Classification Framework for Free Space Optical Communication Links and Systems

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***Abstract*—*Free Space Optical (FSO)* communication technology, also known as *Optical Wireless Communications (OWC)*, has regained a great interest over the last few years. In some cases, FSO is seen as an alternative to existing technologies, such as radio frequency. In other cases, FSO is considered as a strong candidate to complement and integrate with next-generation technologies, such as 5G wireless networks. Accordingly, FSO technology is being widely deployed in various indoor (e.g., data centers), terrestrial (e.g., mobile networks), space (e.g., inter-satellite and deep space communication), and underwater systems (e.g., underwater sensing). As the application portfolio of FSO technology grows, so does the need for a clear classification for FSO link configurations. Most existing surveys and classifications are single-level classifications, and thus not inclusive enough to accommodate recent and emerging changes and developments of different FSO link configurations and systems. In this paper, we propose a multi-level classification framework to classify existing and future indoor, terrestrial, space, underwater, and heterogenous FSO links and systems using common and simple unified notation. We use the proposed classification to review and summarize major experimental work and systems in the area until 2017. Using the proposed classification and survey, we aim to give researchers a jump-start to tap into the growing and expanding realm of the FSO technology in different environments. The proposed classification can also help organize and systematically present the progress in the research on FSO technology. This makes the identification of the market needs for standards an easier task. Moreover, different entities involved in the standardization process including academic, industry, and regulatory organizations can use the proposed classification as a unified language to communicate during the early stages of standard development which require ambiguity-free discussions and exchange of ideas between different standardization entities. We use the proposed classification to review existing standards and recommendations in the field of FSO. It is also envisioned that the proposed classification can be used as a unified framework to define different FSO channel models for simulation tools.**

***Index Terms*—Classification, Free Space Optical (FSO), Indoor, Optical Wireless Communications (OWC), Space, Survey, Terrestrial, Underwater, Wireless Communications.**

I. Introduction

EMERGING Big Data applications and systems found in disciplines like social media and Internet-of-Things (IoT), are characterized by being bandwidth-intensive and performance-sensitive. The IoT market is expected to grow from 9.1 billion devices and objects connected to the Internet in 2013 to 28.1 billion by 2020 [1], that is more than three times the global population expected by 2020. As such applications and systems rapidly move closer to end users, wireless communication systems, are the favored communication technologies as they allow for user mobility. Moreover, wireless technologies avoid most of the inherent complexity that wired technologies suffer from, such as, long setup time, right of the way for digging, and the sunk cost once the cables are laid [2]. It is expected that two-thirds of total IP traffic by 2020 will be generated by wireless and mobile devices [3].

Figure 1 depicts part of the electromagnetic (EM) spectrum and the frequency (and wavelength) ranges for each band of the spectrum. As the frequency increases, the wavelength and effective area of an antenna decrease. The carrier frequency is selected based on the application. For example, ground-to-submarine communications utilize audio waves due to its very long wavelengths (i.e., very low frequency and very large antenna) and the limited propagation capability of RF signals in electrical conductors such as salt water due to absorption. On the other hand, radio frequencies in the Ultra High Frequency (UHF) and Super High Frequency (SHF) band range are capable of penetrating windows, walls, and ceils. Therefore, the IEEE 802.11b/g/n (WiFi) networks utilize the unlicensed 2.4 GHz UHF and 5 GHz SHF radio bands.

RF is a mature technology and is being widely deployed in many indoor, terrestrial, and space communication systems. However, the propagation nature of the RF communication systems raises a problem of interference, which in turn affects the usability of frequencies, and hence, the capacity. Therefore, the RF spectrum is regulated by the local and international authorities to limit the interference, and guarantee proper operation and coexistence of systems relying on RF. As the applications of RF communication are progressively increasing, the RF spectrum becomes more congested, scarce and thus expensive to acquire. Several efforts are put from research and industry to stretch the capability of existing wireless technologies (e.g., alleviating interference) and to develop new ones to fulfill the emerging needs [4], [5].

Free Space Optical (FSO) communication, also known as *Optical Wireless Communication (OWC)* as discussed later in Section II-A, is being extensively investigated over the last few decades as an attractive alternative technology to RF. Similar to fiber optics, data are used to modulate a light beam in FSO. The light beam then propagates from one point to another, however, in a wireless manner. The recent spike in interest

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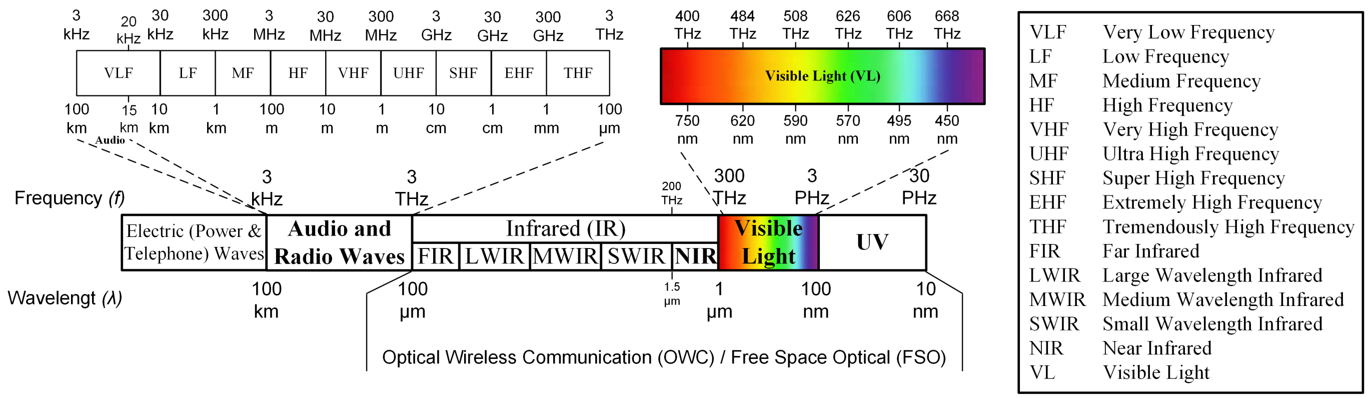

Fig. 1: Part of the electromagnetic (EM) spectrum showing the frequency (and wavelength) ranges for each band.

in FSO technology stems from the fact that FSO combines high-bandwidth of optical communication systems and the flexibility of wireless technologies.

FSO technology operates in a broad spectrum (see Figure 1) including Near Infrared (NIR), Visible Light (VL), and Ultraviolet (UV) bands. Conventionally, terrestrial and space FSO links operate in the NIR band similar to fibre-optic systems [6]. As will be shown in subsequent sections, terrestrial systems can also operate in the VL [7] and UV [8] bands. On the other hand, Indoor FSO links commonly operate in the NIR [9] and VL [10] bands, whereas, underwater OWC systems operate in the NIR [11] and VL [12] bands. The extremely short wavelengths (i.e., high frequencies) at which FSO systems operate make FSO detectors immune to multipath fading (i.e., large fluctuations in received signal magnitude and phase) as opposed to RF links, which are highly susceptible to multipath fading. This can be attributed to the spatial diversity resulting from the fact that FSO detector areas are extremely large compared to the wavelengths [13]. In addition to the unregulated spectrum, most of the optical components used in FSO links are cheaper, smaller, lighter and have lower power consumption as compared to that of RF components leading to cost and energy saving [14]–[18]. Although most of the FSO components are cheaper, lighter, and smaller than that of RF links, one must keep in mind that FSO networking solutions are not as mature and commercially available as their RF counterpart. We believe that this is a main contributor to the fact that FSO commercial solutions can be sometimes more expensive and bulkier especially in the case of terrestrial FSO links [19]. As the technology becomes more popular and with the expected increase in the market competition, the price of FSO solutions is expected to drop. On the other hand, as the technology matures, designer of FSO solutions will be able to develop the best design practices which will influence the size of the modules used in the FSO systems.

FSO technology has also been considered as a complementary technology to existing RF systems since FSO and RFs do not interfere [20]. This property is very important for applications in which interference with RF systems must be avoided such as in hospitals and in personal entertainment systems on commercial aircrafts to mitigate the interference with the RF-sensitive navigation and avionics electronic systems [21]. Moreover, the next generations of wireless communication systems (e.g., 5G) incorporate several complementary access technologies along with the RF technology, including FSO [22], [23].

A preliminary optical communication experiment was among the secondary objectives of the mission Gemini 7 conducted by NASA in 1965 [24]. The experiment was only partially completed due to the cloud obscuration and the spacecraft altitude restrictions [25]. Three years later, Erhard Kube published the original FSO communications white paper "*Information transmission by light beams through the atmosphere*" [26]. In this paper, E. Kube explained the possibility of transmitting data through the atmosphere using green (0.6 μm) and red (0.8 μm) laser sources. Continued development of lasers led to the development of a small and continuous-beam semiconductor light sources that work at room temperature by Zhores Alferov in 1970. This invention opened new horizons for the development of OWC systems. In 1979, Gfeller and Bapst introduced the first indoor OWC system in which the diffuse emissions in the infrared (IR) band were used [27]. The continued research and development by academic institutions, industry and military organizations, enabled the FSO communication to find its place in many applications, such as, mobile networks backhaul [28], [29], space communication [30], underwater (UW) sensing [31], [32], wireless sensor networks (WSNs) [8], indoor local area networks [33], [34], data center networks (DCNs) [9] and many other applications.

A. *Motivation and Contribution*

Advantages of the FSO technology have been known for a long time. However, utilization of these advantages was facilitated by recent development and advances in FSO enabling technologies. As a result, a large number of research papers on new FSO applications has been published recently. Given that most of the FSO technology classification efforts were made in the late 90s, we believe that existing classifications of FSO technologies are outdated [13], [20], [35].

Most of the old classification efforts simply review and differentiate FSO systems without taking into consideration development of new/future FSO links. Therefore, it may be difficult, if not impossible, to fit some of the emerging and future configuration classes into existing *single-level* classification schemes. Accordingly, many survey papers have to introduce additional classes, which makes the overall classification scheme inconsistent and nonsystematic in its expansion. For an example, consider the quasi (multi-spot) diffuse system [36], [37] propagated as a separate class despite its similarities to diffuse systems [13], [21], [38], [39]. Furthermore, a large number of new developments in FSO result in several inconsistencies, and sometimes, contradictions between various classifications and definitions such as in their naming conventions or operational principles. For example, the three notations *LOS/Directed*, *LOS*, and *Point-to-Point* all refer to the same FSO link configuration [13], [20], [21], [35], [38]–[43].

We believe that there is a need for a classification that can express the existing, emerging, and future FSO link configurations and applications in a systematic way. Accordingly, in this paper, we have the following three major objectives.

