received beam, numerous techniques such as pointing, acquisition, pointing (PAT), aperture averaging and wavefront correction. PAT technique is essential to maintain beam centroid stability for long-haul communications like inter-satellite FSO, terrestrial FSO systems. According to Son and Mao (2017), optical wireless inter-satellite require 1–10 μrad pointing accuracy for 10 Gbps bit rate. Wavefront aberrations imply the optical phase variations due to atmospheric disturbances along the wireless propagation path. Generally, a wavefront sensor or charged coupled camera device is used to measure the wave-front distortions, whereas, deformable mirrors (DM) or electromechanical mirrors are employed for error compensation. All the components are working based on a closed-loop control process where a laser power source transmits a Gaussian beam from a distant position and get aberrated as it travels through the free space. The optical lenses (DM) accumulate all the incoming beams and the DM split into two beams: reflected beams incident on the charged coupled camera device (CCCD) and propagating signals fall on the photodetector. The DSP controller drives the DM to rectify the measured distortions through generating appropriate control signals based on CCCD output. Integration of advanced optics in FSO communication improves the system reliability by eliminating phase errors (Li and Zhao, 2017). However, some promising mitigation techniques are illustrated in the following to address the technical challenges encountered by FSO networks.

6.1. Aperture sizing

Averaging of receiver aperture is a popular technique to mitigate received signal fluctuations. The aperture area is determined by the transmission length and strength of the aforementioned limiting factors. Increasing the receiver dimension helps to reduce channel fading and eddies induced fast fading. Aperture averaging manifests the amount of fading reduction in the physical layer platform. Note that the quantity of background noise increases with the increment of receiver aperture. Thus, the choice of aperture radius should be optimum to uplift the power efficiency of the FSO link. The graphical illustration of aperture averaging of FSO transceiver is shown in Fig. 7 where the aperture of FSO receiver is wider than transmitter in order to avoid beam wandering loss.

The aperture averaging factor, F_a at the receiver side can be expressed as

$$F_a = \frac{\sigma_I^2(D)}{\sigma_I^2(D_0)} \tag{6}$$

where D is the receiver aperture, σ_I^2 is the signal power, and $\sigma_I^2(D_0)$ means the variance of signal intensity at the center of the receiver. For a plane wave the F_a can be approximated by (Raj and Majumder, 2019)

$$F_a = [1 + 1.07(\frac{kD^2}{4l})^{7/6}]^{-1} \tag{7}$$

where l represents the link distance, k is the wave number ($2\pi/\lambda$). For the smaller aperture, $(\frac{kD^2}{4l}) \ll (1)$, $F_a = 1.0$ and the signal intensity reduces with the increment of aperture sizing i.e. for larger aperture, $(\frac{kD^2}{4l}) \gg (1)$. Therefore, aperture averaging is a significant parameter to address the power variations since a larger aperture antenna collects all the signal beams falling into it, thereby, exhibits comparatively lower turbulence induced scintillation.

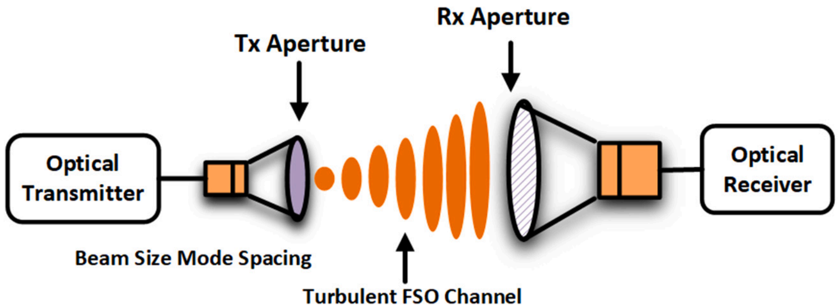

Fig. 7. Aperture averaging of FSO transceiver.

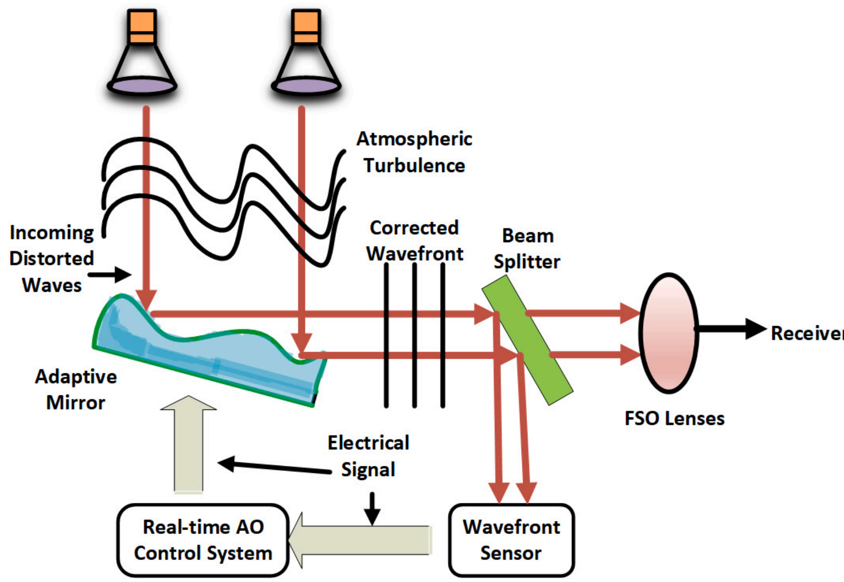

Fig. 8. Illustration of adaptive optics system.

6.2. Adaptive optics (AO)

Adaptive optics is based on the closed-loop control principle that helps to transmit distortion free laser beam through the atmosphere. Precise beam pointing in terms of position and angle is accomplished by implementing adaptive optics with the assistance of steering mirrors in beam propagation path. However, piezoelectricity driven electromechanical devices are commonly used for beam steering, but it suffers due to huge space occupancy and longer processing time. AO system consists of a wavefront sensor and corrector, and a set of deformable mirrors at each transceiver unit to compensate phase floor fluctuations. The study of AO using micro-electromechanical systems (MEMS) for longhaul FSO communication is pointed out in Viswanath et al. (2015b). MEMS based beam steering system enables fast tracking capabilities and precise pointing between two FSO terminals. In addition, MEMS based AO systems control laser beams on a narrow size scale allowing integrated electrical, mechanical and optical systems. The application of AO in the downlink FSO satellite communication is investigated in Védrenne et al. (2016). Fig. 8 depicts the simplified demonstration of adaptive optics system in FSO perspectives.

6.3. Relay transmission

Relay aided transmission is a form of spatial diversity where all the antennas are arranged in a distributed fashion to share their resources by cooperative communication. The fundamental objective of introducing relay nodes in the FSO system is to extend the transmission distance without sacrificing the QoS level. The relay nodes draw intensive attention when the source–destination link suffers poor quality. Relay nodes provide a superior system performance combating the impact of turbulence and offer high SINR manifesting the greater level of received signal intensity over noise (Hayal et al., 2021). Particularly, relay assisted transmission guaranteed an enhanced level of user experience quality service under severe shadow fading or path loss effects. Regenerative relay transmission mechanism also improves the coverage of mobile wireless systems exploiting additional diversity benefits. Relay based transmission eliminates the need for multiple aperture at the transmitter or receiving side, a single antenna has the potential to attain significant diversity gain without sacrificing the quality of experience. The choice of placing relay nodes is an important design criteria to achieve huge diversity gain employing cooperative FSO communications. Buffer-aided (BA) relay networks in FSO allows the cooperative networks to address unbalanced buffer owing to the asymmetric channels. In addition, BA relaying efficiently make tradeoff between packet delay, outage probability, and system complexity. The study of all optical relay placement and system performance combating the limiting factors is carried out in several literatures (Yang et al., 2015a; Trinh et al., 2015). Fig. 9 manifests the operations of relay assisted FSO transmission.

6.4. Modulation

A modulation technique is chosen based on the type of applications. Various modulation schemes have distinctive features such as spectral efficiency (SE) and bit per energy level or energy efficiency (EE). EE implies the maximum achievable data rate at a target BER for a given

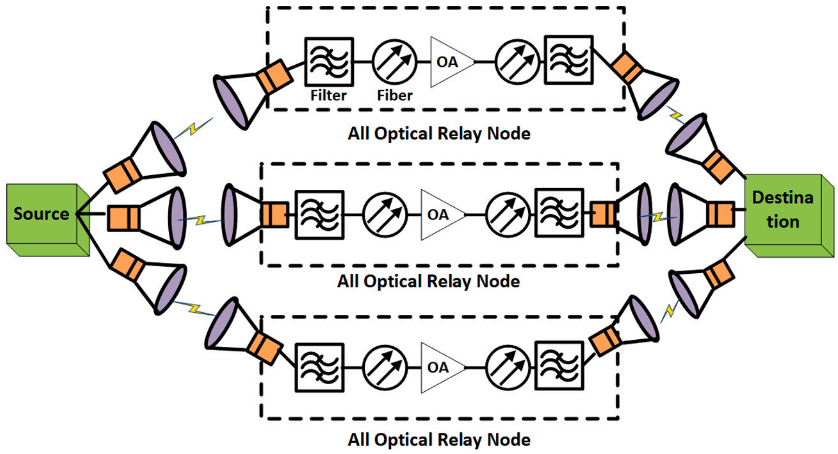

Fig. 9. Illustration of relay aided FSO transmission.

transmit power. Although unlicensed optical band consists of huge bandwidth, still SE is key design parameter as it is proportionally related to the speed of electronic switch circuitry in FSO systems in the practical cases. At the receiver end, it is important to know the instantaneous channel state coefficients for optimal signal detection. A few pilot carriers are used in practice to estimate the channel state information (CSI) with perfect accuracy (Yue et al., 2020). A symbol-by-symbol maximum likelihood (ML) detection technique is used as an alternative approach based on the partial knowledge of the distribution of channel fading coefficients and ML detection based on the information of joint temporal fading coefficients statistics (Xu et al., 2017a; Le Tran and Kim, 2019).

The most commonly used binary level modulation scheme is called On–Off Keying (OOK) in FSO systems due to its simplicity. For ultrafast data communication and complex system architecture, OOK is less efficient due to poor spectral and energy efficiency (EE). Numerous intensity modulation schemes have been carried out to suppress some disadvantages. Alternatively, pulse position modulation (PPM) or variable PPM is a preferred choice for addressing EE applications particularly in deep space communications (Sevincer et al., 2013; Karpagarajesh et al., 2022). Unlike OOK, PPM does not need any dynamic threshold for optimal detection while performing hard signal identification. However, OOK and PPM schemes are single carrier based pulsed modulation and can be unreliable during severe channel impairments for FSO links. Single carrier modulation techniques are inappropriate for high data rate applications due to the high level of inter-symbol interference (ISI) (Islim and Haas, 2016). Subsequently, subcarrier intensity modulation (SIM) and orthogonal frequency division multiplexing (OFDM) based on multi-carrier SIM (MCSIM) techniques are adopted in several literatures (Balti et al., 2018; Arezumand et al., 2017; Bekkali et al., 2010). A pre-modulated RF signal drives the incoming optical signal for carrying data in the SIM technique. In order to maintain all the amplitude of optical pulses are positive, a DC bias is incorporated into the signal before drive an optical source (Bekkali et al., 2010). A SIM based approaches have some advantages over single carrier modulation like mitigating channel impairments, simplicity, cost-effective solution, and improved spectral efficiency (Hassan et al., 2016).

The addition of an external DC bias with RF signal to neglect non-negative amplitude pulses causes reduced power efficiency. With the increment number of subcarriers in the MCSIM scheme, the DC bias signal also needs to increase largely to prevent non-linear distortion and clipping effects. Thus, OFDM based MCSIM modulation technique is severely experienced by peak-to-average power ratio (PAPR) which degrades the power efficiency (Hassan et al., 2016). The nonlinearity of light signals is also a critical challenge in MCSIM technique which leads to inter-carrier interference and widening the signal spectrum resulting in inter-modulation distortion (IMD) (Bekkali et al., 2010). As a consequence, a small number of subcarriers are needed to employ to limit IMD, but this surely reduces the transmission rate. Another solution to reduce IMD effect is to use a separate optical source for each carrier resulting in complexity and cost as well. In comparison to PPM, multi-pulse PMM (MPPM) reduces PAPR and increases the spectral efficiency as well but having higher demodulation complexity (Islam and Majumder, 2019a). MPPM exhibits superior performance over PPM under peak transmit power and PPM outperforms MPPM for an average transmit power. Zhang et al. (2018b) proposed an improved linear non-symmetrical transform to reduce PAPR in OFDM based wireless optical communications. A PAPR reduction technique makes the signal less vulnerable in terms of nonlinear distortion, hence, improve the performance of MSIM techniques. A precoding matrix technique have been proposed to improve the PAPR, SNR, BER performances of the DC-biased optical OFDM (DCO-OFDM) system in the perspective of OWC systems (Jiang et al., 2018). In order to achieve the same bandwidth efficiency and enhanced spectral efficiency with the traditional (DCO-OFDM), authors proposed (Chow et al., 2020) a modified asymmetrically clipped optical OFDM method.

Another well-known modulation technique is pulse width modulation (PWM) has improved spectral efficiency, demand lower peak transmit power, and better performance to inter-symbol interference (ISI) in comparison with PPM (Ebrahimi et al., 2018). However, an extra guard slot is required to add to suppress sending consecutive positive pulses over the symbol period. Both PPM and PWM are known as synchronous modulation since they require slot and symbol synchronization. On the other hand, digital pulse interval modulation (DPIM) is a type of asynchronous modulation scheme which is more spectrally efficient than PPM, PWM and does not require symbol and slot synchronization. The possible error propagation during demodulation at the receiver is the potential limitation of DPIM (Abdullah and Bong, 2014; Guo et al., 2019). Following the concept of MPPM, overlapping PPM (OPPM) (Noshad and Brandt-Pearce, 2014), differential PPM (Abdullah and Bong, 2014), and digital pulse interval and width modulation (DPIWM) (Abdullah and Bong, 2014) are proposed for improving the spectral efficiency. In OPPM, the optical pulses occupy adjacent slots, and symbols end with a pulse that can be exploited for synchronization in DPPM, whereas, the binary sequence is encoded into pulse width of alternating amplitude in DPIWM. The fundamental limitations of all these modulations are the poor energy efficiency, high receiving complexity, and the probability of error propagation while detecting encoded bit sequence.

Being inspired from the aforementioned concerns, multi-level modulation schemes could be employed in FSO systems to attain better SE in comparison with binary modulations. For example, the optical pulse is modulated on M levels in M ary-PAM (Tsai et al., 2020), M ary-PSK (Shakir, 2018), and M ary-QAM (Lei et al., 2020b), which requires a laser source with different emission intensity. All of these M-level modulation methods provide higher SE and EE with respect to binary level modulation schemes. Apart from this, other multilevel intensity modulation and direct detection (IM/DD) schemes such as differential phase shift keying (DPSK) (Amirabadi and Vakili, 2019b), carrier-less amplitude and phase (CAP) (Khalighi et al., 2017) modulation have been considered in FSO systems.

6.5. FSO channel modeling

FSO channels are subject to atmospheric turbulence and fading, so the definitions of channel capacity by means of ergodic capacity and outage probability should be considered because of the random nature of channel fading coefficients. Ergodic capacity is referred to as the expectations of the instantaneous channel capacity which can be computed via mutual information expression in comparison with different fading coefficients. If the mutual information fails to reach the information rate in FSO channels, an outage event is specified which is known as the probability of fade or outage probability. The performance of FSO link is significantly hampered by means of signal fade under the severe atmospheric turbulence factors. In particular, FSO channel is highly variable, unpredictable, and vulnerable due to inhomogeneity in pressure and temperature of the atmospheric layer. The variation of refractive index and multiple scattering along the propagation path results in phase and intensity fluctuations of the received optical signal. The effect of scintillation induced by temperature and spatial fluctuations of light intensity lessens the FSO link performance even under clear weather. As a consequence, bit error rate increases considerably especially for the long distance FSO communication even for the small effect of the aforementioned issues. The link margin (LM) approach is a statistical parameter that is used to quantify the performance of FSO transmission system. LM can be expressed in decibel (dB) which can be defined as the ratio of received optical power to the power required for the target bit rate and error probability. The term LM accounts all the limiting factors associated with the FSO link including transceiver station parameters and link budget models that support the designers for optimum implementation under all weather conditions at a given location (Uysal et al., 2016; Majumdar, 2014; Ghassemlooy et al., 2019). Some other factors such as beam divergence loss, sky radiance, background noise, angle of beam arrival variations, free space seeing, and cloud blockage need to be considered during FSO link implementation.

A numerous research works have been conducted to investigate the channel capacity of turbulent FSO channels. The study of ergodic capacity of FSO channels is carried out in Salhab et al. (2016), El-Malek et al. (2016), Ansari et al. (2013), Usman et al. (2014), Trinh et al. (2017), Bag et al. (2018), Al-Eryani et al. (2018b), Palliyembil et al. (2018) and Balti and Guizani (2018) for the cases of Gamma–Gamma, Rayleigh, Nakagami-m, Malaga, Rician and log-normal fading taken into consideration of AWGN model for the receiver noise. On the other hand, the outage probability (Rakia et al., 2015; Makki et al., 2016; Salhab et al., 2016; El-Malek et al., 2016; Ansari et al., 2013; Zhang et al., 2015; Usman et al., 2014; Balti et al., 2018; Trinh et al., 2017; El-Malek et al., 2017; Bag et al., 2018; Shakir, 2018; Amirabadi and Vakili, 2019b; Petkovic et al., 2015; Soleimani-Nasab and Uysal, 2016; Wu et al., 2017; Chen et al., 2016b; Al-Eryani et al., 2018b; Arezumand et al., 2017; Touati et al., 2016; Varshney and Jagannatham, 2017; Palliyembil et al., 2018; Odeyemi et al., 2020; Varshney et al., 2018; Lei et al., 2020b; Balti and Guizani, 2018), bit error rate analysis (Islam and Majumder, 2019b,a, 2015; Ansari et al., 2013; Zhang et al., 2015; Usman et al., 2014; Balti et al., 2018; Trinh et al., 2017; Yang et al., 2015b; Bag et al., 2018; Shakir, 2018; Amirabadi and Vakili, 2019b; Petkovic et al., 2015; Soleimani-Nasab and Uysal, 2016; Chen et al., 2016b; Al-Eryani et al., 2018b; Arezumand et al., 2017; Touati et al., 2016; Palliyembil et al., 2018; Varshney et al., 2018; Lei et al., 2020a,b; Li et al., 2019b; Xing et al., 2020; Kong et al., 2015; Balti and Guizani, 2018), and throughput performance (Islam and Majumder, 2019b,a, 2015; Tang and Brandt-Pearce, 2014; Rakia et al., 2015; Makki et al., 2016; Najafi et al., 2017; Salhab et al., 2016; Jamali et al., 2016; Trinh et al., 2017; Yang et al., 2015b; Odeyemi et al., 2020; Lei et al., 2020a,b; Tsai et al., 2020; Li et al., 2019b) are studied considering the mentioned fading models with AWGN.

The unguided beam fluctuations on the free space due to the atmospheric turbulence induced channel fading leads to a remarkable FSO system performance degradation in the form of receiving error bits. Channel coding is one of the promising fading mitigation techniques under weak and strong turbulence conditions (Kaushal and Kaddoum, 2017; Safi et al., 2019). To handle the atmospheric turbulence, several fading reduction techniques such as tempo-spatial diversity (Jaiswal et al., 2018; Jurado-Navas et al., 2016; Boluda-Ruiz et al., 2016), sequence data detection algorithms (Dabiri et al., 2017; Dabiri and Sadough, 2018b), and relay enabled communications (Huang et al., 2019b; Kong et al., 2015; Amirabadi and Vakili, 2019b; Nor et al., 2017) have carried out in the context of FSO communications. However, majority of the proposed methods are complex and difficult to implement while processing high data rate communications.

The channel fading of FSO systems is similar to the quasi-static property that is slow varying and the CSI can be estimated with better accuracy and fed back to the transmitter. The FSO transmitter then adjusts its parameter for example, transmit power, modulation level, and code rate according to the current CSI. Note that adaptive transmission is the most suitable approach for full duplex operations of feedback purpose in FSO link (Safi et al., 2019). Therefore, adaptive channel coding and power control scheme is very important for commercial FSO systems under practical constraints to satisfy the target BER and desired ergodic capacity with minimum outage. Ref. Safi et al. (2019) proposed jointly adaptive transmission and power control schemes assuming Gamma–Gamma turbulence channels aiming to achieve the target BER and outage probability. The rate compatible punctured convolutional (RCPC) codes are used to perform adaptive transmission for controlling the channel coding rate. Viterbi algorithm and RCPC codes based maximum likelihood decoder is used to reduce the complexity of the FSO transceivers. Odeyemi et al. (2017) studied the performance of FSO spatial modulation (FSO-SM) systems considering the influence of Gamma–Gamma distribution and pointing errors. The symbol error rate (SER) performance is investigated employing convolution coding. Authors in Malik et al. (2015) examined the bit error rate and pair-wise error probability performance of FSO systems based on bit interleaved coded modulation (BICM)-enabled subcarrier intensity modulation (SIM) employing convolution coding. Authors proposed probabilistic shaping schemes in FSO systems of 16-ary quadrature amplitude modulation (16-QAM) and convolution coding technique under the influence of Gamma–Gamma disturbance in Wang et al. (2019a, 2017a). The bit error rate performance for IM/DD FSO systems with binary phase shift modulation and convolution coding over Gamma–Gamma turbulence channels is investigated in Yang et al. (2013). The expressions of BER and pairwise error probability (PEP) for convolution codes and Q-ary PPM signaling schemes are thoroughly examined in Liao et al. (2013). In Ajewole et al. (2019), the performance of BPSK OFDM-FSO over the Gamma–Gamma turbulence channel is investigated by integrating forward error correction (FEC) coding to improve the error probability. Authors designed error control protocol and analyzed throughput performance employing RCPC code over atmospheric turbulence channels for FSO burst transmission in satellite communications in Le et al. (2019). The operation of novel space–time trellis codes (STTCs) for FSO communication using IM/DD under atmospheric turbulence and misalignment of fading channels is investigated in García-Zambrana et al. (2015).

A simple rate adaptive transmission approach based on OOK modulation formats with memory is demonstrated in Jurado-Navas et al. (2010). Authors in Hassan et al. (2018a,b) analyzed QoS aware delay constraint power allocation for a coherent FSO system considering the

Table 5
A comparison of FSO channel model, channel coding and modulation scheme.