- Develop a rigorous multi-level classification based on a set of notation that can be systematically used to express various present and emerging FSO link configurations to help reduce ambiguity. To show the effectiveness of the proposed classification, we use it to classify different link configurations listed in various existing classifications. We also use the proposed classification to classify FSO link configurations that could not be classified before. Furthermore, we show how the proposed classification can evolve to include any future FSO link configurations.
- Survey FSO technology applications in different communication environments, namely: *indoor*, *atmospheric*, *space*, *underwater*, and *heterogenous*. To the best of our knowledge, there exists no classification/survey that addresses the variety of the FSO technology applications in all environments. For each environment type, we summarize recent research efforts and provide a list of selected references for applications on each link configuration. We also discuss the typical impairments encountered by each link configuration and possible solutions for these impairments. Finally, we classify and review existing standards and recommendations for FSO technology in each environment.
- Put the proposed classification into action and use it to describe different existing FSO systems. We review *heterogenous FSO systems* in which different types of FSO links are combined to realize an efficient system. We also review *hybrid FSO systems* in which FSO is combined with a different technology (e.g., RF). In addition to classifying FSO systems, we envision that the unified framework presented here can also be used to develop modular and consistent FSO channel models for FSO simulation tools.

It should be noted that the development of FSO in each of the four environments (or a subfield thereof) represents a broad research area in its own right. Thus developing a single comprehensive survey to cover all the developments, impairments, and solutions in detail is infeasible. That being said, in this paper, we aim to give researchers a jump-start to tap into the growing and expanding realm of the FSO technology in different environments. To this end, we present a novel classification scheme for FSO links. To demonstrate the effectiveness of the proposed classification, we bring recent advances in all fields of FSO in a single place saving researchers the time and effort to capture the big picture. Therefore, our contribution is a comprehensive breadth-focused survey and we acknowledge that, focused and dedicated survey papers based on our proposed classification may be needed to cover a particular domain in detail in the future.

To improve the readability of the paper, we summarize in Table I all acronyms and abbreviations used in this article.

B. Paper Organization

The remainder of this paper is organized as follows. In Section II, we discuss the generic FSO link components, including light sources, photodetectors, and modulation schemes. We dedicate Section III to discuss related work. In Section IV, the proposed classification of *FSO link configurations* is presented and various schemes are explained. Sections V - IX demonstrate the use of the proposed classification scheme to classify FSO applications and related standards/recommendations in indoor, terrestrial, space, underwater, and heterogenous environments, respectively. We then use the proposed classification to review different FSO systems in Section X. Research directions and open problems for FSO systems are discussed in Section XI. Summary is given in Section XII.

II. Preliminaries and Basic Concepts

In this section, we discuss preliminaries and basic concepts related to optical wireless communication. We discuss the naming convention of the optical wireless technology since it has been observed that researchers use different names to refer to the optical wireless technology in the literature. We also briefly discuss the preliminaries and basic components of a generic FSO link, such as light sources, photodetectors, and modulation schemes. The details of the components used in optical communication systems and the advances in the research related to these components are, however, beyond the scope of this paper. Interested readers can refer to the papers and books discussing the theory of operation, variations and advancement of different types of light sources and photodetectors [44]–[52]. Discussion on eye safety and existing regulations can be found in [53]–[56]. Moreover, excellent summaries and taxonomy of modulation schemes in OWC are available in [29], [38], [57].

A. Naming Convention - FSO vis-à-vis OWC

Optical wireless and fiber-optic communication systems operate in the same band of the spectrum and have similar transmission bandwidth capabilities, therefore, optical wireless communication is used to be referred to as *fiber-less optics*. As the fiber-less optics technology continued to advance and used in new domains, new names for the technology emerged in the literature, such as; *Lasercom*, *Optical Wireless Communication*

(OWC), and *Free Space Optics (FSO)*. Over the last few decades, the notations "OWC" and "FSO" became widely used whereas "fiber-less optics" and "lasercom" are considered archaic [58].

It has been noticed that the term OWC is used in the literature to refer to indoor and outdoor fiber-less optical systems, whereas, the term FSO is mostly used to refer to outdoor fiber-less optical systems. In a recent classification and survey [17], Kaushal and Kaddoum use the notation OWC to refer to the fiber-less optics technology. The authors then classify OWC technology into Indoor Systems and Outdoor Systems (FSO). The FSO system is further classified into Terrestrial Links and Space Links. The use of FSO to refer to outdoor links is because the technology utilizes an unguided channel in both the terrestrial atmosphere and the vacuum (outer space). However, this is also true for indoor and underwater environments where the fiber-less optical systems are utilizing unguided channels. This led many researchers to refer to the fiber-less optical systems using the notation FSO in indoor [18], [59] and underwater [60]–[62] environments.

Since FSO and OWC refer to the fiber-less communication with unconfined medium disregard the environment in which the link is established, and taking into consideration the fact that both terms have been widely used in the literature, we use both terms interchangeably in this paper to refer to the *fiber-less technology* in *any environment*. It is found that the OWC in the underwater (UW) environment is widely referred to as Underwater Optical Wireless Communication (UOWC). Therefore, for research related to UW OWC, we use the term UOWC to maintain the consistency with the literature.

B. Light Sources

The most commonly used light sources in FSO systems are *Laser Diodes (LDs)* and *Light Emitting Diodes (LEDs)*. LDs are preferred in applications with high data rate requirements due to their high optical power outputs and broader modulation bandwidths. There are, however, standards and power restrictions controlling the usage of the LDs to mitigate potential eye and skin safety hazard [57].

LEDs, on the other hand, are preferred in low/medium data rate indoor applications. This is because LEDs are cheaper than LDs and more reliable. Moreover, LEDs are extended sources with large-area emitters. Therefore, LEDs can be operated safely even at relatively high powers. Compared to LDs, LEDs support lower data rates [41], [63]. However, data rates up to 1 Gpbs using LEDs and rate-adaptive discrete multitone modulation are achieved [64]. In [65], Tsonev et al. present a 3 Gbps FSO link operating in the visible light band using a single 50-μm gallium nitride LED and Orthogonal frequency division multiplexing (OFDM) modulation scheme.

C. Photodetectors

Positive-Intrinsic-Negative (PIN) photodetectors and Avalanche Photodetectors (APDs) are the most commonly used types of photodetectors in FSO systems [13], [57]. PIN photodetectors are preferred in low cost and low data rates

TABLE I: Acronyms and Abbreviations

Acronym	Description
5G	5^{th} Generation of Wireless Communication Systems
APD	Avalanche Photodetector
APT	Acquisition, Pointing and Tracking
AUV	Autonomous Underwater Vehicle
BER	Bit Error Rate
CATV	Cable Television
CC	Cellular Coverage
CRL	Communication Research Laboratory
CSK	Color-Shift Keying
DC	Data Center
DD	Direct Detection
DoD	Department of Defense
E/O	Electrical-to-Optical
EE	Energy Efficiency
EM	Electromagnetic
ESA	European Space Agency
FEC	Forward Error Correction
FOV	Field of View
FSO	Free Space Optical
GEO	Geostationary Earth Orbit
GSFC	NASA's Goddard Space Flight Center
HPF	High Pass Filter
IM	Intensity Modulation
IR	Infrared
IrDA	Infrared Data Association
ISI	Intersymbol Interference
ISL	Inter-satellite Link
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LD	Laser Diode
LED	Light Emitting Diode
LEO	Low Earth Orbit
LOS	Line of Sight
MITLL	Massachusetts Intstitute of Technology-Lincoln Laboratory
MMF	Multimode Fiber
MRR	Modulating Retroreflector
MT	Mobile Terminal
NIR	Near Infrared
NLOS	Non-Line of Sight
NR	Narrow Receiver
NT	Narrow Transmitter
OAM	Orbital Angular Momentum
OOK	On-Off Keying
OW	Optical Wireless
OWC	Optical Wireless Communications
PC	Point Coverage
PD	Photodetector
PIN	Positive Intrinsic Negative
PON	Passive Optical Network
PPM	Pulse Position Modulation
PSD	Power Spectral Density
RF	Radio Frequency
RS	Reed-Solomon
SE	Spectral Efficiency
SNR	Signal to Noise Ratio
ToR	Top-of-Rack
UOWC	Underwater Optical Wireless Communication
UV	Ultraviolet
UW	Underwater
UWSN	Underwater Wireless Sensor Network
VLC	Visible Light Communication
VPPM	Variable Pulse-Position Modulation
WLOS	Wide Line of Sight
WR	Wide Receiver
WSN	Wireless Sensor Network
WT	Wide Transmitter

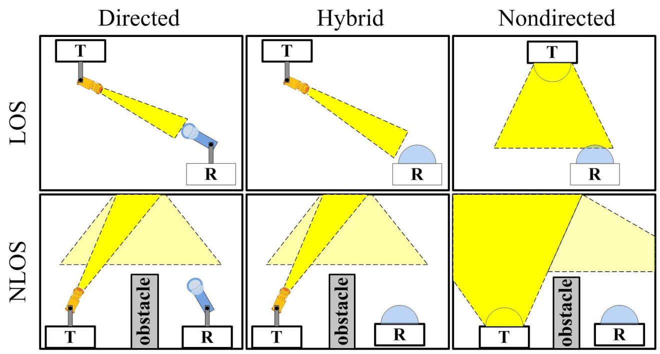

Fig. 2: Classification of Indoor FSO communication links by Kahn and Barry [13].

FSO links. This is because they are cheap, can operate at low-bias, and have tolerance to wide temperature fluctuations [13], [41]. APDs are PIN photodetectors operating at very high reverse bias. This leads to high internal electrical gain that increases the SNR at the receiver [13], [20]. Compared to PIN photodetectors, APDs have superior performance especially in systems with limited ambient light noise. Therefore, APDs are favored in high data rates and high-performance FSO systems. On the other hand, APDs are more expensive and their gain is temperature-dependent. Analysis of different noise sources related to PINs and APDs are discussed in [57].

Recent advances in the field of graphene, two-dimensional materials, and (nano)materials, such as plasmonic nanoparticles, semiconductors, quantum dots have paved the way to the development of ultrafast photodetectors that work over a broad range of wavelengths [66]–[68]. These photodetectors facilitate ultrahigh bandwidth optical communication systems supporting higher data rates.

D. Modulation

Different modulation schemes have different transmission reliability, energy, and spectral efficiencies. A modulation scheme is selected based on the type of the application. For example, the simplicity of On-Off keying (OOK) modulation makes it the most commonly used modulation scheme in FSO systems. However, OOK can be inefficient in more complex systems that require high data rate such as deep space communication. For such applications, Pulse Position Modulation (PPM) or one of its variations, e.g., Variable-PPM (VPM), is usually preferred [32], [57], [69].

Both OOK and PPM are considered as single-carrier pulsed modulation. As the data rate increases, single-carrier modulation schemes become inefficient due to the increased intersymbol interference (ISI) [70]. Moreover, PPM requires complex time-domain equalization which can be problematic for FSO links with severe channel conditions and impairments [38]. In this case, Subcarrier Intensity Modulation (SIM) and Multiple SIM (MSIM) such as Orthogonal Frequency-Division Multiplexing (OFDM) are used. In SIM-based approaches, an optical source is driven by a pre-modulated RF signal carrying the data. A DC bias is added to the signal before it is used to drive the optical source to maintain an all positive amplitude because the input of the LD must be non-negative [71]. Compared to single-carrier modulation schemes, SIM techniques help mitigate channel impairments and provide a simpler and cost-effective implementation [72]. Moreover, SIM improves bandwidth efficiency as compared to that of PPM techniques [73].