References	Channel model	Channel coding	Modulation
Varshney and Jagannatham (2017)	Nakagami-m	OSTBC	IM/DD OOK
Balti et al. (2018)	Malaga	Repetition coding	SIK
Safi et al. (2019) and Jurado-Navas et al. (2016)	Gamma–Gamma	FEC RCPC	OOK
Jaiswal et al. (2018)	Generalized gamma	OSTBC	PAM, OSSK
Dabiri et al. (2017)	Gamma–Gamma	Convolution	OOK, PPM
Odeyemi et al. (2017)	Gamma–Gamma	Convolution	Spatial modulation
Malik et al. (2015)	Gamma–Gamma	BICM, Convolution	M^2-QAM
Wang et al. (2019a)	Gamma–Gamma	Convolution	16-QAM
Wang et al. (2017a) and Mudge et al. (2016)	Log-normal, K-distribution	LDPC	OOK
Yang et al. (2013)	Gamma–Gamma	Convolution	BPSK
Liao et al. (2013)	Log-normal	Convolution	Q-ary PPM
Ajewole et al. (2019) and Le et al. (2019)	Gamma–Gamma	FEC RCPC	BPSK
García-Zambrana et al. (2015)	Gamma–Gamma	STTC	IM/DD OOK
Jurado-Navas et al. (2010)	Non-fading	RC	OOK
Amirabadi and Vakili (2019a)	Gamma–Gamma	Alamouti	DPSK
Zhu et al. (2017)	Gamma–Gamma	BMST	PPM
Priyadarshani et al. (2017) and Boluda-Ruiz et al. (2019a, 2017)	Gamma–Gamma	RC	OOK
Khodadadi et al. (2017)	Gamma–Gamma	BCHB	PPM
Jaiswal et al. (2017)	Gamma–Gamma	RC	PAM
Ji et al. (2019)	Gamma–Gamma	OOC	PPM
Bhowal and Kshetrimayum (2019)	Gamma–Gamma	PLNC	BPSK
Shang et al. (2018)	Gamma–Gamma	IMC	BPSK, 8-PPM
Arya and Chung (2019a)	Gamma–Gamma	RC	BPSK
Amhoud et al. (2020)	Generalized gamma	Alamouti, space–time	4-PAM
Varshney et al. (2018)	Gamma–Gamma	OSTBC	BPSK
Liu et al. (2017a)	Exponentiated Weibull	LDPC	16-PSK, 16-QAM
Li and Dang (2017)	Gamma–Gamma	OCDMA	BPSK
Khallaf et al. (2017)	Gamma–Gamma	Reed–Solomon	OOK, QAM-MPPM
Fang et al. (2018)	Gamma–Gamma	Polar	OOK
Tapse et al. (2011)	Gamma–Gamma	Turbo	OOK
Nayak (2014)	Gamma–Gamma	LT, BCHB	BPSK
Liverman et al. (2018)	Non-fading	Reed–Solomon	OOK
Huang et al. (2019a)	Non-fading	Reed–Solomon	CSK
Lu and Tiffany (2016)	Non-fading	Miller, Concatenation Convolution	OOK
Ndjiongue and Ferreira (2019)	Non-fading	Trellis	MPSK-CSK
Mejia and Georghiades (2019)	Non-fading	Trellis	CSK

atmospheric turbulence fading channel. An optimal power allocation problem under eye safety constraints is studied for adaptive WDM-FSO systems in Zhou et al. (2015). Authors proposed an adaptive uncoded transmission policy for a channel state dependent transmit power and modulation level in FSO communications in Karimi and Uysal (2012). Ref. Anguita et al. (2010) proposed a coding rate adjustment policy based on the temporal conditions of fading channels under fixed transmit power. To improve the FSO link performance in the presence of strong turbulence, an adaptive low-density-parity-check (LDPC) coded modulation is considered in Djordjevic (2010). In Amirabadi and Vakili (2019a), authors presented a dual-hop relay-assisted hybrid RF/FSO communications using Alamouti coding in the presence of pointing error over the Gamma–Gamma atmospheric turbulence channels. Authors investigated indoor FSO link reliability in terms of packet error rate using rateless code (RaptorQ code) under the locally generated turbulence effect in Pernice et al. (2016). A summary of optical signal modulation schemes, wireless link models, and channel coding schemes is presented in Table 5.

6.6. Background noise reduction

The background noise is created due to solar irradiation in the daytime. The background radiation noise is a function of wavelength, higher background noise at lower operating wavelength. The introduction of spatial filters with an adaptive modulation technique having high PAPR can able to mitigate this noise. In such a case, some crucial design parameters like Doppler shift, angle of signal arrival, and spectral width of laser source need to be considered to build spatial filters. M-ary PPM is the best choice for FSO links as it is more energy efficient and sharply reduces the background radiation noise. Mapping narrow FOV with the help of AO including an array of actuators in the receiver side, and corresponding filter selection is another approach to combat background noise (Hashmi et al., 2015).

6.7. Diversity

Diversity techniques can operate in three different domains such as time, frequency, and space to diminish atmospheric disturbances. In contrast with the single large aperture, an array of multiple transmitters and receivers are used to generate/receive multiple copies of mutually correlated signals either in the three above domains. It is widely recognized that diversity techniques restrict the need for active tracking during misalignment that has the capability to improve BER performance with desired QoS. To achieve the full benefits of spatial diversity, the separation between antennas should be equal to or greater than the coherence length at either transmitter or receiving end. However, spatial correlation is a function of beam width, beam divergence, and variance of beam wander. For SIMO receive diversity, the diversity gain can be derived by averaging the multiple independent laser beams. However, three receive diversity techniques namely selective combining (SC), maximal ratio combining (MRC), and equal gain combining (EGC) can be used at receiving end. The diversity gain for MRC scheme is comparatively higher that proving maximum level of SINR. On the other hand, ECG is a preferred choice over two other methods because of simplicity and low cost installation (Ma et al., 2015). FSO MIMO is quite similar to RF MIMO that increases the channel capacity linearly scaled with the number of transmitting antennas. Time diversity is normally deployed for time selective fading channels where repetitive symbols are transmitted in different coherence time. However, time diversity can be implemented either by incorporating coding or bit interleaving in accordance with the difference between the length of data frame and channel coherence time. The generalized spatial diversity technique in FSO networks is depicted in Fig. 10.

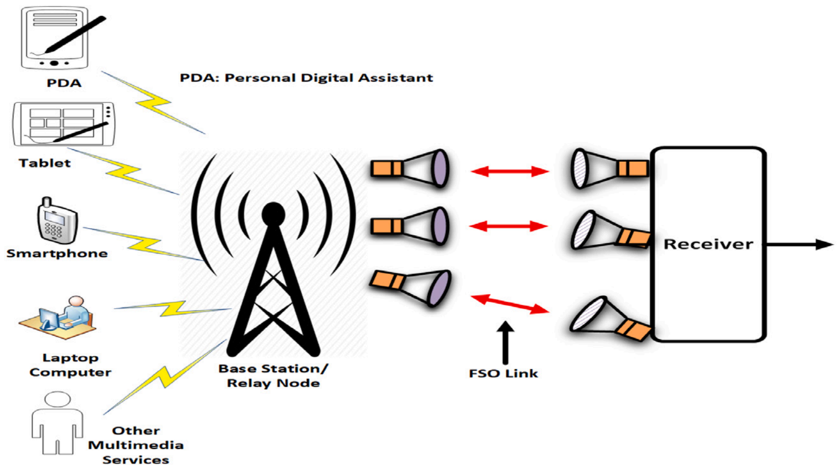

Fig. 10. Spatial diversity mechanism in FSO networks.

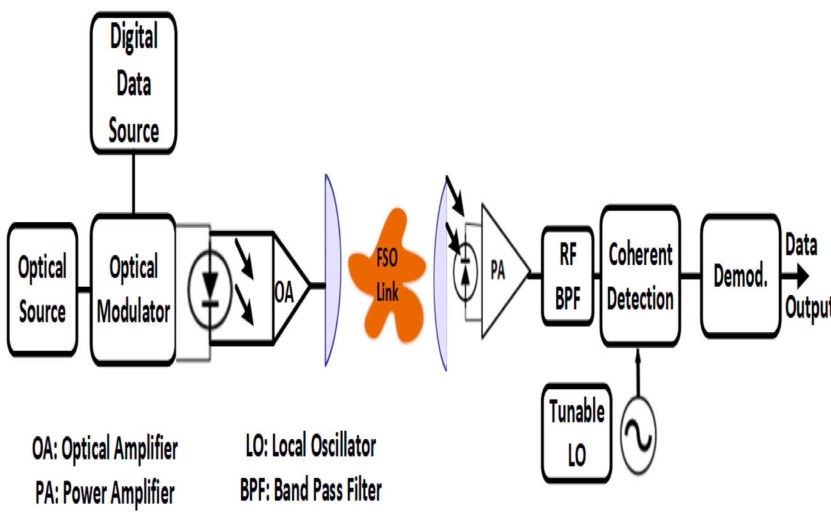

Fig. 11. Coherent detection in FSO systems.

6.8. Coherent FSO

The fluctuations of amplitude and phase of the received signal result in decreasing SINR and degrade the BER performance. Based on the detection techniques, FSO communication can be classified into: direct detection (DD) FSO and coherent detection (CD) FSO (Zhang et al., 2021). In DD-FSO communication scheme, the intensity of source light carries the information and the photodetector directly detects the changes of all photons entering into it without any external mechanism at the receiver side. In contrary to IM/DD systems, amplitude, frequency or phase can be used for information encoding in coherent FSO systems allowing to enhance spectral efficiency. The receiver unit is equipped with a local oscillator (LO) beam where the received signal is mixed with LO generated optical field before photo detection. Thereafter, the signal is amplified and passed through the filter in order to rejection of background noise and interferences (Al-Jarrah et al., 2020). It has been recognized that a coherent FSO scheme provides a greater level of receiver sensitivity over IM/DD systems. Numerous modulation techniques such as M-ary quadrature amplitude modulation (M-QAM), multilevel quadrature phase shift keying (M-QPSK), or multilevel polarization phase shift keying (M-PolSK) are commonly used in CD-FSO systems (Liu et al., 2017a; Khallaf et al., 2017).

Despite the potential benefits of coherent FSO by means of noise rejection, handling turbulence induced multipath fading, and improved level of receiver sensitivity, DD-FSO systems are mostly used because of simplicity and lower cost. With the advancement of ultra-speed digital processing integrated units, coherent FSO schemes are implemented increasingly (Li et al., 2019a). Atmospheric disturbances distort the transmitted signal and resulting imperfection of wave front with the LO at the receiving end. The relevant phase distortions severely curbing the system performance particularly when the receiver aperture is higher than the coherence length of the incoming signal wavefront. Phase compensation technique through tracking the optical beam offers a promising solution of turbulence-induced distortions. Two different approaches named homodyne and heterodyne detection are followed in coherent receivers. Homodyne reception technique requires a precise level of phase matching i.e. proper phase locked loop that makes the device very expensive. Because of this constraint, heterodyne receiver is widely adopted although the prior technique provides a better detection sensitivity (Barua and Majumder, 2020). Recently, several research works have been done to improve spectral efficiency, link distance, and system capacity employing advanced modulation formats in the context of coherent FSO communications (Kakati and Arya, 2020; Wang et al., 2016a, 2018b; Li et al., 2018; Zhu et al., 2018). Ref. Toyoda et al. (2012) demonstrated a 160 Gbps of 256 QAM OFDM over 160 km single mode fiber (SMF) for optical backbone and 4 km FSO links. Authors in Wang et al. (2016a) presented a 200 Gbps, 20 Gbaud dual polarization (DP) 1024-QAM transceiver scheme of spectral efficiency

(SE) 14 bit/s/Hz, whereas, Kakati and Arya (2020) demonstrated maximum 640 Gbps data rate with 40 Gbps symbol rate, SE of 15.3 bit/s/Hz for both in optical core infrastructure and free space optics over the same transmission distance (i.e. 160 km SMF and 4 km FSO). However, receive diversity under different turbulence nature has attracted special attention in coherent systems providing much benefits of mitigating fading, noise, and interfering signals. Fig. 11 presents the graphical illustration of coherent receiving technique in FSO systems.

An optical WiMAX transmission system enables longer distance free-space communication, massive information carrying capacity, and proximity repeatability combining the merits of optical and wireless technologies. In the FSO-WiMAX scheme, OFDM divided the channel into N number of narrowband slots assigning appropriate subcarriers. OFDM technique improves the spectral efficiency and dispersion rate. A tightly coherent optical beam adopts the spatial light modulator to a broadband optical WiMAX transport system over the long distance FSO data channel.

6.9. Sub-carrier Multiplexing (SCM)

Employing multiple wavelengths using the sub-carrier multiplexing (SCM) technique can achieve 1 Tb/s bit rate over 3 Tb/s-km bandwidth-length product and curtails the overall cost per bit (Raj and Majumder, 2019). As a result, the integration of SCM based modulation with FSO systems offers an emerging solution to the last-mile applications particularly for the large temporal and spatial bandwidth of light signal. According to the definition, N subcarriers employing multiplexing are transmitted and Mach–Zehnder modulator (MZM) is used for modulating the optical carrier signal. Thereafter, the modulated signal is passed through FSO channels; photodiode demultiplexed the incoming information to their destinations. Due to the coherent electrical detection at the receiving end, the full spectrum can be efficiently utilized in SCM-FSO systems.