The addition of the DC bias (non-information signal) to the pre-modulated RF signal to avoid non-negative amplitudes leads to poor power efficiency. As the number of carriers increase, such as in MSIM techniques, the DC bias required may become very large to prevent clipping and nonlinear distortion in the optical domain. This, in turn, leads to high peak-to-average power ratio (PAPR) and worsens the power efficiency [73]. The nonlinearity of light source is another challenge in MSIM techniques [71], [74]. The nonlinearity at the light source leads to interference among the subcarriers and broadening of the signal spectrum resulting in mixed signals and Inter-Modulation Distortion (IMD). To limit the transmit power and reduce the IMD, MSIM techniques need to employ small number of carriers. However, this limits the transmission data rate. Another approach to eliminate the IMD is to transmit each subcarrier using a separate optical source [75].

To improve the performance of the MSIM techniques, a PAPR reduction technique can be used to make the signal less vulnerable to the nonlinear distortion [76]. Another approach is to have the nonlinearities compensated for by pre-distortion or post-distortion [77], [78]. In [73], Hassan et al. present a detailed survey of SIM techniques. They discuss the advantages and challenges of SIM/MSIM.

III. Existing Classifications and Surveys of FSO Links

We briefly review main classifications of FSO communication technology. FSO technology can be deployed in four different environments: indoor, atmospheric, space, and UW. Out of the four different scenarios, indoor FSO has the largest share of surveys and classifications [13], [20], [21], [35], [38]–[43]. The last few decades have witnessed the development of various FSO communication schemes. Therefore, it is important to develop a classification that accommodates current and future FSO link configurations in different environments.

In [13], Kahn and Barry proposed one of the most popular and widely used classifications of indoor FSO communication systems in the literature to date. Therefore, it is reasonable to present a little-detailed discussion of this classification.

The classification by Kahn and Barry is based on two criteria: the directionality of the transmitter and receiver (i.e., directed, non-directed or hybrid), and whether the link is a line-of-sight (LOS) or non-line-of-sight (NLOS) link. These two criteria result in a total of six different FSO link configurations (see Figure 2).

In directed links, transmitted beam is directional and the receiver has a narrow field of view (FOV). Directed links maximize power efficiency since it experiences low path loss and ambient light noise. However, this comes at the expense of the added complexity of aligning the transmitter and receiver due

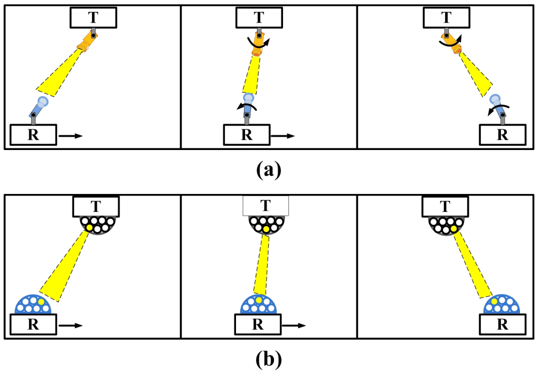

Fig. 3: Tracked systems (a) steerable optics. (b) arrays of emitters and detectors.

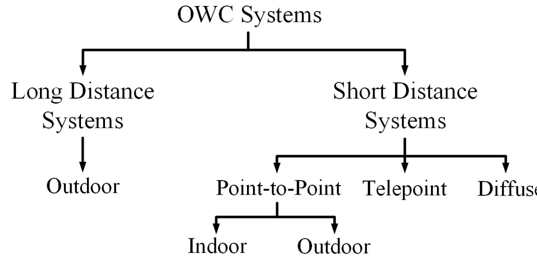

Fig. 4: Classification of OWC systems by Heatley et al. [20].

to their directionality. Contrary to directed links, undirected links utilize wide transmitters and receivers with wide FOV. This rules out the aligning constraint allowing a degree of receiver mobility. However, the performance of the undirected link is reduced due to the distribution of the source power on a large beam spot size. In hybrid links, the transmitter and receiver have a different degree of directionality.

LOS links are realized using an uninterrupted path between the transmitter and receiver. This maximizes the power efficiency and minimizes multipath distortion. On the other hand, NLOS links utilize the reflection of light from *diffusely* reflecting surface such as ceiling or walls, which improves the robustness of the FSO link especially with the existence of barriers. Apart from increasing robustness and ease of use, Nondirected/NLOS link, which is often referred to as a *diffuse* link, allows user's mobility.

During the same year (1997), Street et al. presented a tutorial review of indoor FSO systems [35]. Four different link configurations were used to classify FSO links, namely: LOS, wide-LOS (WLOS or cellular), diffuse and tracked. It might be noted that LOS, cellular and diffuse links are similar to the Directed/LOS, Nondirected/LOS and Nondirected/NLOS links presented by Kahn and Barry in [13], respectively.

In a tracked system, a narrow down-beam (spotlight) from the base station is used to illuminate only a single user station. A base station produces several narrow spotlights simultaneously. Each spotlight establishes a LOS link with one of several user stations, offering high bit rate links to multiple users within the same cell. Moreover, the spotlights produced by the base station are steerable [see Figure 3-(a)], therefore, they can track the mobile user stations as they move around and between cells. Similarly, for a high data rate uplink (from user to base stations), the steerable spotlight at the mobile user station would be required. In addition to supporting high bit rates, tracked systems integrate the high power flux densities and low losses inherent in LOS links with the extended coverage provided by the WLOS (cellular) systems.

In [79], [80], Wisely et al. proposed tracked FSO links in which spotlights are steered using mechanically steerable optics. The authors also discussed realizing solid-state tracking functionality using multi-element transmitter and receiver arrays. Using a tracking algorithm, appropriate array element depending on the position and user station is activated. As the user station moves within the cell, the activated beams would migrate from one PIN to the adjacent one in the array such that the LOS link is maintained [see Figure 3-(b)]. This process continues until the user station becomes again stationary or leaves the cell.

In 1998, Heatley et al. (including Wisely), published a paper which can be considered as the first attempt to present a classification that is not limited to the indoor FSO communication systems [20]. In this classification, FSO systems are classified as *long distance systems* and *short distance systems*.

Long distance systems are outdoor point-to-point links, whereas, short distance systems are further classified into four categories, namely, point-to-point, telepoint (similar to Nondirected/LOS in [13] or cellular in [35]) and diffuse. The point-to-point class includes short distance point-to-point outdoor links, and indoor point-to-point links. Moreover, Heatley et al. discussed the tracking architecture for indoor systems in a separate section, however, they showed no attempt to classify it. We summarize the classification presented by Heatley et al. in Figure 4.

In [29], Khalighi and Uysal classify an FSO link based on its range into five categories, ultra-short, short, medium, long and ultra-long range OWC. The authors focus on long-range links used in outdoor terrestrial OWC links. The paper is divided into two parts. In the first part of the paper, the authors describe the channel model of an FSO terrestrial link. In the second part, the authors discuss information theoretical limits of FSO channels. Moreover, they review system design research to approach these limits.

In [81], Ghassemlooy et al. (including Khalighi and Uysal) extend their previous work [29] and present an overview of FSO applications in the four environments using the link distance as a classification attribute. It is worth pointing that, classifying FSO links merely based on distance overlooks several crucial factors and attributes such as environment properties, LOS/NLOS nature of the link, coverage, and mobility.

The remaining survey papers can be divided into two groups: one group directly refers to one of the three main classifications [16], [40]–[43], the other group [21], [39] uses a subset of previous classifications which best indicate the most practical types of FSO links according to the authors point of view. For example, in [39], Elgala et al. chose Directed/LOS, Nondirected/LOS, and diffuse links from previous classifications and added the quasi diffuse links as a separate,

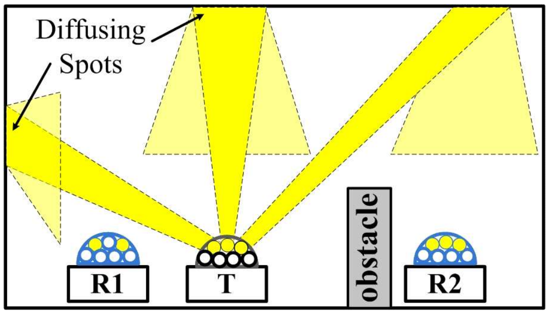

Fig. 5: Quasi (multispot) diffuse FSO links.

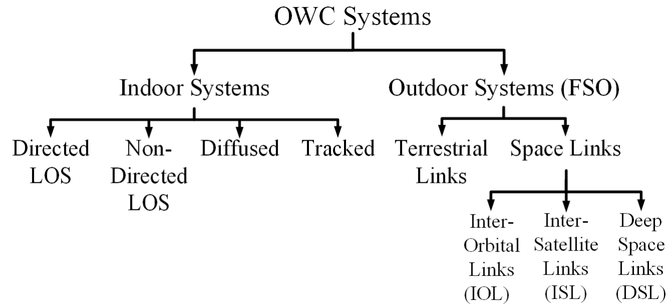

Fig. 6: Classification of OWC systems by Kaushal and Kaddoum [17].

fourth class, whereas, Borah et al. picked point-to-point and diffuse links from previous classifications and added multi-spot diffuse as separate class [21].

In [36], [37], Yun and Kavehard proposed the *quasi (multi-spot) diffuse* indoor optical wireless link. In multi-spot diffusing links, a transmitter sends more than one IR narrow beams to geographically separated diffusing spots. The use of narrow beams in quasi-diffuse FSO links help to reduce the channel power loss as compared to that of indoor diffuse systems, in which the transmitted power is distributed over a single wide beam.

At the receiver, multiple receivers aimed at different diffusing spots can be used. The added redundancy promotes the robustness of the system as compared to a single wide diffusing spot in diffuse systems.

Figure 5 depicts a quasi diffuse link. The transmitter is creating three diffusing spots. Receiver $R1$ is capable of receiving two out of the three diffusely reflected beams, whereas $R2$ can be illuminated by one of the beams. More diffusing spots can be created and their positions can be changed by steering the beams [37].

It might be noted that quasi-diffuse links can be considered as a set of Directed/NLOS communication links, however, the function performed is very similar to the Nondirected/NLOS links. Even though Kahn and Barry have mentioned multi-spot diffusing systems in [13], they showed no attempt at classifying the multi-spot diffusing system using their proposed classification in that paper. Moreover, recent classification attempts result in considering quasi/multi-spot diffuse as a separate class of indoor FSO links [13], [21], [38], [39].

In [82], Johnson et al. present a brief survey and classification of UOWC. Similar to [38], [39], Johnson et al. classify UOWC links into four link configurations, namely; LOS, non-directed LOS, non-LOS, and retro-reflector. More recent and comprehensive surveys on UOWC are presented in [12], [83]. The authors survey the progress in the field of UOWC and present detailed discussions on the impairments of UOWC. However, similar to the work by Johnson et al. in [82], Kaushal et al. [83] and Zeng et al. [12] also use the classification with four configurations; LOS, non-directed LOS, non-LOS, and retro-reflector.