6.10. Hybrid FSO

Each individual technology of RF based network and optical wireless have some advantages and limitations. The fundamental limitations of FSO systems including blocking of communications by obstacles can be effectively overcome using the concept of the coexistence of RF and FSO networks taking their individual advantages. The presence of hybrid RF/FSO systems improves the link reliability and facilitates load balancing under different scenarios (Torabi et al., 2022). The convergence of heterogeneous architecture including RF and FSO networks incorporating diverse frequency bands plays a pivotal role to provide a higher degree of QoS and work well under all adverse weather conditions. The simultaneous operation of the hybrid approach endeavors seamless system capacity and end users avail the inherent benefits from the RF/FSO technology. In other words, RF systems address the blockage hole providing wider coverage area at the user end and FSO ensures high data rate that can operate in the same environment without causing interference among each other. Hybrid technology can play a significant role in the link-reliability enhancement, energy-efficient operations, seamless wireless connectivity in remote distances, interference minimization, and security issues. The goal of combined wireless systems is to attain better performance by eliminating the limitations of individual technologies. Some technical hurdles like shadow effects, inter-symbol interference (ISI), phase induced noise, multi-access interference (MAI), and multipath fading reduces the intensity of the received signal. The RF networks perform as a backup path whenever blockage occurs, NLOS conditions, antenna misalignment, or the severe degradation along FSO link. The transmission link switches back to the optical link when the signal is recovered (Tonk et al., 2022).

In the response to escalating FSO link reliability, RF link serving as a backup path in parallel with the FSO channel propagation path offers a potential solution during FSO link outage. Thermal expansion, heavy wind loads, and little earthquake causes the vibration, thereby break the tight pointing (i.e. misalignment) of the FSO transmitter toward the photodetector position (Al-Qahtani et al., 2017). The combined use of RF systems like microwave and mmWave with FSO can suppress these restrictions. Although RF system exhibits inferior data rate performance in compared to FSO link, it can guarantee the connectivity while FSO channel fail. However, RF channels are less affected by pointing errors, fog, and atmospheric turbulence. Notably, RF link is typically configured in the millimeter (mm) wave bands ranging around 60 GHz that facilitate high bandwidth incorporating with FSO link. Moreover, RF-based communications enable improved performance in NLOS conditions and support better mobility, but RF technology is electromagnetic interference sensitive. For the long-span combined RF/FSO systems, RF links can be used for beam pointing and acquisition for ensuring better reliability (Khalighi and Uysal, 2014). These special features of RF technology mitigate the limitations of FSO deployment. The energy efficiency (bps/Watt) of FSO system is comparatively higher than an RF system. Shifting the traffic load to optical networks from RF minimize the overall energy consumption. Provisioning the RF/FSO systems is the best choice for spectrum utilization particularly for the indoor user's performance. Mobility support with extremely high speed is paramount benefit of the RF/FSO hybrid systems. Hybrid FSO scheme offers excellent communication distance for vehicular systems (V2X) handling dense traffic densities over the wider geographical region (Căilean and Dimian, 2017). An FSO network plays as a primary link and RF system is used as a secondary backup path to realize high reliability. The wireless connectivity through relay nodes is termed as mixed RF/FSO network.

The problem encountered in hybrid FSO system, a re-transmission approach is adopted in literature (Pratama and Choi, 2018) where the lost packets are retransmitted via RF link. The proposed technique is based on a throughput-optimal scheduler that has the capability of handling handover between optical networks and RF architecture efficiently. The function of hybrid infrastructure gateway is scheduling, re-transmitting and handling all the incoming data from packet scheduler. However, the key challenge of vertical handover is to maintain expected QoS. Markov decision process (Hou and O'Brien, 2006) and fuzzy-logic approach (Purwita et al., 2018) is proposed to manage the vertical handover issue. Markov decision scheme minimizes the ping-pong effects i.e. the redundant switching is avoided when blocking occurs in the LOS link. The optical link interruption primarily depends on the user distribution based on space, time and duration. In accordance to the user mobility predictions, the packet scheduling of hybrid FSO networks can be determined using Markov chain process. On the other hand, fuzzy-logic process addresses the uncertainty of decision metrics. Ref. Saber et al. (2019), Tubail et al. (2020) and Abd El-Malek et al. (2017) demonstrates the physical layer security of hybrid RF/FSO systems formulating the minimum power consumption satisfying the users' secrecy rate. Fig. 12 demonstrates the fundamental hybrid RF/FSO communication system.

WiFo (WiFi-FSO) communication. WiFo is a hybrid (i.e. a combination of both RF and FSO technologies) high capacity indoor wireless communication system based on femtocell architecture to increase spectral efficiency and reduce interference (Nguyen and Nguyen, 2018). WiFo can be used to handle multi user FSO communication problems where end users received multiple FSO signals simultaneously in overlapped areas. With the added benefits of high modulation bandwidth of VCSEL, the WiFo typically adopt embedded coding PAM technique for short distance indoor communications resulting in low energy consumption and PiN photodiode (Nguyen and Nguyen, 2018). A set of FSO transmitters are comprised in WiFo directly under the roof. All FSO transmitters generate invisible light that are connected to high speed 100 Gbps Ethernet network controlled by the access point (AP). Whereas, AP manages the simultaneous data communications of FSO

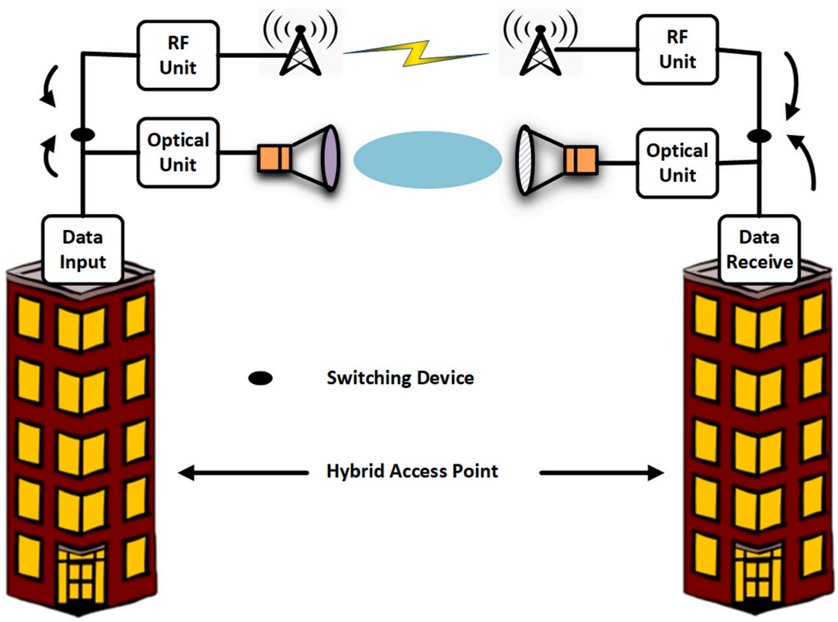

Fig. 12. Demonstration of hybrid RF/FSO mechanism.

signals and the existing WiFi links. WiFo permits denser deployment of light sources where a single receiver can capture all FSO transmitted signals like MISO systems. These crowded installations enable end users in overlapped areas to achieve a higher data rate.

Underwater optical wireless communications (UOWC) by means of the aggregate technology of RF, acoustics, and optics has drawn deep attention for multiple potential applications, for instance, oil pipe monitoring, underwater environment, and offshore investigation. UOWC based on RF and acoustic technology cannot support long distance communication and high speed data rate as well. Acoustic waves enable maximum 20 km underwater link distance with bit rate ranging from tens Hz to hundred of kHz (Alimi et al., 2017b). On the other hand, RF systems also exhibit extremely poor performance that is limited to short link distance. The excellent technical benefits of hybrid RF/acoustic/optical technology can overcome limitations such as link delay, low coverage, and strong signal attenuation.

Recently, optical/optical hybrid wireless technologies such as FSO/VLC, FSO/OCC showing different characteristics has also received much attraction among researchers. FSO/OCC hybrid solution provides long distance V2X communications while maintaining stable link performance eliminating their individual limitations. OCC support comparatively short distance communications between vehicles with low data rate. In contrast, FSO networks provide communication between cars far apart. Therefore, the hybrid system satisfies user demand and increases reliability as well. However, the performance is considerably suffered by the atmospheric conditions in outdoor particularly precise control of the transceiver (Vats et al., 2019). To address precise indoor and outdoor localization, pointing, navigation, interference effect, handling of diverse data rates, bit rate requirement, coverage area, a hybrid FSO/VLC heterogeneous interconnection is proposed in the literature (Pesek et al., 2019; Huang et al., 2017). The implementation and deployment of FSO/VLC hybrid network coordination together with user mobility support, localization, routing algorithm, traffic management, and handover issues are clearly discussed in Huang et al. (2017).

In order to measure the effectiveness of any system, performance analysis is a vital issue. The performance metrics assessment can be carried out in various ways such as analytical evaluation, numerical method, simulation environments, and experimental verification. Different works used different performance metrics such as throughput analysis, BER, spectral efficiency, outage probability, secrecy rate analysis, symbol error rate, ergodic capacity, SINR, and power efficiency to investigate received signal quality, system capacity, and reliability. Some applications of hybrid FSO systems with brief descriptions are presented in Table 6. Table 7 and Table 8 summarize the key objectives and detailed discussion on different aspects of recent research trends of hybrid FSO.

7. Multi-user FSO communication

Multiple users transmit different signals, which are mixed in the wireless propagation medium. Blind source separation (BSS) technique is used to extract the original information from the mixed signals. This problem exist in numerous applications such as biomedical data analysis, speech signals identification, machine learning based communications, etc. (Aveta et al., 2017). Since users are randomly distributed over space, different channels will experience independent fading. Exploiting multiple antenna diversity techniques can considerably improve the FSO wireless transmission performance. Multiuser diversity offers some inherent benefits over antenna diversity as it explores independent fading channels. It can also supports a simple receiver structure where a single antenna is equipped per receiver. Introducing a number of access points through a long-range FSO link that amplifies the received signal via short distance RF link and forward to next hop increases the transmission distance and reliability of data services as well. Authors (Amirabadi and Vakili, 2019b) reported a multi user multi hop combined RF/FSO communication system that offers lower energy consumption, low delay processing, and minimum complexity. Amplify and forward relaying is used for fixed gain amplification when channel state information (CSI) is unknown, in contrast, adaptive gain is a suitable choice when CSI is known. Chen et al. (2016b) studied the multi-user diversity RF/FSO point-to-multipoint MISO communication systems consisting of hybrid access points aiming of minimum error probability and BER. A multiuser mixed RF/FSO two way relaying (TWR) method considering asymmetric channel gain is presented in Al-Eryani et al. (2018a) to examine the outage probability and energy-efficient power allocation. However, Multiuser MIMO transmission is a better choice over spatial multiplexing as it can considerably extend the capacity of wireless communication systems (Yang and Alouini, 2020). Fig. 13 shown the basic multiuser MIMO communications in FSO perspectives.

Table 6
Summary of hybrid FSO applications.

Hybrid type	Objective	Contributions	References
Microwave/FSO and mmWave/FSO	Backhaul connectivity	Seamless microwave photonic link composed of RoFSO, RoF and RF, traffic shifted from RF to FSO network. Effect of channel impairments like chromatic dispersion, atmospheric turbulence, and multi-path induced fading are considered. Complementary properties of the FSO and mmWave channels, diversity selection combining technique improves the link reliability in terms BER of under strong turbulence.	Nguyen et al. (2019a), Alavi et al. (2017), Bohata et al. (2018), Zhang et al. (2018a), Dat et al. (2019), Esmail et al. (2019), Rakia et al. (2017), Zhou et al. (2017), Shakir (2018), Lei et al. (2017) and Khan and Jamil (2017)
RF/FSO	Backhaul connectivity	Hybrid RF/FSO improve the link reliability for long distance communication. Extensive simulation is conducted to evaluate SINR, BER taking into account of limiting factors under different network scenarios.	Jamali et al. (2016), Kong et al. (2015), Salhab et al. (2016), Trinh et al. (2017), Enayati and Saeedi (2016), Varshney and Jagannatham (2017), Soleimani-Nasab and Uysal (2016), Tang and Brandt-Pearce (2014), Palliyembil et al. (2018), Varshney et al. (2018), Hassan et al. (2020), Odeyemi et al. (2020) and Lei et al. (2020a)
Acoustics UWC/FSO	High bit rate, link reliability enhancement	Based on the link distance, oceanic turbulence induced scintillation and misalignment in underwater links, and pointing, acquisition, and tracking (PAT) establishment, LOS/NLOS condition, a UWC/FSO system is established for reliable communication.	Kaushal and Kaddoum (2016), Zeng et al. (2017), Lei et al. (2020b), Yadav and Kumar (2017), Tsai et al. (2020) and Sun et al. (2020)

Table 7
Summary of hybrid FSO research trends.

Reference	Metrics	Objectives	Description	Remarks
Zhou et al. (2017)	Throughput, Outage probability	Data rate maximization of vehicular ad-hoc network (VANET)	Developed a joint channel allocation and rate control to enhance throughput and solve the cross layer design problem incorporating carrier sense multiple access (CSMA). Capacity and outage probability are also satisfied through alternating detection method.	System capacity
Enayati and Saeedi (2016)	Throughput	Orthogonal frequency division multiple access (OFDMA) based scheme ensure the backhaul performance of FSO link	Proposed a relay assisted OFDMA based throughput maximization of hybrid RF/FSO link considering multiuser resource allocation scheme including power and subcarrier allocation.	System capacity, signal quality
Tang and Brandt-Pearce (2014)	Throughput	Network control approach for throughput optimization based on various channel conditions	Studied the achievable throughput enhancement using mixed linear integer problem. Also, proposed a heuristic scheduling and traffic demand routing adopting physical channel interference model.	System capacity, reliability
Rakia et al. (2015)	Outage probability, SINR	Power adaption technique driven by truncated channel inversion for ensuring fixed SINR at receiver	Determined the improvement of outage performance assuming two distinctive power adoption strategies with analytical derivations.	System capacity, signal quality
Makki et al. (2016)	Throughput, outage probability, power efficiency	Performance evaluation assuming precise channel state information at receiver	Derived the closed form expressions for the signal decoding. Also, analyzed the throughput and outage probability in consideration of adaptive power allocation and state of channel conditions.	System capacity
Najafi et al. (2017)	Throughput, power efficiency	Throughput maximization using parallel relay assisted networks	Focused on the optimal system design according to sub-optimal buffer aided mechanism such as the optimal relay selection strategies and optimal time allocation.	System capacity, reliability
Salhab et al. (2016)	Ergodic capacity, outage probability, blocking probability, SINR	System performance optimization with opportunistic scheduling	Closed-from expressions are derived to evaluate the system performance analyzed varying different atmospheric turbulence conditions. Monte-Carlo simulations are conducted to justify the exact and asymptotic results in the presence of turbulence fading and pointing error.	System capacity, signal quality, reliability
El-Malek et al. (2016)	Ergodic capacity, power efficiency, outage probability	Investigate the performance of multiuser SIMO hybrid relay networks with opportunistic user scheduling	Outage probability, symbol error probability and ergodic channel capacity are assessed based on closed-from expressions using maximal ratio combining and selective combining in the presence of different fading model	System capacity, signal quality.
Ansari et al. (2013)	Ergodic capacity, outage probability, BER	Performance evaluation of asymmetric link of dual-hop relay transmission system with pointing error	Develop the closed-from expressions of CDF, PDF, and moments of SINR validated with the help of different metrics.	System capacity

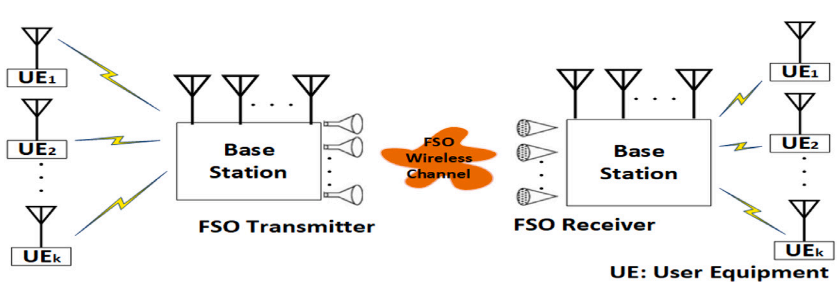

Fig. 13. Generalized multiuser MIMO FSO system.

Table 8
Summary of hybrid FSO research trends.

Reference	Metrics	Objectives	Description	Remarks
Usman et al. (2014)	Ergodic capacity, outage probability, BER	Performance investigation of switching-based transmission scheme	Investigate average BER, ergodic capacity and outage probability considering gamma–gamma fading and Nakagami fading.	System capacity
Balti et al. (2018)	Ergodic capacity, SINR, SER, outage probability	Hardware impairments for heterodyne IM/DD with fixed gain relay scheme	Impact of hardware impairments for different SNR is illustrated. Analytical expressions for different performance parameters are derived and compared the numerical results through the numerical integration method.	System capacity, signal quality
Jamali et al. (2016)	Throughput, delay tolerant performance	Cascading of small cell networks to hybrid RF/FSO backhaul link	Developed optimal fixed and adaptive link allocation algorithms based on channel state information to investigate delay limited and delay tolerant transmission schemes	System capacity, signal quality
Trinh et al. (2017)	Throughput, BER, outage probability, ergodic capacity, SNR	Cost reduction and scalability improvement of mmWave RF/FSO	Examined the performance metrics considering the effect of pointing errors owing to the misalignment between the transmitter and receiver. Note that the cascaded channels are modeled by the Rician and Malaga distributions.	System capacity, reliability
Yang et al. (2015b)	Throughput, BER, outage probability, SINR	Mitigation technique of multipath fading and atmospheric turbulence for a dual hop hybrid system	Proposed a transmit diversity at the sending end and selection combining technique at the receiver end to investigate the effect of pointing errors on the FSO link. Also, examine the system performance and provide a light of way to mitigate limiting factors.	System capacity, reliability, signal quality
El-Malek et al. (2017)	Outage probability, power efficiency	Determine the optimal transmit power and co-channel interference	Exact closed-form expression is derived to find an optimal power allocation. The secrecy performance and physical layer security performance is studied under different constraints.	Reliability
Bag et al. (2018)	Ergodic capacity, outage probability, BER	Estimation higher link reliability under extreme atmospheric constraints	To avoid needless switching, a single FSO link is considered to active whereas an extra mmWave RF/FSO link is used as a backup. The primary link is modeled by gamma–gamma distribution assuming strong turbulence.	Reliability, system capacity
Shakir (2018)	SNR, BER, Outage probability	Switching strategies to minimize the bandwidth wastage maintain the same data rate	Performance investigation using selection combining diversity based on closed-form expression of BER and outage probability. Ensure the same data with the same data rate over the FSO link without having CSI.	Reliability, system capacity
Petkovic et al. (2015)	BER, Outage probability	Impact of outdated CSI based relay selection on the system performance	Considered partial amplify-and-forward relay selection. RF link is subject to Rayleigh fading and FSO link is modeled by gamma–gamma distribution. Mathematical expressions of various performance metrics are derived.	Reliability
Wu et al. (2017)	Outage probability, power efficiency	Cost minimization due to power consumption while ensuring packet success probability	Performance investigation by joint consideration of power allocation and dynamic link selection for guaranteeing the long-term reliability requirements. The closed form of power allocation policy is derived for link selection and Lyapunov optimization algorithm is used to solve the problem.	Reliability
Chen et al. (2016b)	BER, Outage probability	Effective link quality scheduling using multiuser diversity	Analyzed a hybrid RF/FSO point-to-multipoint system assuming multiple FSO users, RF users and access points. The asymptotic closed form expressions for average BER, outage probability are derived considering multiuser diversity gain.	Reliability, signal quality
Al-Eryani et al. (2018b)	SINR, SER, ergodic capacity, Outage probability	Two way multiuser relay networks with opportunistic scheduling and non-uniform channel fading is investigated	An efficient optimal power transmission algorithm is developed for a heterodyne detection scheme. The system performance is evaluated for two way relaying network and single way relaying network in the presence of weather turbulence and pointing error effect.	System capacity, reliability, signal quality
Arezumand et al. (2017)	SINR, BER, Outage probability	Dual hop hybrid system based on cognitive amplify and forward relay networks	Fixed gain and channel assisted relaying policy is derived according to the asymptotic expressions. Heterodyne IM/DD detection receiver with double gamma fading channel is considered. In addition, the diversity order and diversity multiplexing trade-off is carried out to investigate the overall system performance.	System capacity, reliability
Touati et al. (2016)	BER, Outage probability	Controlling the FSO link fragility and reduction of outage probability	Analytical expressions of outage probability and BER are derived varying different modulation scheme with its different channel impairments.	System capacity, reliability
Lei et al. (2020b)	SINR, BER, Outage probability	Performance analysis of dual hop RF/UWOC hybrid systems under fixed and variable gain relaying schemes	Evaluate SINR, BER, and outage probability under the effect of water bubble levels, temperature gradient, water conditions and detection techniques of underwater wireless optical communication.	Reliability
Tsai et al. (2020)	Throughput, BER	Boosting of total channel capacity with FSO backbone UWOC	Total achievable throughput of FSO/UWOC link is 500 Gbps integrating PAM4 modulation with five (5 R/G/B LD transmitters of two stages) wavelength-polarization multiplexing scheme.	System capacity, signal quality

It is essential to sense the optical spectrum periodically in order to avoid interference among multiple users particularly to detect the channel occupancy. Spectrum sensing plays a significant role in multi-user FSO communications that allow users to monitor the available optical frequency spectrum in their operating range (Kong et al., Apr 2020). A generalized blind spectrum sensing [i.e. applicable to all optical wavelengths] policy based on SNR estimation for an unknown optical signal over strong atmospheric turbulence conditions is reported in Arya and Chung (2019c). An extensive investigation of energy detection method based optical free spectrum sensing for FSO communication over exponentially distributed channels is conducted in Arya and Chung (2019b).

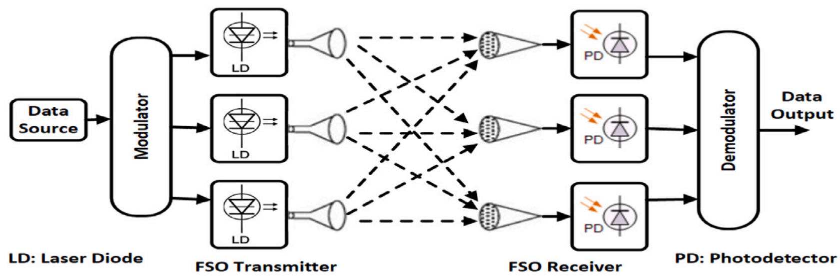

Fig. 14. Simplified illustration of MIMO FSO system.

8. MIMO FSO systems

Diversity techniques e.g. spatial diversity realized multiple beams at either the transmitter or multiple apertures at the receiver end can considerably improve the wireless FSO transmission over fading induced channels. The spatial diversity technique helps to enhance the FSO transmission reliability introducing inherent signal redundancy (Sharda and Bhatnagar, 2020). It is worthy to mention that turbulence-induced fading considerably deteriorates single input single output (SISO)-FSO link (Alimi et al., 2017a). As an indication of the context, additional power margin is employed to achieve the desire QoS, this power penalty can be alleviated by increasing the transmission power. However, this approach is impractical due to eye safety regulations and relatively lower reliability. Typically, a conventional Gaussian light signal can experience a beam wandering effect, which causes power fluctuations and wavefront distortions due to unwanted atmospheric turbulence. In addition, misalignment between transceivers causes significant power loss at the receiver end as explained beforehand. There have been several approaches to handle possible signal degradations. Aperture averaging is a potential technique of improving system performance by means of incorporating a wider lens at the receiver side to mitigate fading effect via averaging intensity fluctuations. This technique is efficient under moderate-to-strong atmospheric turbulence when the receiver aperture is greater than fading correlation length, $\sqrt{\lambda l}$, with l denote the transmission distance and λ represents the wavelength (Khalighi and Uysal, 2014). Using multiple small apertures instead of large aperture at the receiver is a suitable way to reduce fading by taking the advantage of aperture averaging. Employing several apertures is more advantageous under a strong turbulence regime but involves implementation complexity. For single input multi output (SIMO) spatial diversity systems, equal gain combining (EGC) method is used that offer less complexity but shows comparatively inferior performance to optimal maximal ratio combining (MRC) (Yang and Alouini, 2020). On the other hand, multi input single output (MISO) FSO scheme at the transmitter end is mostly used to transmit the same signal on the separate beams, which is referred to as repetition coding (RC). Authors in García-Zambrana et al. (2015) pointed out that MISO FSO based spatial diversity technique combat the fading effects implementing the multiple laser sources at the receiving end. Moreover, generalized selective combining (GSC) method is recognized as a low complexity diversity scheme to select the best possible path from a subset and combining them using MRC fashion. However, the weak channel estimation limits the merits of MRC scheme that may degrade the system performance considerably. A simplified illustration of MIMO FSO system is displayed in Fig. 14.