In [17], Kaushal and Kaddoum present a comprehensive survey of FSO in space environment. The authors adopt the classification depicted in Figure 6. In this classification, the notation OWC is used to refer to the optical wireless technology in general. The authors then classify OWC technology into Indoor Systems and Outdoor Systems (FSO). Similar to existing surveys on indoor OWC, Kaushal and Kaddoum use the classification of Street et al. [35]. On the other hand, Kaushal and Kaddoum classify the Outdoor System (FSO) into Terrestrial Links and Space Links (see Figure 6). According to their classification, Space Links include Inter-Orbital, Inter-Satellite, and Deep Space links. It is noted, however, that the classification by Kaushal and Kaddoum completely disregards the classification of OWC in the Underwater environment.

In [84], Chowdhury et al. present a general overview and a comparative survey of OWC-based technologies. The survey, however, adopts the distance-based classification developed by Khalighi and Uysal [29].

Table II summarizes the classifications of FSO communication systems appeared in the literature. We use the notation used in [13] as a reference in the literature summary. A check mark indicates the presence of a certain FSO link configuration in the classification of the referenced paper. We also include the name of the configuration if it is different from that of in [13]. A closer look at Table II reveals the following:

- In [13], Kahn and Barry present an interesting classification, however, we notice the following:
  1) The classification limits NLOS links to diffusely reflected links, and thus Directed/NLOS link configuration is not used by any practical system in the literature. However, as we will discuss later in Section IV, some applications use FSO link configurations similar to the Directed/NLOS FSO links by replacing the diffuse reflecting surfaces, such as walls and ceils, with specularly reflecting surfaces such as mirrors.
  2) Out of the six possible FSO link configuration classes presented based on their classification, only three classes are used to describe configurations reported during the period 1997-2017. Therefore, there is a need for a more inclusive classification that can accommodate existing and emerging classes of FSO link configurations.
- A limited number of surveys show an attempt to classify terrestrial FSO systems in addition to the typical indoor systems. However, most of the existing classifications consider only Directed/LOS link configuration and thus is not sufficient for accommodating other configurations

TABLE II: Summary of OWC/FSO Link Classifications in Literature.

Link Configuration	[13], [40], [41], [43]	[35], [42]	[20]	[38], [39]	[21]	[29]	[12], [82], [83], [85]	[17]
Environment	Indoor	Indoor	Indoor/ Terrestrial	Indoor	Indoor	Terrestrial	Underwater	Indoor/ Terrestrial/ Space
Directed/LOS	✓	✓ LOS	✓ Point-to-Point	✓	✓ Point-to-Point	✓	✓ LOS	✓
Hybrid/LOS	✓	✗	✗	✗	✗	✗	✗	✗
Nondirected/LOS	✓	✓ Wide-LOS or Cellular	✓ Telepoint	✓	✗	✗	✓	✓
Directed/NLOS	✓	✗	✗	✗	✗	✗	✗	✗
Hybrid/NLOS	✓	✗	✗	✗	✗	✗	✗	✗
Nondirected/NLOS (Diffuse)	✓	✓	✓	✓	✓	✗	✓	✓
Additional Classes	✗	Tracked		Quasi/Multi-spot Diffuse		✗	Retro-Reflector	Outdoor (Terrestrial and Space)

that have been recently developed.

- Several existing classifications refer to the same FSO link configuration using different names. This leads to more confusion in the FSO community and hinders the integration of knowledge reported in the various survey and classification papers reported in the literature.
- Most of the classifications reported are developed to simply review and differentiate existing FSO systems without taking into consideration future development of new FSO links. Therefore, it may be difficult, if not impossible, to fit some of the emerging and future configuration classes into existing classification schemes. Accordingly, many survey papers needed to introduce additional separate classes, which makes the overall classification scheme inconsistent and nonsystematic in its expansion.

IV. Proposed Framework for FSO Link Classification

After analyzing various existing classification schemes for OWC link configurations discussed in Section III, we observe that one of the main issues that led to ambiguity in previous classifications is that OWC link configurations are classified based on the nature of their implementation rather than their functionalities. To this end, in this section, we develop and introduce a new function-based (scenario-oriented) classification model for OWC link configurations. The proposed classification abstracts the implementation details of various configurations, such that configurations with different implementation details but perform the same function are combined into a single class. For example, using the proposed classification, it is now possible to combine diffuse and quasi (multi-spot) diffuse systems under the same link configuration since they are similar in function, but different in implementation as pointed earlier.

A. Elements of the Proposed Classification

In our proposed classification, we use five criteria, namely: *Environment*, *Coverage Type*, *LOS Availability*, *Mobility*, and *Link Distance*, in order to classify any OWC link. In the following, we first discuss the five criteria, their variations, and used notation, and then we present the general structure of the proposed classification.

- **Environment** (ε)**:** OWC technology can be used in four different environments, namely: *Indoor (I)*, *Terrestrial (T)*, *Space (S)* and *Underwater (UW)*. An indoor OWC link established in a confined space such as a chip, room or building. On the other hand, *Terrestrial (T)* OWC link is used to refer to OWC links realized in the outdoor environment where atmospheric factors affect the quality of the link. Contrary to Terrestrial OWC link, a Space link refers to the outdoor links that do not experience atmospheric effects such as in outer space inter-satellite communication. Finally, an Underwater OWC link is the link that is realized under any water surface. An FSO link may traverse a *set* of environments in some applications. We refer to this link as a *heterogenous FSO link*.
- **Coverage Type** (κ)**:** An OWC link can be either a *Point Coverage (PC)* or a *Cellular Coverage (CC)* link. In *PC* configuration, an OWC link is established between a single transmitter and a single receiver such that the data transmitted cannot be received except by the intended receiver. A *PC* system usually deploys a narrow transmitter (NT), whereas, the receiver can be either a narrow receiver (NR), or wide receiver (WR). On the other hand, a *CC* link utilizes a wide transmitter (WT) or an array of NTs. This allows multiple receivers (NRs or WRs) to simultaneously receive the beam of the transmitter. WTs spread the transmitted light over a large coverage area, reducing the density of the light per unit area. Using a single NR is not practical since it may not collect enough light, and thus, WR or angle-diversity receiver which utilizes multiple NR elements is preferred.
- **LOS Availability** (α)**:** An OWC link can be achieved using *LOS* or *NLOS* link configuration. In case of LOS, an uninterrupted line between the transmitter and receiver exists. LOS systems do not suffer the negative effects of a multipath. Also, the receiver in a LOS system does not

require a large FOV or a concentrator. Therefore, LOS links are used for higher data rates. NLOS links, on the other hand, are used when a direct view of the transmitter and receiver does not exist or blocked by obstacles. In *NLOS* links, an active repeater or a passive reflector is used to connect the transmitter and the receiver. An active repeater receives a signal from the transmitter and retransmits the signal to the intended receiver. This is similar to relays used in wireless communication to extend the coverage or to boost the performance. On the other hand, a passive reflector can be a *diffuse* surface (e.g., walls, ceils, etc.) or a *specular* surface (e.g., mirrors, beam splitters, etc.). In our classification, we consider links with passive reflectors as the NLOS links. On the other hand, a NLOS system with active repeater is discussed as a relayed system in Section XI since there is a discontinuity in the propagation of the original light beam and a different link budget calculation is used each time the link is regenerated at one of the active repeaters used.

- **Mobility (μ):** An OWC link can be either a *fixed (F)* or *mobile (M)* link. For the *F* links, once installed, both transmitter and receiver remain fixed and aligned. If mobility is required, a mobile link is used, where transmitter and receiver are configured such that the link is maintained at the expense of complexity. Mobility can be realized using mechanically steerable optics or solid-state multi-element transmitter and receiver arrays.
  By mobility, we strictly mean the intended motion of the transmitter/receiver. As we will discuss later, it is possible that FSO links undergo unintentional displacements that may affect the link existence and quality. For example, an FSO link on top of a building can be affected by the continuous sway of the buildings. Another example is a UOWC that may be affected by the unstable hovering of two terminals due to water streams.
- **Link Distance (δ):** For the distance criterion, we adopt the classes proposed by Khalighi et al. [29]. Depending on the environment and the application, OWC links can be one of five different link distances (ranges): Ultra-short range [e.g., chip-to-chip communications], Short range [e.g., underwater communications], Medium range [e.g., indoor wireless local area networks (WLANs)], Long range [e.g., terrestrial connections], and Ultra-long range [e.g., deep space links].

B. The Proposed Classification

Based on the above discussion, an OWC link configuration can be expressed using the tuple $(\varepsilon/\kappa/\alpha/\mu/\delta)$, where:

$\varepsilon \in \mathcal{P}\left(\{\ I, T, S, UW\ \}\right) \setminus \{\emptyset\}$, where $\mathcal{P}(.)$ is the power set.
$\kappa \in \{\ PC, CC\ \}$
$\alpha \in \{\ LOS, NLOS\ \}$
$\mu \in \{\ F, M\ \}$
$\delta \in \{\ UShort, Short, Medium, Long, ULong\ \}$

Combinations of first four criteria are more cohesive than any combination that includes the fifth criterion. Therefore, in our proposed classification, we divide the five criteria into two dimensions (groups). First four criteria form the first dimension, and link distance represents the second dimension.

Any combination of criteria in the first dimension yields an OWC link configuration. A total of 32 different OWC link configurations can be expressed. However, there are clear dependencies and relations among the various criteria in the first dimension. In the following, we highlight these dependencies and discuss various link configurations and their implications.

A *CC* link differs from a *PC* link in that a CC link inherently supports mobility. This is because, in a *CC* link, the transmitter has a large coverage area (cell), and hence, a receiver can be either fixed or mobile within the cell. Since, CC OWC links inherently support mobility, we do not use *F* or *M* in our notation in case of *CC* systems. Therefore, the number of possible OWC link combinations expressed using the first four criteria becomes 24 different configurations.

It is possible that few of these link configurations are not populated with practical OWC systems today, however, the main aim of the proposed classification is to accommodate any new OWC link configuration that can be developed as the OWC technology continues to develop and advance.

In (x/PC/LOS/F) link, transmitter and receiver are connected using a LOS, fixed link forming a point coverage form of communication. This class refer to Directed/LOS [13], LOS [35] and point-to-point [20] in indoor environment, while it is equivalent to long distance systems [29] in atmospheric environment. On the other hand, an (x/PC/LOS/M) is similar to (x/PC/LOS/F) except that the receiver is mobile. This class describes all kinds of tracked systems (i.e., systems based on mechanical steerable or solid multi-element transmitters) [20], [35], [79], [80].

A *NLOS* FSO link can be realized using relayed systems utilizing active repeaters, or a passive reflector that diffusely/specularly reflects light beams. Both, relays and passive reflectors can be used to realize (x/PC/NLOS/F) links since the link does not change once aligned and established. To establish NLOS link with mobility, relay systems can be used such that the uplink and/or the downlink are (x/PC/LOS/M). On the other hand, realizing an (x/PC/LOS/M) link using a specular passive reflector can be very difficult. This is because both transmitter and receiver will need a synchronized motion to maintain the link, which in turn adds to the complexity of the link.