Likewise RF systems, MIMO technique is very popular to combat turbulence induced multipath fading increasing the bit rate and quality of signal transmission through spatial multiplexing (Yang and Alouini, 2020). Under this scenario, the FSO transceiver serves multiple end users simultaneously using the same frequency band where multiple co-located antennas provide the larger multiplexing gain. In order to control inter-user interference, several precoding techniques are studied for multiuser MIMO transmission. Typically, intensity modulation/direct detection (IM/DD) method is implemented in MIMO-FSO systems, where IM is used for signal transmission and DD is employed at the receiver. According to Yang and Alouini (2020), nonlinear precoding schemes attain better performance over the linear precoding method, which considers the total rate capacity of all users but involves increased implementation complexity. For instance, the dirty paper coding (DPC) cancel out inter-user interference prior to data transmission with full knowledge of CSI. On the other hand, zero-forcing beamforming (ZFBF) (Yoo and Goldsmith, 2006) and random unitary beamforming (RUB) (Sharif and Hassibi, 2005) are popular linear precoding schemes have significantly lower implementation complexity. The precoding matrix is modeled pseudo inverse matrix of selected users in ZFBF, whereas, the precoding matrix in RUB is designed based on the channel quality of randomly selected users on distinctive beamforming directions. Ref. Safari and Uysal (2008) studied the orthogonal space time block code (OSTBC) and repetition code (RC) under log-normal fading channels conditions. However, the log-normal atmospheric channel model is not sufficient when the huge number of heterogeneous devices are connected in 5G (Alimi et al., 2018). Recently, numerous research works conducted focusing on MIMO-OSTBC FSO applications due to higher diversity gain and a wide range of FSO applications (Wang et al., 2019c; Amhoud et al., 2019; Biagi et al., 2020). Besides the OSTBC, the RC scheme outperforms OSTBC in terms of diversity gain but the RC applications with MIMO are challenging because of timing asynchronous alignment between transceivers and thereby, resulting in the time difference of signal propagation (Alimi and Muga, 2020). The use of repetition coding in MIMO FSO systems endeavoring to combat turbulence effects by introducing redundancy is studied in Djordjevic (2018). However, several laser beams having identical frequencies are interfering with each other when simultaneously received at the same aperture.

To address the timing misalignment of asynchronous MIMO FSO channels, OSTBC based MIMO scheme offers better performance and is robust to inter-symbol interference (ISI) maintain the orthogonality conditions. However, the system performance gap between RC and OSTBC schemes is more significant for the higher order of MIMO FSO systems. Saidi and Hamdi (2020) presented BER performance for multihop hybrid RF/FSO systems using M-ary pulse position modulation (MPPM) and MIMO technique under gamma–gamma turbulence channels. The enhancement of average secrecy capacity and improvement of secrecy outage probability for MIMO-FSO link with equal gain combining reception technique over gamma–gamma atmospheric turbulence channels is demonstrated first time in literature (Boluda-Ruiz et al., 2020). Ref. Song et al. (2020) investigated satisfactory BER, power penalty reduction, and outage probability performance for 10 Gb/s QPSK FSO links using aperture averaging receive diversity and MIMO spatial technique. Eghbal and Abouei (2019) studied the received signal intensity of MIMO FSO systems accounting destructive interference with small variations of path length between optical transmitter and photodetector. A disaster management method for MIMO-OFDM FSO links employing polarization division multiplexing (PDM) with Malaga channel model is presented in Jeyaseelan et al. (2020). With PDM, the two high speed OFDM signals are mutually orthogonal polarizations is an excellent way to uplift spectral efficiency. Unlike fiber-based communications, PDM is a suitable choice for FSO systems as it is immune from cross polarization modulation, polarization mode dispersion, and associated losses. Under the proposed scheme, two different OFDM subcarriers i.e., eve and odd subcarriers are multiplexed using PDM that enable to transfer of two independent data signals on a single wavelength. Das et al. (2020) employed Almouti STBC transmit diversity and switch-and-examine combining (SEC) scheme at the receiver side for MIMO-FSO communication systems to investigate ergodic capacity, BER, and outage probability over the Malaga turbulence wireless channels.

9. Research challenges, directions and open issues

The existing RF system is incapable to fulfill the intended diverse type of multimedia applications and high data rate digital wireless services offered by 5G and B5G. As a result, FSO scheme offering an ultra-band frequency range of license free spectrum is an attractive viable solution (Sarker and Samad, 2021). FSO communication is typically taking place with a narrow directional beam using line-of-sight (LOS) propagation technique over a long-haul link distance. A 40 GB/s data rate through FSO communication has already been implemented. Recently, FSO system can cover link distances ranging from nm (inter-integrated circuit design) to 10 000 km (ground base to satellite FSO link) (Raj and Majumder, 2019). Despite the potential benefits of FSO, to handle ever-increasing growth of smartphones, cloud big-data, electronic devices, IoT/IoE devices, artificial intelligence, etc. developing a robust infrastructure is become challenging. We discussed different application scenarios ranging from residence to space for the FSO links and systems, still research on fully harvesting the inherent potential is immature. A number of important challenging problems are needed to be figured out for the efficient deployment of FSO systems. In this section, we shed the light on research challenges, future research directions, and open problems related to FSO systems and application.

9.1. 5G/B5G and IoT/IoE solutions

It is obvious that FSO is the most emerging technology to support next generation cellular networks and gigantic connectivity of IoT devices. The substantial deployment of LDs for the FSO technology creates high inter-cell interference in the 5G/B5G and IoT/IoE networks which become a challenging issue. In addition, different modulation techniques of LDs may cause flickering (i.e. fluctuation of modulated signals) (Khan, 2017), thereby avoiding this issue also challenging. A coordinated multipoint (CoMP) enabled cellular network remarkably reduce the inter-cell interference assuring throughput maximization (Jahid et al., 2017; Shams et al., 2017; Jahid et al., 2019). It is commonly accepted that the augmentation of deployed OWC nodes leads to an increase inter-cell interference (ICI). ICI coordination and mitigation techniques in the OWC domain have been studied utilizing the recognized approach used in the RF domain (Liu et al., 2017b). It is important to realize how to manage interference in optical wireless link. A last mile bottleneck problem may arise if the backhaul system for next generation mobile networks fails to handle an enormous volume of data traffic to support high speed services at the end users. Hence, the enhancement of the FSO backhaul capacity for data rate improvement to address last mile problem has become a challenging issue. Furthermore, a massive amount of throughput demand by the access network is generated owing to support huge connectivity of high data rate devices to the network. Therefore, an extensive backhaul capacity is required to solve aforementioned issues. Notably, user traffic backhauling via distinctive backhaul networks needs precise synchronization. Some of the future FSO applications include both cellular backhaul and front haul architecture contemplating at the transport and access network levels. Therefore, FSO system optimization for mobile network backhauling by means of cost and reliability metrics is an important issue.

Finally, machine-learning/deep-learning based networking is one of the prime keys in future generation cellular networks. Nowadays the demand of artificial controlling and remote decision making increasing which can be tackled by supervised learning such as smart healthcare and smart home load controlling (Hasan et al., 2019). Integrating reinforcement learning and machine learning in 6G networks enhance data rate, manage network traffic, enables intelligent network re-assignment, automatic error correction, and efficient decision making among surrounding networks (Nawaz et al., 2019).

The seamless deployment of IoT devices triggers a demand to incorporate and inter-operate a variety of hybrid connectivity technologies. For example, numerous applications need the integration of technologies like RFID, wireless sensor networks (WSN), cloud networks using Bluetooth, WiFi, and ZigBee connectivity onto a single or hybrid network. As a consequence, the conventional RF spectrum is more congested to support a variety of IoT applications. One promising key technology is hybrid FSO under OWC technology since it does not interfere with RF spectrum and using the visible light spectrum more than thousand times the modulation bandwidth of RF signal (Bruzzi and Boone, 2012). To realize the IoT/IoE paradigm, OWC technologies must evolve to accommodate the huge data volume and expected transmission speed. Because of the aforementioned benefits exploited by an unregulated OWC technology, FSO will play a key role in future IoT connectivity. The co-deployment of FSO and VLC ensure the capability of physical systems of 5G/B5G network, smart cities (connectivity of heterogeneous wireless services and IoT devices to urban infrastructure) with a number of thins in synergy to connect and reach (Li et al., 2015). Moreover, connecting smart devices to IoT and beyond IoT networks, FSO plays a core backbone network in a convenient way adopting OFDM modulation scheme particularly in an indoor environment (Hussein and Elgala, 2018). Hence, an efficient and practical solution of FSO schemes for the smart approach of internet of everything (IoE) is a major design factor.

9.2. THz and quantum communications

FSO communication provides high data rates over a long coverage distance of LOS connections especially in outdoor applications. FSO support some indoor applications like to connect devices inside offices, residences, hospitals, shopping malls, etc. The THz spectrum can provide the concrete solution for the data transmissions in non-LOS (NLOS) applications where the transmitted signal is reelected off by various objects. However, THz wireless system can be applied for both indoor and outdoor applications with a very high data rate including LOS and NLOS links. Therefore, the efficient design of NLOS FSO in consideration of shadow fading and non-linear channel response is a critical design issue. On the other hand, the aspect of quantum computing applications is an emerging choice to attain secure and reliable communication both in the atmosphere and space. So, FSO in optical wireless communications integrating quantum communication will enter a new era in inter-space links (Majumdar et al., 2019).

9.3. Relay-enabled FSO networks

A terrestrial FSO link performance can be severely degraded by beam misalignment, attenuation, and atmospheric turbulence. In this regard, relay assisted FSO networks have the capability to cope with atmospheric turbulence through allowing the transmitted data to an intermediate relay node in order to avoid direct link (Jamali et al., 2016). A high transmission power can be forced to overcome the degradation of the end-to-end performance due to such impairments. Nonetheless, such additional transmitted power may affect the level of secrecy. So, optimal power allocation in RF/FSO hybrid networks is a key concern for the relay assisted optical wireless systems. The relay assisted buffer based heterogeneous networks for unmanned area vehicles (UAVs) with fixed and moving relay stations are presented (Fawaz et al., 2018). Multi hop transmission (i.e., serial) and cooperative diversity (i.e., parallel) relaying is these two types of relay configuration reported in Hamza et al. (2019). Multi hop transmission relaying technique extends the coverage range where the signal is transmitted in between relay node to destination node in a serial fashion. Under the parallel relaying approach, the same information is transmitted to the both receiving node and relay node from the sending end, and thereafter relay node retransmit the data again to the destination node. Data forwarding protocols using the relay nodes particularly amplify and forward, and decode and forward are discussed in Boluda-Ruiz et al. (2018). With the introduction of all optical relaying has the potential to avoid the need for optical-electrical-optical (OEO) conversion at relay each node (Dabiri and Sadough, 2018a; Huang et al., 2018). The cascaded use of saturation gain semiconductor amplifier (SOA) in FSO systems are capable of eliminating scintillation, atmospheric turbulence even without having the knowledge of channel state information (CSI) (Yiannopoulos et al., 2013). However, the idea of relay assisted networking is established for RF technology, still the scope of relaying is immature in optical wireless communication literature.

9.4. WDM FSO links

The integration of wavelength division multiplexing (WDM) techniques with FSO communication pushes toward a new dimension by expanding the capacity of FSO links. With the introduction of dense WDM (DWDM), FSO systems capacity can be greatly enhanced (Arimoto et al., 2008; Mbah et al., 2017; Tan et al., 2018; Zhao et al., 2018). A realization of 320 Gbps LOS/Long WDM FSO links were developed and experimented using OOK modulation (Arimoto et al., 2008) and an FSO link of 200 Gb/s bit rate is demonstrated in Zhao et al. (2018). The outage probability of WDM FSO links in the presence of inter-channel crosstalk and turbulence is analyzed (Mbah et al., 2017). On the other hand, the optical CDMA technique received more attention for future FSO networks to support ever-increasing user demand especially fiber to the home (FTTH) service via optical access network. A few research works (Islam and Majumder, 2015) have been devoted to OCDMA-WDM optical ring networks in the context of FSO communication considering pointing error effect using received diversity which provides augmented capacity and overall system performance as well. Multi wavelength (MW) OCDMA offers an attractive solution to enhance channel capacity by means of reducing multi access interference (MAI) and crosstalk. A combined solution of WDM-OCDMA supports a massive number of simultaneous users over conventional WDM scheme and also enable dynamic add/drop function for the next generation access network. The study of hybrid DWDM-MIMO FSO communication (Hamzah and Murdas, 2020) is conducted aiming to increase transmission coverage with minimum BER and outage probability taking into account severe weather conditions. Despite the recent advances, more research is needed to contemplate low cost and high speed integrated FSO WDM links under different scenarios such as terrestrial, point coverage, cellular coverage, LOS, transmission range, fixed or mobile relay structure.

9.5. Channel characterization

Over the past few decades, various channel models namely lognormal, lognormal-Rician, and Gamma–Gamma distributions have been proposed to quantify the impact fading properties and turbulence effect of FSO links (Son and Mao, 2017). The performance of FSO links is heavily affected by atmospheric turbulence such as scattering, scintillation, air absorption, free space loss, and refraction. Besides, storms, fog, heavy rain, and dust may severely degrade the successful communication link between transmitter and receiver in the outdoor environment. Hence, the mitigation technique to address atmospheric turbulence is a difficult issue. Statistical modeling of combining the effect of atmospheric turbulence, mobility of obstacles, and pointing error of intensity fluctuation of received optical signal has been a challenging research issue. The power allocation and the link performance is strongly depend on atmospheric loss which may lead to scope to research for the counterbalancing of the atmospheric loss. A high speed NLOS data communication in the UV band is a significant option. A methodological assessment in consideration of transceiver geometrical configurations, atmospheric conditions, and effective channel modeling is still the issue of future research. However, modeling of optical scattering communication (OSC) channels is more difficult than traditional LOS FSO links. This is due to the longer link range pushes the complexity of combined modeling attenuation and multiple scattering (Ghassemlooy et al., 2015). Therefore, designing the channel and system models that capture different limiting factors of OSC has become a great interest particularly for connecting distributed objects in IoT devices. The application of MIMO with optical wireless technology is quite challenging due to the characteristics of IM/DD channel (Ghassemlooy et al., 2016). The application of MIMO could lead increase the hardware complexity and may limit its application. However, the deployment of MIMO with accurate channel modeling is a good research issue.

9.6. Pointing, Acquisition, and Tracking (PAT)

In general, FSO transmitter has broadband and point-to-point directional link in a beeline between the sending node and destination. PAT schemes are typically incurred in static and mobile FSO communication systems when transceivers shoots out narrow beams and the divergence of the beams is smaller than a few µrad (micro-radian) (Kaymak et al., 2018). This ultra-narrow beam property results high speed data rate, long reach span, less interference, and more energy efficient along with the FSO link. The properties of a narrow spectral beam make the FSO link more difficult to build between two endpoints. A precise LOS direction of transmission link is required to maintain connectivity between endpoints. However, PAT problems have not completely addressed despite its promising significance. For the successful deployment of PAT mechanism, integrated and flexible hardware architecture is need to be developed for dynamic PAT.

Under the pointing mechanism, FSO node starts to coordinate the potential nodes existing in the free space prior connection procedure in mmWave networks (He et al., 2015). Therefore, synchronizing between coordinating nodes is an inherent network design issue related to the pointing mechanism. The acquisition mechanism is associated with the modulation–demodulation techniques. FSO receiver aperture is designed in such a way that it can accept multiple optical beams, then the receiver decides the desired sign for decoding. As an indication of physical architecture, the dimension of receiver aperture is required to be adjusted based on the divergence angle emitted from the laser beam distance. Such a technique substantially reduces outage probability, high data transfer rate, and enhances the efficiency of power budget. The tracking mechanism is related to the problem raised by the narrow spectral beam property. The link performance heavily depends on the geometric alignment of transmitter and receiver and beam shape as well. Tracking mechanism under mobile transceivers, a misalignment of optical beams results to increase the outage probability and reduce the available capacity. On the other hand, very high pointing accuracy is to be maintained between stationary transceivers.

The recent growing interest in an intelligent transportation system such as V2V, V2I, or Vehicle-to-everything (V2X) requires LOS connectivity with vehicle (Cheng et al., 2015). The optical wireless technology can be applied for traffic management (Yamazato et al., 2017). Such scenario causes a challenge for signal acquisition and tracking in the presence of dense building in urban areas. The high speed moving vehicle, for instance, cars, electric trains, or unmanned area vehicles may be a challenging task for FSO system in the area of V2X communications. An agile PAT mechanism can keep track with the high speed vehicles to handle the optical link between V2X (Urabe et al., 2012). In addition, the development of PAT scheme in smaller size and low complexity required by the mobile systems (e.g., battery powered drone) is a challenging issue. The design of a suitable PAT model to provide multi-directional coverage and has the ability to mitigate vibration is another interesting area. Moreover, a directive PAT mechanism is an important feature where the laser beam focused toward the moving direction of the tracked vehicle is another scope to research. This directive mechanism for mobile FSO communication reduces the handover time with the advanced knowledge of trajectory objects. One disadvantage of this mechanism is the error incurred due to a mismatch of the actual and expected speed of vehicle, therefore, it needs GPS or other localization technology support. Time synchronization between two transceivers in the PAT process is another crucial issue. As a potential solution, transceivers should allow to exchange of control information, channel state information such as location, mobility, and time for a synchronized alignment.

9.7. Underwater communication (UWC)

Nowadays UWC received much attention for oil pipe investigation, offshore monitoring, and object detection. Long coverage distance and high speed optical links are a much priority in many UWC applications. The adaptive modulation and coding (AMC) technique in underwater environments is an important issue (Zeng et al., 2017). Moreover, the adaptive switching mechanism between an acoustic and optical mode for hybrid optical/acoustic networks in underwater is needed for various applications (Saeed et al., 2019).

9.8. FSO networking

5G/B5G technology is comprised of ultra-dense heterogeneous networks (a combination of mixed networks such as macrocell–picocell, macrocell–femtocell, macrocell–microcell) to increase the data transportation capacity. A small cell dense heterogeneous network (HetNet) will generate frequent handover between optical and RF networks which could lead to many needless handovers (Du et al., 2018). Thus, controlling an unwanted handover and the ping-pong effect is a crucial issue. Supporting two different types of receivers (heterogeneous) is important for hybrid FSO networks. The properties of RF-based transceiver and the optical transceiver are different, both networks must be active simultaneously for the hybrid framework. Thus, combining the two different architectures in the same platform and the same data transmission over the distinctive systems simultaneously is a vital issue. On the other hand, the distinctive nature of physical layer properties and data link layer for the hybrid optical and RF wireless networks arise a major challenge for mobility support. A suitable handover algorithm may overcome the continuity of user mobility applications. It is important to enabling horizontal handover (Haas et al., 2016) and vertical handover (Sarigiannidis et al., 2014) mechanisms to allow seamless user mobility. For example, a user can seamlessly move around LiFi cells (horizontal handover) and among LiFi and WiFi networks (vertical handover) under LiFi—WiFi hybrid systems. Meanwhile, the effect of user mobility based on channel estimation and handover is also challenging. The time taken for the handover process should be short enough to meet the specification of 5G/B5G. The time taken for exchanging the information between user equipment and central station depends on the algorithms (Jin et al., 2016). Note that a smaller coverage area incurred large handover and the wireless optical channel is vulnerable to channel barrier due to handover. Also, a precise handover is required for switching among the backhauling networks. The challenging of backhauling includes the continuous change of pointing of backhaul link for the moving objects.

9.9. Load balancing

The effective user association policy among the different available access networks is a research concern. An optimal user association mechanism solve the joint resource allocation and user allocating problem. User equipment (UE) may need to be transferred to different access points for better performance under the load balancing technique (Wang et al., 2016b). Therefore, optimal load balancing can be considered as a potential technical issue.

9.10. Physical layer security

According to Skorin-Kapov et al. (2016), optical wireless communications e.g. FSO networks are vulnerable to cyber-attacks at the physical layer. In recent years, the security and privacy issues of FSO communications received growing interest in the presence of an external eavesdropper. Unlike the conventional encryption in the top layer, no secret code is needed in physical layer security for long FSO communications. Authors in Boluda-Ruiz et al. (2019b) analyzed secrecy outage probability (SOP) of FSO schemes taking into account an external eavesdropper with a generic orientation at the physical layer. A new framework focusing on misalignment error and corresponding approximate and asymptotic solutions for the non-orthogonal light beams at the eavesdropper receiver is proposed. External eavesdropping causes the larger beam waist compared to the receiver size due to the pulse spreading of optical beam through the wireless link. An extensive analysis of FSO physical layer security for multiple input single output (MISO), MIMO systems, and cooperative systems are reported in Lei et al. (2016) and Van Nguyen et al. (2018) respectively. The state-of-the-art of physical layer security is still immature for FSO communications. The SOP analysis over the Malaga turbulence channels without accounting pointing errors is pointed out in Lopez-Martinez et al. (2015). The impact of channel impairments on physical layer security for mixed RF/FSO relay architectures is clearly presented in Lei et al. (2018b). The average secrecy capacity (ASC) analysis under active eavesdropping for mixed RF/FSO relay networks based on decode-and-forward (DF) is studied in Lei et al. (2018a) and Pan et al. (2019). The performance of ASC is examined over Malaga turbulence for zero boresight misalignment errors without considering eavesdropper location in Saber and Sadough (2017). It is important to investigate nonzero boresight pointing errors distributions in the FSO channels including eavesdropper's location and orientation in order to realize realistic scenarios on secrecy performance.

9.11. Software Defined Networking (SDN) control

SDN can effectively control and manage the hybrid optical networks through SDN controller under dense deployment (Kobo et al., 2017). However, several OWC applications based on network demand such as traffic re-routing, network flaw management, and security issues can be handled by the first application layer in SDN system (Cox et al., 2017). On the other hand, updating the flow control, network selection mechanism along with other essential control can be performed in the control layer (Haque and Abu-Ghazaleh, 2016). SDN technology can be incorporated into the FSO system for the purpose of minimization of energy consumption through data traffic control. The approach of real time applications and virtualizing of network function in SDN systems can be the emerging research issue.

Extending the optical spectrum beyond the UV band allows the advantages from high power and lower cost light sources (Ghassemlooy et al., 2015) which is another research issue. The RF-enabled indoor positioning systems are greatly affected by multipath fading and penetration loss (Lin et al., 2017). Both indoor and outdoor positioning with greater accuracy using free space optics can be one of the potential research issues.

In order to guarantee data loss reduction, selection of optimal transmitter among multiple nodes, and delay minimization, the seamless steering of transferred information become an eminent challenging problem. The optical wireless system is usually designed for downlink communications purposes because of some challenges in the uplink direction such as energy constraint of portable devices and the limitations of narrow beam controlling for mobile devices. Hence, uplink transmission is an open research issue that needs to be addressed. A few research works have been conducted on RF/optical hybrid wireless from the perspective of physical layer whereas barely focus on datalink level metrics (Hammouda et al., 2018a). The QoS analysis tool of cross layer design between physical and data link layer is an important research zone.