An (x/CC/LOS/x) link is similar to the (x/PC/LOS/F/x) except that the narrow beam used in the (x/PC/LOS/F/x) is replaced with a wide diverging beam. A common configuration used as (x/CC/LOS/x) is a base station with a wide beam forming a *cell*, which is the coverage area of the base station. Any user outside this cell cannot receive the data transmitted by this base station. Depending on the area that must be covered, single or multiple cells can be used, and inter-cell mobility via handover means can be supported. Nondirected/LOS [13], Wide-LOS (cellular) [35] and telepoint [20] refer to the same class (I/CC/LOS).

Unlike specular reflection, NLOS links with mobility can be easily realized using diffuse passive reflectors. In

TABLE III: Proposed classification framework and notation of FSO communication link configurations. Grayed cells indicate infeasible link environment-range combinations. We use No Application (NA) to indicate that an application for the specific environment-range combination has not been reported in the literature yet.

					Link Distance				
					UShort ≤ 5 cm	Short 5 cm - 50 m	Medium 50 m - 500 m	Long 500 m - 500 km	ULong ≥ 500 km
Indoor (I)	Point Coverage (PC)	LOS	F	I / PC / LOS / F	[86]–[89]	[90]–[95]	[33], [34], [96], [97]		
			M	I / PC / LOS / M	NA	NA	[79], [80], [98], [99], [99]–[106]		
		NLOS	F	I / PC / NLOS / F	[107]–[116]	[117]	[118]–[120]		
			M	I / PC / NLOS / M	NA	NA	NA		
	Cellular Coverage (CC)	LOS		I / CC / LOS	NA	[121]	[122], [123]		
		NLOS		I / CC / NLOS	NA	NA	[10], [27], [36], [37], [57], [123]–[126]		
Terrestrial (T)	Point Coverage (PC)	LOS	F	T / PC / LOS / F		NA	NA	[29], [54], [56], [127]–[131]	
			M	T / PC / LOS / M		NA	NA	[132]–[140]	
		NLOS	F	T / PC / NLOS / F		NA	[141]	[141]	
			M	T / PC / NLOS / M		NA	NA	NA	
	Cellular Coverage (CC)	LOS		T / CC / LOS		[7]	[142]	[142]–[145]	
		NLOS		T / CC / NLOS		NA	NA	[8], [146]–[168]	
Space (S)	Point Coverage (PC)	LOS	F	S / PC / LOS / F					NA
			M	S / PC / LOS / M					[169]–[172]
		NLOS	F	S / PC / NLOS / F					NA
			M	S / PC / NLOS / M					[172]
	Cellular Coverage (CC)	LOS		S / CC / LOS					NA
		NLOS		S / CC / NLOS					NA
Underwater (UW)	Point Coverage (PC)	LOS	F	UW / PC / LOS / F	[11]	[173]–[187]	[188]–[193]		
			M	UW / PC / LOS / M	NA	[194]–[197]	NA		
		NLOS	F	UW / PC / NLOS / F	NA	NA	NA		
			M	UW / PC / NLOS / M	NA	NA	NA		
	Cellular Coverage (CC)	LOS		UW / CC / LOS	NA	[198]	[199]		
		NLOS		UW / CC / NLOS	NA	[200]–[202]	[203]		
Heterogenous FSO Links				{S-T} / PC / LOS / F					[30], [58], [204]–[217]
				{S-T} / PC / LOS / M					[58], [206]
				{I-T} / PC / LOS / F		NA	NA	[218]	

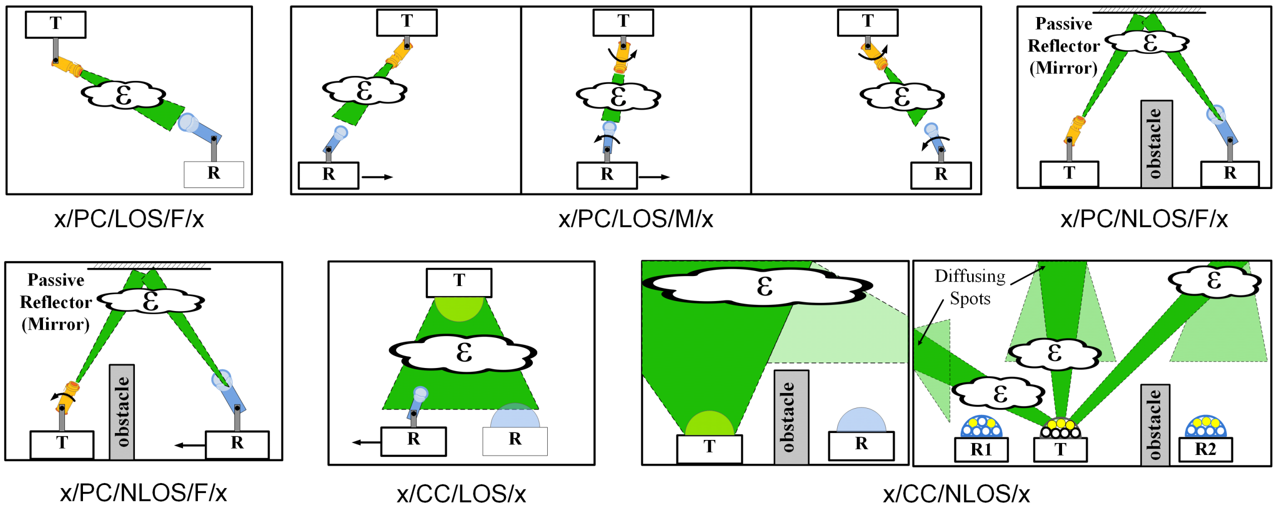

Fig. 7: Different FSO link configurations in the proposed classification. The link configurations are consistent across different environments, and therefore we use the cloud symbol to represent the environment (ϵ).

(x/CC/NLOS) links, wide beams or a set of narrow beams are diffusely reflected off of surrounding surfaces such as the ceiling, walls, floor, and furniture. Receivers deployed have a wide FOV or multiple receivers with narrow FOV in order to capture the reflected beams from the different angles in addition to the LOS (if existed). Compared to previous classifications, the proposed (I/CC/NLOS) link configuration captures both diffuse and quasi-diffuse systems since both of them allow cellular coverage using NLOS links, yet using a different implementation.

Figure 7 shows the different link configurations in our proposed classification. We use the proposed classification in the following five sections to briefly review FSO applications in the different environments (indoor, terrestrial, space, underwater, and any combination of these environments). We also discuss the typical impairments encountered by each link configuration and review related standards and recommendations. We focus on the physical layer of the standards and recommendations since the physical layer is directly related to the classification of different FSO link configurations. Table III summarizes the proposed classification with its 24 FSO link configurations in addition to few examples of heterogenous FSO links and a list of selected references for each. Figure 8 depicts a classification of existing standards and recommendations using the proposed classification.

As mentioned earlier, it is possible that few of the link configurations in the proposed classification may not be populated with practical OWC systems today. One of the possible reasons is that the environment-range combination of an OWC link is infeasible. For example, an ultrashort OWC link can only be realized in an indoor environment, whereas an ultra long link can only be realized in space communication. Infeasible environment-range combinations are grayed out in both Table III and Figure 8.

V. Indoor FSO Links

In this section, we discuss different indoor FSO link configurations and their recent research efforts.

A. *Indoor FSO Link Configurations*

1) I/PC/LOS/F/x: The I/PC/LOS/F/x FSO links deploy highly directional transmitters and receivers with narrow FOVs. The highly directional transmitters help eliminate the multipath dispersion effect and the receivers with narrow FOVs reject the majority of the ambient light. Therefore, I/PC/LOS/F/x links are capable of rejecting the majority of noise, and thus preferred in high data rate applications.

In [86], Rachmani and Arnon investigate the use of I/PC/LOS/F/UShort FSO link for card-to-card communication in a computer backplane. The authors study the impact of temperature and air turbulence caused by cooling air flow on the link. Wavelength-diversity is proposed to mitigate the scintillation and fading caused by the temperature and turbulence. A link using dual-wavelength transmitter (1550 and 670 nm) is deployed. Results indicate that wavelength-diversity can help reduce the link outage caused by temperature and turbulence. Following the work by Rachmani and Arnon multiple recent papers investigated the use of I/PC/LOS/F/UShort FSO links in computer backplanes [87]–[89].

I/PC/LOS/F/Short links have been used in low data rate remote control applications [90]–[92]. In 1998, Matsuda et al. demonstrated an IR multimedia home network based on the IEEE 1394 standard (FireWire) [93].

Since 1993, the Infrared Data Association (IrDA) group, has been using the I/PC/LOS/F/Short link configuration ($\leq 1m$) in its standards for applications that use the concept of point and shoot [94]. The links in IrDA standards provide data rates from 9.6 kbps to 512 Mbps [42], [94], and are mainly used to connect portable devices such as laptops, smart phones, and digital cameras. The details of different IrDA standards are discussed in Section V-C1.

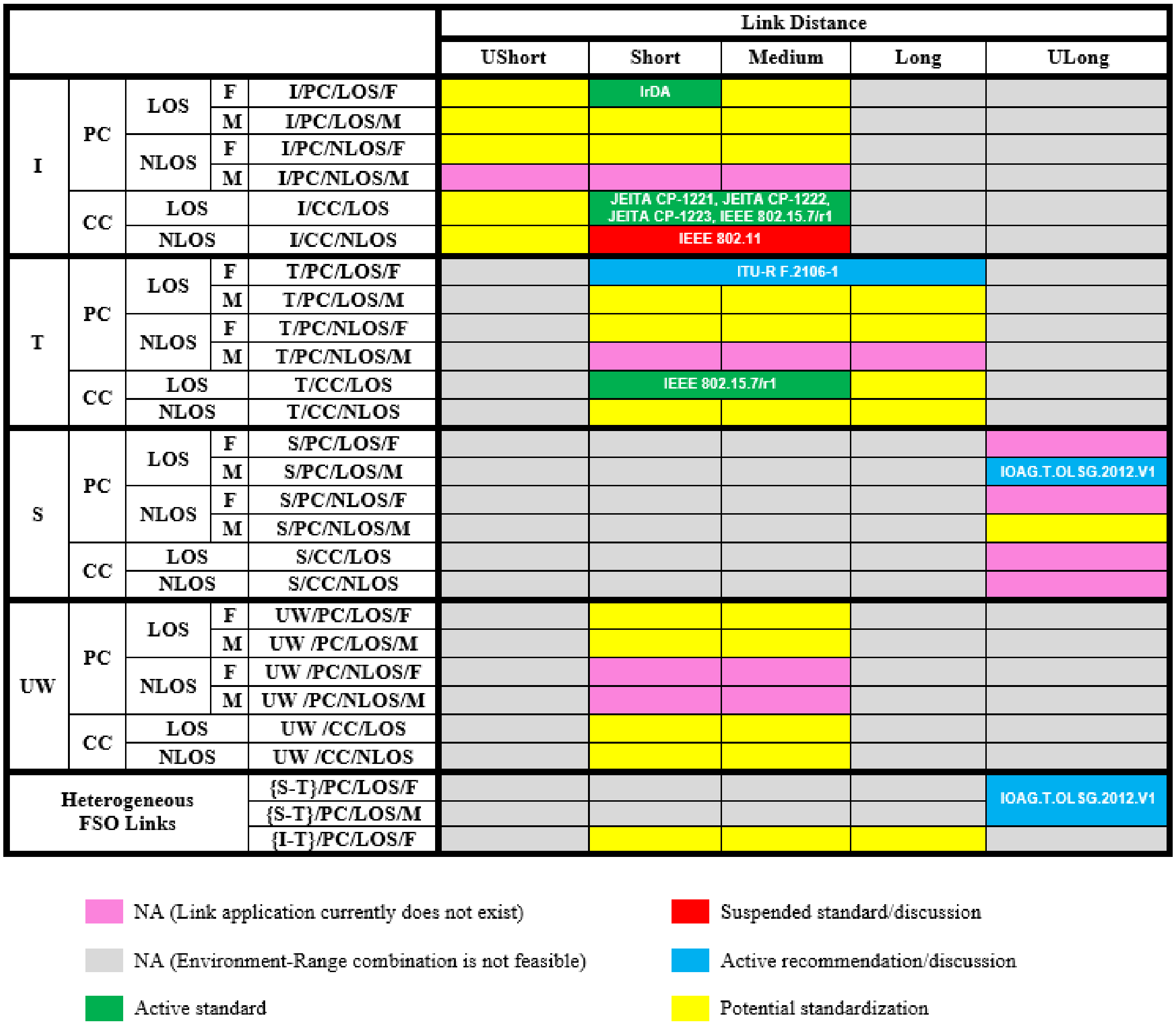

Fig. 8: Classification of existing FSO standards and recommendations using the proposed FSO classification scheme.