9.12. Machine learning enabled FSO systems

The integration of machine learning/deep learning approaches into the design and optimization of future FSO networks is an emerging dimension of intelligent signal processing and operation by eliminating complex numerical models. DL driven FSO systems provide intelligent communication architectures while tackling a range of concerns, for instance, channel modeling, channel prediction and estimation, constellation shaping, optimize the modulation and coding schemes, privacy and security analysis, and so on (Esmail et al., 2021). In addition, machine learning schemes are used in some other applications such as optical SNR measuring, chromatic dispersion assessing, signals demodulation, decoding, and end-to-end system modeling (Musumeci et al., 2019; Darwesh and Kopeika, 2020). The study of turbulence compensation method using deep learning techniques to mitigate the distorted vortex beam and OAM multiplexing performance is conducted in Amirabadi et al. (2020). An experiment of estimating received signal strength of FSO link over a maritime scenario contemplating machine learning approach is presented in Lionis et al. (2021). However, measuring the signal impairments (e.g., pointing error, amplified spontaneous emission noise, distortion correction, etc.), real-time FSO link performance, and signal format classifications involved in FSO systems using ML is not mature yet (see Table 9).

10. Summary and lessons learned

With the proliferation of diversified multimedia applications, RF systems are not capable to fulfill the unprecedented demand by IoT, 5G, and beyond communication systems. Various wireless access technologies have a variety range of appealing features with some limitations. It is widely known that RF and optical wireless technologies (e.g. FSO) perform reciprocal characteristics. FSO technology can be deployed in broader aspects ranging from healthcare, industry to space communications to underwater communications. An extensive comparison of different optical wireless technologies is carried out at the beginning of this article to pointing out the key difference of FSO technology compared to other OWC schemes. Thereafter, the wide range of FSO applications in different perspectives such as space communications, cyber security, solution of last mile problems, and core networks are clearly described.

FSO deployment is much cheaper than traditional fiber connectivity because of no licensing fees above 300 GHz frequency band. Some additional features such as extremely high SINR, easy installation, ease of compatibility with the existing infrastructure, least operation and maintenance cost, immune from health hazards, less energy consumption, ultra-low latency, and so on makes the FSO systems more lucrative for practical implementation. FSO transmitter emits a much narrower laser beam with higher intensity compared to other OWC technologies which downsize the antenna size remarkably to achieve the same transmission gain. As a consequence, the increased level of directivity is less suffered by pointing induced fading. However, FSO home networking establishes a bridge for geographically separated premises to connect end users wirelessly instead of physical connectivity (e.g., fiber to the home service), thereby, it provides an efficient solution to the bottlenecks of the last mile problem. FSO technology achieves high throughput and exhibit more robust performance compared to other non-LOS links.

However, the reliability issue of FSO communications is degraded due to some limiting factors such as fog, heavy rain, dense snowfall, thick cloud, pointing errors, scintillation effect, and atmospheric molecular absorption. Beam dispersion, light radiation, shadow effect, uneven temperature distribution, variation of wind velocity, scintillation, atmospheric pressure discrepancy, jitter, etc. are the limiting factors that deteriorate the system performance in terms of outage probability, BER, and ergodic capacity. FSO backhaul capacity enhancement is a challenging task while handling the tremendous growth of traffic volumes. A beam divergence effect due to diffraction of light causes signal loss at the receiving end and results in high BER. However, a narrow laser beam with receive diversity techniques could be employed to address the beam wandering issue. Note that a tight narrow beam propagation with a confined divergence incurs link loss, thus, pointing, acquisition, tracking (PAT) mechanism is essential to mitigate such aspect.

The goals of FSO systems are different, and numerous approaches have been proposed to address reliability issues. In addition to PAT technique, some other mitigation schemes are thoroughly discussed, for example, receive tempo-spatial diversity policies, aperture averaging for minimizing received signal fluctuations, advanced optics for optimum narrow beam transmission, relay aided cooperative FSO communications to maintain huge diversity gain and eliminates weak signals at the receiver terminal. Moreover, adaptive modulation and coding scheme based on the channel state information, integration of spatial filters for background noise reduction, the impact of coherent FSO benefits, and subcarrier multiplexing FSO for enhancing spectral efficiency are critically analyzed. Thereafter, different hybrid FSO systems are extensively demonstrated to overcome the limitations of a single technology and to guarantee better system performances in terms of link-reliability enhancement, energy-efficient operations, seamless wireless connectivity in remote distances, interference minimization, reduction of phase induced noise, multi-access interference, phase induced noise, multi-access interference (MAI), and multipath fading, and multipath fading, etc. Furthermore, the prospect of multi-user FSO, massive MIMO FSO, and WiFi-FSO technologies for future generation access communications and applications are comprehensively covered with graphical illustration.

A number of research works have been performed to address several technical issues, however, some issues remain. For the successful deployment of FSO systems, several issues have been counted as paramount research concerns, including interference mitigation, automatic error correction, throughput enhancement, energy efficiency for 5G, B5G, and IoT applications. Under the research roadmap, machine-learning/deep-learning based FSO networking is an emerging field for massive IoT solutions and beyond 5G communications particularly in the core backbone sector. The design of FSO based THz and quantum communications provide the concrete solution for the data transmissions in non-LOS (NLOS) applications. The integration of WDM techniques with FSO technology pushes toward a new dimension by expanding the capacity of FSO links under different scenarios such as terrestrial, point coverage, cellular coverage, LOS, transmission range, fixed or mobile relay structure. The addition of software defined networking into FSO systems minimizes energy consumption through huge data traffic control. But the approach of real time applications and virtualizing of network functioning is a challenging task. However, the cross layer design between physical and data link layer, and physical layer security based on FSO communications are another new attribute of the research zone. In addition, the efficient FSO system design issues including adaptive switching mechanism in underwater optical wireless

Table 9
Summary of FSO channel capacity and link design.

Reference	Modulation	Link model	Ergodic capacity	Outage probability	BER/SER	Throughput
Islam and Majumder (2019b)	OCDMA-WDM, PPM	Non fading	No	No	Yes	Yes
Islam and Majumder (2019a)	OCDMA-WDM, PPM	Gamma–Gamma	No	No	Yes	Yes
Islam and Majumder (2015)	OOK	Non fading	No	No	Yes	Yes
Tang and Brandt-Pearce (2014)	OFDMA OOK	Rayleigh	No	No	No	Yes
Rakia et al. (2015)	M-QAM	Gamma–Gamma, Nakagami-m	No	Yes	No	Yes
Makki et al. (2016)	IM/DD BPSK	Gamma–Gamma, log-normal	No	Yes	No	Yes
Najafi et al. (2017)	OOK	Gamma–Gamma	No	No	No	Yes
Salhab et al. (2016)	BPSK	Gamma–Gamma, Rayleigh	Yes	Yes	No	Yes
El-Malek et al. (2016)	BPSK	Gamma–Gamma, Nakagami-m	Yes	Yes	No	No
Ansari et al. (2013)	DBPSK, CBPSK, CBFSK	Gamma–Gamma, Rayleigh	Yes	Yes	Yes	No
Zhang et al. (2015)	OOK	Rayleigh, Nakagami-m	No	Yes	Yes	No
Usman et al. (2014)	QAM	Log-normal	Yes	Yes	Yes	No
Balti et al. (2018)	SIM-BPSK	Malaga	Yes	Yes	Yes	No
Jamali et al. (2016)	OOK	Rician	No	No	No	Yes
Trinh et al. (2017)	M-QAM, M-PSK	Rician, Malaga	Yes	Yes	Yes	Yes
Yang et al. (2015b)	BPSK	Rayleigh	No	Yes	Yes	Yes
El-Malek et al. (2017)	IM/DD, BPSK	Gamma–Gamma, Nakagami-m	No	Yes	No	No
Bag et al. (2018)	OOK	Gamma–Gamma, Rayleigh	Yes	Yes	Yes	No
Shakir (2018)	BPSK, QPSK, 8-PSK	Gamma–Gamma	No	Yes	Yes	No
Amirabadi and Vakili (2019b)	DPSK	Gamma–Gamma	No	Yes	Yes	No
Petkovic et al. (2015)	DBPSK, SIM BPSK	Rayleigh	No	Yes	Yes	No
Soleimani-Nasab and Uysal (2016)	DBPSK, CBPSK, CBFSK	Gamma–Gamma, Nakagami-m	No	Yes	Yes	No
Wu et al. (2017)	OOK	Nakagami-m	No	Yes	No	No
Chen et al. (2016b)	BPSK	Gamma–Gamma	No	Yes	Yes	No
Al-Eryani et al. (2018b)	BPSK	Gamma–Gamma	Yes	Yes	Yes	No
Arezumand et al. (2017)	SIM (CBFSK, CBPSK, DBPSK)	Nakagami-m	No	Yes	Yes	No
Touati et al. (2016)	OOK	Gamma–Gamma	No	Yes	Yes	No
Varshney and Jagannatham (2017)	OSTBC	Nakagami-m	No	Yes	No	No
Palliyembil et al. (2018)	IM/DD BPSK	Nakagami-m, Malaga	Yes	Yes	Yes	No
Odeyemi et al. (2020)	IM/DD BPSK	Gamma–Gamma, Rayleigh	No	Yes	No	Yes
Varshney et al. (2018)	BPSK, DBPSK, BFSK	Gamma–Gamma	No	Yes	Yes	No
Lei et al. (2020a)	IM/DD BPSK	Nakagami-m, Malaga	No	No	Yes	Yes
Lei et al. (2020b)	OOK, BPSK, QPSK, M-QAM	Generalized Gamma, Nakagami-m	No	Yes	Yes	Yes
Tsai et al. (2020)	Four-level PAM	Non fading	No	No	Yes	Yes
Li et al. (2019b)	PAM4	Non fading	No	No	Yes	Yes
Xing et al. (2020)	M-PSK	Non fading	No	No	Yes	No
Kong et al. (2015)	M-PSK, DPSK	Gamma–Gamma	No	No	Yes	No
Balti and Guizani (2018)	CBFSK, CBPSK, DBPSK	Generalized Gamma, Nakagami-m	Yes	Yes	Yes	No

Table 10
Comparison of throughput and latency (Chowdhury et al., 2018, 2019).

Technology	Data rate (Gbps)	Latency (ms)	Communication link
Optical fiber	100	<1 ms	E2E
FSO	40	<1 ms	E2E
mmWave	10	<1 ms	E2E
Microwave	1	<1 ms/hop	P2P/P2mP

communications, multi-hop communications based on relay transmission, user association policies for optimal load balancing, horizontal and vertical handover issues in heterogeneous networks issues are also rigorously discussed. In light of existing research works, we focused on the prospect of the future generation FSO networks incorporating deep neural networks, efficient routing algorithms, QoS controlling methods. Tables 9 and 10 discuss the summary of different FSO systems in terms of distinctive performance metrics.

11. Conclusions

Owing to spectrum scarcity of radio-frequency (RF) counterparts, free space optical (FSO) communication has been recognized as a promising option for next generation optical networking that can support tremendous traffic demand initiated from the internet of things/everything (IoT/IoE) devices and modern cellular communication systems. The realization of an unlicensed extremely wide optical band can fulfill the exponential growth of traffic demand and complementarily overcome the RF spectrum shortage in a cost effective way. In this review paper, first we have discussed a brief overview of promising OWC technologies such as VLC, LiFi, OCC, LiDAR, FSO from various viewpoints and thereafter, a comprehensive comparison between FSO and other OWC technologies are steered. An extensive research on the deployment issues of different FSO wireless networks addressing the related challenges is underway. Principle, advantages, limitations, design issues, mitigation techniques, significance, worldwide achievements, state-of-the-art of recent developments, and revolutions free space optical communications are presented. Advancements of hybrid FSO, coherent FSO, FSO link budget, research challenges of FSO infrastructure deployment of different application scenarios such as acoustic underwater communication, 5G and B5G communication, FSO-IoT/IoE interface are also demonstrated in different tabulated form. Provisioning of quality of experience (QoE), massive connectivity, high capacity, tight security, low power consumption are also focused in perspective of the coexistence FSO and RF wireless technology. In summary, this survey discuss key research challenges, addresses the key research aspects, and key opportunities of FSO communication technology emphasizing the further improvement among counterpart networks in the context of wireless communication and IoT paradigms. It can be concluded that FSO is increasingly becoming a prominent technology for future generation communication systems and extending the realm of FSO technology in indoor, healthcare, industry, offices, shopping malls, offices, stadiums, residences, transportation, space, and terrestrial environments. This survey paper provides a valuable resource for a clear understanding of the recent research contribution of optical free space communication in different implications and is anticipated to persuade further effort for the eminent deployment of other OWC systems in the forthcoming years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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