In [96], Glushko et al. demonstrate a 1-10 Gbps I/PC/LOS/F/Medium (2-6 m) bidirectional FSO link with bit error rate better than 10^{-9}. The Person Area Network (PAN) system developed by Glushko et al. consists of a central station that serves up to 8 subscribers. On the other hand, Chowdhury et al. demonstrate an experiment involving a I/PC/LOS/F/Medium (15 m) link in the 1550-nm wavelength range directly modulated by the Cable Television (CATV) signal with data rates of 1 and 10 Gbps [33], [34]. In [97], we propose OWCells, a class of optical wireless cellular data center network architectures in which I/PC/LOS/F/Medium links are used to connect racks of servers arranged in regular polygonal topologies.

2) I/PC/LOS/M/x: As pointed our earlier, I/PC/LOS/F/x link is the preferred link configuration for high data rate applications. In some applications, it is desirable to provide a high data rate link for a mobile user. In I/PC/LOS/M/x links, narrow beams are steered to create high data rate FSO links with mobile terminals. The steering can be done using mechanical or passive solid state tracking systems [79], [80], [98], [99], [99]–[106].

Tracked systems presented by McCullagh et al. in [79], [98], and discussed in Section III, can be classified as I/PC/LOS/M/Medium FSO links.

In [103], [104], Jungnickel et al. demonstrated electronic tracking system using I/PC/LOS/M/Short FSO links over a distance of 2 m and data rate of 155 Mbps. A transmitter with an array of LDs and a receiver with an array of wide FOV PDs are used. Tracking is achieved by activating the appropriate receiving element based on the location of the receiver with respect to the transmitter.

Despite the added complexity for tracking and handover, I/PC/LOS/M/x links have many advantages. Using I/PC/LOS/M/x links guarantees point coverage and LOS link, which means that reduced eye-safe power levels can be used for transmission to realize high data rate while covering large areas. Moreover, the use of a narrow FOV receiver means smaller transceiver which is suitable for mobile devices.

It is worth pointing, however, that I/PC/LOS/M/x links are not usually utilized independently. Instead, other FSO links are used for tracking the mobile terminal and pointing the I/PC/LOS/M/x links. We refer to the systems in which multiple FSO link configurations are used together as *Heterogenous FSO Systems* which we discuss in detail in Section .

3) I/PC/NLOS/F/x: This link configuration is widely used in applications where the delivery of point-to-point high bit rates are required between spatially distributed transmitters and receivers. Usually, the connecting terminals are distributed over the same plane, and thus any-to-any LOS links are unfeasible.

In 1988, Feldman et al. proposed the first intra- and inter-chip optical interconnect. The interconnect uses integrated optical signal transmitters, detectors, and a hologram to establish I/PC/NLOS/F/UShort links [107]. The authors presented a power and switching delay comparisons between the FSO interconnect and the conventional electrical interconnects. Results showed that the FSO intra-chip interconnects proposed by the authors are promising in high data rates and/or large fan-outs large area VLSI circuits.

Following the work by Feldman et al., many papers on the topic of intra- and inter-chip FSO interconnects using the I/PC/NLOS/F/UShort link model are published [108], [109], [111]–[113]. In [111], a 3D FSO interconnect (FSOI) that enables all-to-all direct communication links between processor cores with varying topological distances is introduced by Xue et al.

In [114]–[116], [219], we propose a new class of non-blocking multicast FSO interconnect using non-moveable tri-state switching elements (T-SEs). A T-SE is a switching element that can be reconfigured in one of three states (Figure 9): *Reflective*, Transmissive, or *Splitting* state (half reflective/half transmissive). Any material similar to the one used in SMs can be used to realize T-SEs. Using the splitting state, a beam can split into any number of copies enabling multicast using I/PC/NLOS/F/UShort.

An FSO data bus for nanosatellites developed by NASA is proposed in [110]. The system model consists of multiple adjacent transceivers that are normally connected using a wired bus topology. Replacing the wired bus topology with a reflector surface and FSO transceivers to establish I/PC/NLOS/F/UShort FSO links, the authors demonstrate a lighter communication system as well as significant power savings.

In [117], we propose a fully connected FSO rack of servers for FSO Data Center networks using what we refer to as *FSO bus* topology. The full connectivity is realized by steering I/PC/NLOS/F/Short FSO beams emitted by transmitters on one side of the rack, using mirrors, to the other side of the rack where beam splitters are used to distribute the optical beam to different servers.

Using a similar approach to the one used in [111] by Xue et al., however, at a different scale, Hamedazimi et al. develop *FireFly*, a configurable DC using I/PC/NLOS/F/Medium FSO links [118], [119]. In FireFly, the I/PC/NLOS/F/Medium FSO links are used for inter-rack communications, where top-of-rack (ToR) switches are connected using pre-configured FSO links that reflects off a reflector (mirror) mounted to the ceil.

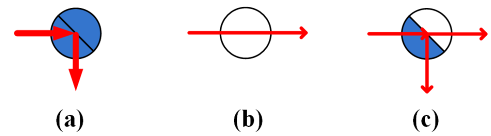

Fig. 9: T-SE (a) R-State. (b) T-State. (c) S-State.

In [120], Bao et al. propose FlyCast FSO DCN. FlyCast is essentially a modification of FireFly using the concept of T-SEs used in our interconnects to provide multicast. In FlyCast, the authors utilize the splitting (referred to as mixed) state of the SMs to enable multicast without the need for a switch.

4) I/CC/LOS/x: The I/CC/LOS/x configuration represents three link types mentioned in the literature, namely; nondirected/LOS [13], Wide-LOS (cellular) [35], and *Telepoint* [20]. This link configuration can be thought of as an I/PC/LOS/F/x link with wide angle transmitter. To realize the wide angle at the transmitter, I/CC/LOS/x links utilize LEDs, or LDs with diffusers. The I/CC/LOS/x link is designed such that the receiver detects the light from the LOS beam. It is possible, however, that the receiver will also collect beams that are reflected from walls which can be negligible as compared to the LOS component of the link [98], [220], [221].

Visible Light Communication (VLC) is a form of OWC in which LEDs are utilized to transmit data. The main OWC link configuration used in VLC is I/CC/LOS/x. VLC represents an emerging mainstream research in its own right and has been well-surveyed in several recent survey papers [23], [123], [222]. VLC has also received great attention and wide range of standardization efforts as we will discuss in detail in Section V-C. Although LEDs are usually used as transmitters in VLC, LEDs are limited in modulation bandwidth and efficiency. Therefore, researchers are investigating VLC systems that deploy LDs instead of LEDs [223].

One of the VLC applications that utilizes I/CC/LOS/Short FSO links is the passengers' entertainment systems in different vehicles such as cars and airplanes. The overhead light units associated with each passenger is used as a BS to transmit/receive entertainment and communication contents. In [121], Tagliaferri and Capsoni present an in-flight VLC I/CC/LOS/Short downlink that can provide each user a 10 Mbps link with uncoded BER of 10^{-6} along with an IR uplink. The downlink proposed takes into consideration the terminal misalignment due to the random movements of the passenger.

I/CC/LOS/Medium FSO links can be found in *Light fidelity (Li-Fi)* networks. Li-Fi is a high-speed bidirectional network in which mobile wireless communications using VLC is implemented. The LEDs in a network are used for illumination and data communication [123].

It should also be noted that VLC links can be deployed in outdoor terrestrial links as will be discuss in Section VI.

5) I/CC/NLOS/x: An I/CC/NLOS/Medium link configuration is realized by diffusely reflecting a single (diffuse) [27] or a set of narrow (quasi-diffuse) light beams [36], [37] off of diffuse reflecting surface, such as, a wall or a ceil. As pointed out in Section III, in diffuse systems, the transmitted light is distributed over a single wide beam spot leading to reduced power and weaker received signal. On the other hand, using multiple narrow beams in quasi-diffuse links can help reduce the channel power loss, and hence the transmitted power. Moreover, quasi-diffuse links enable user mobility by covering the same area the single wide beam in a diffuse link would cover while reducing reflections and multipaths [39]. It is worth pointing that the advantages quasi-diffuse systems provide come at the expense of increased system complexity [39]. Multiple receivers can receive the diffusely reflected beams with different angles and positions. This type of links may appear even when I/CC/LOS/Medium links are used due to unintended reflection off of walls. In this case, each of the two channels will have its own model.

Depending on how the system is designed, it is possible to utilize the I/CC/NLOS links especially in case of shadowing during which an object or a human blocks the LOS link. In that case, it is important for the system to exploit the diffused light in a timely manner [10].

The estimation of the I/CC/NLOS channel has been investigated by Hashemi et al. in [125]. The performance and analysis of the I/CC/NLOS link has been well-investigated [57], [126]. Moreover, I/CC/NLOS can also be used in VLC as discussed by Bao et al. in [123]. On the other hand, an I/CC/NLOS link using multiple light beams that can achieve a data rate of 70 Mbps has been reported by Carruther and Kahn in [124].

Optical Camera Communications (OCC) is another form of OWC in which flash, displays, and image sensor transceivers (or cameras) are used for data transmission, positioning/localization, and message broadcasting. Information is modulated in the pixels of the LED array at the transmitter. At the receiver, an image sensor or a camera captures the images of the LED array of the transmitter. The receiver then analyzes the intensity variation and extracts the transmitted signal [224], [225]. A camera can be operating in one of two modes; global-shutter and rolling-shutter modes [226].

The wide spread of smart devices with embedded LED flash lights and ever developing high quality cameras makes OCC a pragmatic form of OWC communication. Compared to other OWC technologies such as VLC, OCC operates at a wider spectrum that extends from IR to UV and including VL [224], [225]. Unlike conventional OWC link deploying a single PD at the receiver, a camera can be modeled as a 2D array of PDs [227]. The use of an image sensor allows the receiver in an OCC system to separate light signals both spatially and based on their wavelengths. Therefore, OCC system is convenient for spatial-division multiplexing (SDM), imaging Multiple-Input-Multiple-Output (MIMO), and Wavelength Division Multiplexing (WDM) modulation [225], [227].

Similar to I/CC/LOS, MIMO system can be used to improve the performance of the system, however, optical MIMO for I/CC/NLOS links has received little attention [10], [228], [229] and thus, optimizing MIMO performance for I/CC/NLOS channels should be investigated further [10].

B. Impairments of Indoor FSO Links

The most dominant noise source in indoor FSO systems is the shot noise due to ambient light from natural and artificial light sources [13], [57]. Natural light sources are classified as point sources (e.g., the Sun) and extended (e.g., the sky). Artificial Light sources are incandescent (tungsten), fluorescent lamps, and LEDs..

Although, optical filters can be used to minimize received background light, shot noise due to the background noise will still be existent. Shot noise is signal-independent and can be modeled as white Gaussian noise due to its high intensity [13]. On the other hand, in the absence of the ambient light, receiver preamplifier noise becomes the dominant noise source.

Sunlight and skylight represent unmodulated sources that have higher average power as compared to that of the desired signal [13]. In particular, sunlight extends over a broad spectral width with a background current that can reach 5 mA [57]. Artificial ambient light sources, on the other hand, are modulated.

Multipath induced dispersion (distortion) is another impairment for indoor FSO links. In particular, I/CC/NLOS/x in which a beam is allowed to diffusely reflect off of diffusing surfaces such as ceils and walls is the highly susceptible link configuration to the multipath induced dispersion. Multipath induced dispersion depends on the size of the room and the reflection coefficients of the reflecting surfaces. Moreover, the severity of the dispersion depends on the I/CC/NLOS/x implementation. For example, in diffuse (single-spot) I/CC/NLOS/x, the transmitted wide beam can experience multiple reflections. Using a single wide FOV receiver will collect large number of reflections. This, in turn, leads to ISI, and thus, data rate reduction [21]. To overcome the multipath induced dispersion in diffuse systems, quasi-diffuse (multi-spot) I/CC/NLOS/x is used. Although quasi-diffuse links has the same theory of operation as diffuse systems, quasi-diffuse implementation has the advantage of the spatial-diversity which helps limiting the ISI [21]. The use of multiple spots allows for a controlled projection of spots both in numbers and directions. Moreover, since the reflections are narrower, multiple narrow FOV receivers can be used. The narrow FOVs blocks most of the ambient light and rejects large number of undesired reflections. The main challenge of quasi-diffuse implementation is the complexity of the transmitter and the receiver with diversity combining [104]. For example, projecting multiple spots can lead to a complex and bulky transmitter with multiple sources. This can be avoided by using holograms [13], [21].

There are several challenges facing OCC systems. For example, the frame rate of the camera used as a receiver is an important factor to determine the achievable data rate of the system. Since the frame rate of a commercial camera is usually low, around 30 and 60 frames per second (fps), the total achievable data rate in an OCC system is usually low [224]. Using cameras with high fps can help improve the data rate [225], [226]. Such high speed cameras supporting hundreds of fps are already developed [225]. Furthermore, it is expected that the frame rates of commercial cameras will continue to increase as the image sensor nanotechnology continues to

TABLE IV: Indoor FSO Link Impairments.

Impairment	Causes	Effects	Solutions
Ambient light	Sunlight Skylight Incandescent lamps Fluorescent lamps LEDs	Reduced SNR	- High transmitted power - Highly directional links. - Using LEDs out-of-band of the light sources used in the FSO link.
Multipath induced dispersion	Reflection off of diffusing surfaces	-Reduced SNR - Intersymbol Interference (ISI)	- High transmitted power - Multi-spot diffusing - Spatial Diversity - Equalization - FEC

advance. Symbol synchronization is another challenge facing OCC systems. Since OCC is mostly used for broadcasting systems, a feedback channel is not available. With the absence of the feedback channel, the variable sampling rates, and the randomness of the sampling, it is possible to sample during a symbol and thus losing it. To solve the synchronization problem, reference signal or code embedded in the image can be used is most cases [224]. Detailed discussions on the advantages, limitations/challenges, and applications of OCC can be found in [224]–[227].

A summary of indoor FSO impairments, their causes, effects and solutions is tabulated in Table IV

C. Indoor FSO Standards and Recommendations

1) IrDA: Infrared Data Association (IrDA) developed several layer-based standards for low cost half-duplex I/PC/LOS/F/Short FSO links ranging from 6 cm to 1 m and operating at wavelengths of 850-900 nm. Protocols are then implemented on different layers for applications such as contact information exchanges to ultra-fast file transfers. Table V summarizes different IrDA standards and data rates supported.

The next version of Giga-IR standard is expected to support data rate up to 10 Gbps. However, as the data rate increases so do the restrictions on the beam alignment. For example, in case of Giga-IR, a docking station is used which limits the link length to 6 cm.

2) JEITA VLC Standards: The recent development of highly-efficient LEDs, in addition to the inherent advantages of VLC over RF communications are the reasons that motivated academic and industrial communities to investigate the deployment of VLC in a broad spectrum of applications. In response to the advances in the VLC technology and its deployment in many applications, several standardization organizations, such as Japan Electronics and Information Technology Industries Association (JEITA) and IEEE, are developing standards for VLC technology. In the following, we discuss the efforts by JEITA and IEEE to standardize the VLC technology.

In November 2003, the Visible Light Communications Consortium (VLCC) [the predecessor of the Visible Light Communications Association (VLCA)] was established in Japan to explore different applications of VLC. In 2006, members of VLCC proposed the standards, CP-1221 (VLC System), and CP-1222 (Visible Light ID System) [230] to avoid fragmentation and proprietary protocols, and to prevent interference between different optical communication equipments.

TABLE V: Summary of IrDA Standards.

Standard	Data Rates
Serial Infrared (SIR)	2.4-115.2 kbps
Medium Infrared (MIR)	0.576 and 1.152 Mbps
Fast Infrared (FIR)	4 Mbps
Very Fast Infrared (VFIR)	16 Mbps
Ultra Fast Infrared (UFIR)	96 Mbps
Gigabit Infrared (Giga-IR)	512 Mbps and 1.024 Gbps

Light in the range of 380-750 nm is used for communication. Sub-carrier modulation is used instead of single-carrier modulation schemes to avoid ISI. Three major frequency ranges are defined in CP-1221 and CP-1222:

- Range 1 (15 kHz-40 kHz): Communication purposes and used by JEITA Visible Light ID System.
- Range 2 (40 kHz-1 MHz): In this range, the noise radiated from the inverter fluorescent lamp is fairly large, and thus fluorescent lights cannot use this range.
- Range 3 ($>$1 MHz): Dedicated to vast data transmission using special LEDs.

More recommendations regarding the PHY are proposed by JEITA CP-1222. The transmission frame consists of an ID (fixed data) and arbitrary data (non-fixed). It is recommended to use SC frequency of 28.8 kHz and SC-4PPM modulation scheme to avoid flickering. The transmission rate of 4.8 kbps is achieved using cyclic redundancy checks (CRC) for error detection/correction.

In 2013, JEITA proposed the CP-1223 (Visible Light Beacon System) to TC-100 of the International Electrotechnical Commission (IEC) and was approved as IEC 62943 in 2014 [231]. The standard CP-1223, which is a simplified and improved version of CP-1222, is designed to support single directional visible light beacon system. This type of links is particularly useful in applications such as identification of objects, providing positional information for localization, and the establishment of various guiding systems by transmitting simple identification (ID) information unique to the visible light source. Similar to CP-1222, visible light of peak wavelength in the range of 380 nm to 750 nm is used. Visible light is intensity modulated by 4PPM signals at 4.8 kbps. A data frame of 158 bits is used with a start of frame (SOF) and end of frame (EOF) data of 14 and 16 bits, respectively, and payload of 128 bits.

3) IEEE Standards: IEEE has demonstrated early efforts to standardize the FSO technology. However, as mentioned earlier, only recent development in FSO enabling technology has allowed the realization of products and systems that can be efficiently used. In the light of these recent advances, IEEE proceeds with developing new standards for emerging systems. In this section, we will discuss old and recent efforts by IEEE in the domain of standardizing the FSO technology.

IEEE 802.11: In 1997, IEEE released the standard IEEE 802.11 in which two data rates of 1 and 2 Mbps are specified. Transmission is specified to be using IR signals and the 2.4 GHz frequency in the Industrial, Scientific and Medical (ISM) band [95], [232].

The IEEE 802.11 specification was developed for I/CC/NLOS/Medium links (i.e., diffuse link) with a link range of 10 m and transmitting in the range of 850-950 nm [232]. Two modulation schemes, 16 and 4 PPM are used for the two data rates 1 and 2 Mbps, respectively.

Despite the advantages of the communication in the IR band, the drawbacks exhibited by indoor IR communications, discussed in Section V-B, prevented the implementation of the infrared channels of IEEE 802.11. Therefore, IR channels remains a part of the standard IEEE 802.11, but has no actual implementations.

IEEE 802.15.7-2011: In 2011, the *IEEE 802.15.7* standard for VLC was released defining the PHY and medium access control (MAC) layers for {*I,T*}*/CC/LOS/*{*Short,Medium*} links. Three classes of VLC devices are defined in IEEE 802.15.7:

- Infrastructure: Also called coordinator is a stationary device that has unconstrained form factor and power supply.
- Mobile: Movable devices with limited power supply and constrained form factor. Mobile VLC devices use weak light sources, and thus operates at short ranges and can transmit at high data rates.
- Vehicle: Mobile devices with unconstrained form factor and moderate power supply. Employs intense light source to communicate over long distances at low data rates.

The above VLC devices can be arranged in one of three network topologies; star, peer-to-peer, or broadcast.

- Star: Supports communication between several mobile devices and one coordinator.
- Peer-to-peer: Supports communication between two close devices, one of which acts as the coordinator.
- Broadcast: Uni-directional transmission from a coordinator to one or more devices.

The IEEE 802.15.7 standard supports three PHY operation mode [95], [233]:

- PHY I: Low data rate outdoor applications (11.6 to 266.6 kbps). Employs On-Off Keying (OOK) and variable pulse-position modulation (VPPM). Also supports concatenated coding with Reed-Solomon (RS) and convolutional codes.
- PHY II: High data rate outdoor/indoor applications (1.25-96 Mbps). Similar to PHY I, PHY II employs OOK, VPPM and supports RS coding, but does not support convolutional codes.
- PHY III: Designed to support systems with multiple light sources/detectors at different frequencies (colors). Employs Color-Shift Keying (CSK) and Reed-Solomon coding to achieve 12-96 Mbps.

The three physical layers supported by IEEE 802.15.7 are designed to co-exist but not to interoperate [95]. A VLC device compliant with IEEE 802.15.7 must implement PHY I and/or PHY II. Moreover, for co-existence purposes, PHY II must be implemented along with PHY III [95].

IEEE 802.15.7r1: In 2014, the IEEE 802.15 has formed a Short-Range Optical Wireless Communications Task Group to write a revision for IEEE 802.15.7-2011. The aim is to accommodate wider spectrum, IR and near UV in addition to VLC, [234] as well as developing new communication links and modes of operation such as Multiple Input/Multiple Output (MIMO). In particular, the task group works on accommodating the following communication techniques and networks:

- Optical Camera Communications (OCC)
- LED-ID: Wireless light Identification system.
- LiFi: LiFi is a high-speed bidirectional network in which mobile wireless communications using light is implemented.

In [224], Saha et al. present a survey discussing the key technology consideration in IEEE 802.15.7r1, impairments, and enhancements in application scenarios of the OCC systems. A detailed discussion on the reference channel models endorsed by the IEEE 802.15.7r1 Task Group for evaluation of VLC system proposals are discussed by Uysal et al. [235].

VI. Terrestrial FSO Links

Terrestrial FSO link is finding its place in several applications including, metropolitan network extensions, last-mile access, enterprise connectivity, fiber backup, cellular network backhaul, service acceleration and network disaster recovery [218]. It is also expected that FSO links will have a great potential for applications in the fifth generation (5G) wireless systems and beyond [22], [23]. Future wireless networks will be hybrid and will incorporate complementary access technologies with higher channel capacities, multiple antennas, and Gbps data rates [22]. For example, FSO links can be used to carry cellular traffic from base stations to the base station controller [218]. Terrestrial FSO links can also be used in wireless sensor networks where a large number of nodes are distributed over a wide area and need to communicate using NLOS links.

A. Terrestrial FSO Link Configurations

1) T/PC/LOS/F/x: The T/PC/LOS/F/x is the most commonly used configuration to realize a high data rate terrestrial FSO link. The performance of T/PC/LOS/F/x links has been investigated thoroughly in the literature [54], [127]–[131]. In [29], Khalighi and Uysal focus on the modeling and performance of the T/PC/LOS/F/x link configuration. T/PC/LOS/F/x FSO links are now a commercial reality [19] that is deployed in a wide range of applications. A list of 29 companies with T/PC/LOS/F/Long FSO link products can be found in [56].

2) T/PC/LOS/M/x: FSO T/PC/LOS/M/x link configurations are used for applications in which the stringent acquisition, pointing, and tracking requirements need to be relaxed due to the mobility of one (or both) communicating terminal such as in aircraft to ground communication [236]. In [132], Ortiz et al. present an experiment in which an Unmanned-Aerial-Vehicle (UAV), named Altair, is used to collect data and fly in a predefined circle around a ground station. Altair was designed to receive an optical beacon from the ground station, and using tracking systems, it sends the collected data using an T/PC/LOS/M/Long downlink to the ground station. In November 2013, the first experiment of an OWC link using jet platform was performed. A 60 km T/PC/LOS/M/Long link was established between a jet platform (i.e., Tornado) flying at 800 km/h and the ground. Data is transmitted at a rate of 1 Gbps using a ViaLight Communications laser terminal [139], [140].

During the late 1990s, the U.S. Naval Research Laboratory (NRL) started conducting experiments on modulating retroreflector (MRR) FSO communication links. An MRR link provides a mean for limited duplex communication link with an interrogator at one end and a small passive optical retroreflector at the other end. The source housing the interrogator is assumed to have high power. The retroreflector can be corner cube or a cat's eye and is coupled to an optical modulator. The interrogator transmits a continuous wave beam towards the retroreflector which passively reflects the beam back after the optical modulator has imposed a signal on it. Shore-to-shore, boat-to-shore and sky-to-ground MRR FSO links were successfully realized [133], [134], [137], [138], [237]. In [136], Rabinovich et al. establish a 1 km MRR FSO link with a robot at data rate of 1.5 Mbps. A bidirectional 16 km MRR FSO link is established in [135]. One of the most recent experiments in the domain of T/PC/LOS/x/x was performed by Li et al. [237]. In their experiment, Li et al. test a T/PC/LOS/x/Medium link between a ground station that is used as an interrogator and a UAV equipped with a retro-reflector. The distance between the ground station and the UAV is 100 m roundtrip and thus we classify the link as terrestrial (T) and medium range (Medium). Two PC/LOS links are established with the UAV. The first link is established while the UAV is hovering (T/PC/LOS/F/Medium) and the other is with the UAV moving (T/PC/LOS/M/Medium). Using two Orbital Angular Momentum (OAM) multiplexed beams, Li et al. realize 80 Gbps with each beam carrying a 40-Gbps Quadrature Phase Shift Keying (QPSK) signal. As expected, the T/PC/LOS/F/Medium link provides better performance as compared to that of T/PC/LOS/M/Medium in terms of the power fluctuation of the on the desired mode and the crosstalk to the other mode.

3) T/PC/NLOS/F/x: As mentioned earlier, T/PC/LOS/F/x link configuration is used to establish point-to-point high bit rate communication link. However, finding a LOS between two points may become infeasible, especially in urban cities with varying building heights, and thus T/PC/NLOS/F/x link is needed. In [141], Rahman et al. discuss FSONet, an FSO backhaul for multi-gigabit picocells using T/PC/LOS/F/Medium and T/PC/LOS/F/Long steerable links. In FSONet, links are steered using reconfigurable mirrors. This is very similar to the FireFly Data Center Network developed by the same lab.

Due to beam divergence, which can be relatively big for long distance terrestrial links, using passive reflectors (mirrors or walls) may become impractical. Therefore, to establish T/PC/NLOS/F/x links, relay systems utilizing active repeaters with two or more T/PC/LOS/F/x link segments can be used. Such systems will be discussed in detail in Section XI.

4) T/CC/LOS/x: In addition to indoor deployment (discussed in Section V-A4), VLC communication deployment in Intelligent Transportation Systems (ITS) is being investigated [7]. This model aims to utilize the LEDs that are widely deployed for traffic lights, vehicular (head, tail, and brake) lights and street lights as transmitters. Traffic lights and vehicles are equipped with receivers such as high-speed cameras [7] in case of OCC (discussed in Section V-A5) to establish vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) T/CC/LOS/Short OWC links. Traffic safety-related information along with infotainment applications are broadcasted using the LED array at the transmitter and the data captured by receiver's camera interacts with the computers in vehicles to enhance traffic flow and reduce accidents and fatalities.

Data Communications (Data Comm) is an essential module of the Next Generation (NextGen) framework being developed by Federal Aviation Administration (FAA). Data Comm aims to enable the exchange of digital information that can be visually displayed and interpreted between air traffic controllers (ATCs) and pilots. Compared to the conventional audio communication currently used in the aviation field [238], Data Comm messages will require significantly less bandwidth. Moreover, Data Comm is expected to lead to safer operation as it will help improve the visual, auditory, and cognitive workload for controllers and pilots. Moreover, future versions of Data Comm will be designed such that the digital messages exchanged between the ATCs and aircrafts can interact with the computers on-board enforcing rules and safety measures [239], [240].

Delivering Data Comm traffic between ATCs and pilots requires a data communication networking infrastructure. Similar to the application of OWC in vehicular communications, we envision that aircraft-to-aircraft (A2A) and aircraft-to-infrastructure (A2I) can be achieved using T/CC/LOS/{Medium,Long} links serving as the infrastructure for Data Comm [142]. We envision that the airport's infrastructure of lights and signages along the taxiways and runways for Data Comm can be utilized for this purpose. Furthermore, OWC links can be used for aircrafts localization on the airport ground and help raise pilots' situational awareness.

High-speed trains (HSTs) traveling at speeds between 250 and 575 km/h are gaining popularity across the world especially in China, France, Germany, Japan, Spain, and potentially the United States [241]. Maintaining a reliable ground-to-train communication link is essential for delivering the signaling traffic of the train operation control system which is the system responsible for the safety of the high-speed railway (HSR) [241]. In addition to the train operation control system, there is an increasing demand by users aboard HSTs for high data rate internet access [143]. However, providing high data rate access to users aboard HSTs is another application that is testing the boundaries of RF-based communication systems. RF-based communication networks are not capable of meeting the high data rate demand on HSTs due to several technology limitations such as Doppler frequency shifts, penetration losses, and the frequent handovers.

Initially, a dedicated narrow-band Global System for Mobile communications for railway (GSM-R) network was realized. GSM-R, however, utilizes the same frequency band used by the public land GSM network [241]. This poses a risk on the safety of the HSR's operation due to the potential co-channel interference [241]. Moreover, GSM-R network is incapable of meeting the demands for the high data rate [242]–[245]. To overcome the challenges facing GSM-R, the broadband Long Term Evolution for Railways (LTE-R) was developed to achieve high capacity, low latency, and high reliability [242]–[245]. LTE-R networks features fast synchronization, channel estimation and equalization, Doppler shift estimation and correction, and MIMO technique. LTE-R, however, experiences frequent handovers which may lead to interrupted transmission of critical train control signals as well as call drops and spotty internet access [241], [246]. In addition to GSM-R and LTE-R, IEEE 802.11p and IEEE 802.15.4p are also being utilized for ground-to-train communication links [241].

Despite the recent advances in RF-based technologies for HST systems, the data rates RF-based technologies provide is limited and does not meet the increasing demands by HSTs and their passengers [247], [248]. This makes HST an application in which the FSO technology can be utilized [18]. In [143]–[145], the authors utilize T/CC/LOS/Long links to create overlapping coverage cells along the railroad of HSTs such that an HST travels within the coverage area of the FSO beam eliminating the need for tracking systems. FSO transceivers mounted on top of the trains and directed towards the source of the FSO beams along the railroad are used to maintain a permanent communication link with handovers performed in the overlapping regions of adjacent base stations (BSs).

5) T/CC/NLOS/x: PC/LOS FSO communication links are usually preferred to achieve high data rate communication links between two points. This is notably true in the terrestrial environment due to the atmospheric impairments that can limit the performance of the FSO link. However, contrary to what was widely believed, FSO in the atmospheric scenario does not require PC/LOS setup for operation [249].

The solar radiation in the deep UV spectral region (i.e., 200-280 nm) is absorbed and scattered by ozone in the upper atmosphere (about 40 km away from the Earth's surface). This means that FSO links transmitting in this region do not encounter background noise, and thus this band is referred to as *solar-blind ultraviolet* [146].

Although the scattering of light by particles and aerosols is considered an impairment for most of the FSO links as it degrades the link quality, the unique propagation attributes of the solar blind ultraviolet wavelengths, such as being strongly scattered by particles and aerosols, facilitate the realization of T/CC/NLOS/Long FSO links. This type of communication is referred to as *optical scattering communication (OSC)* which can be very useful when a LOS link between the transmitter and the receiver is infeasible. In OSC, a transmitter emits a light beam with preselected divergence and elevation angels forming a cone. A receiver with large FOV pointing towards the formed cone of transmitted beam detects the scattered light from the atmosphere. To collect more backscattered optic power from the transmitter, receivers with large FOVs are needed. A possible application for OSC is to establish T/CC/NLOS/Long links between nodes in energy-constrained distributed WSNs [250].

In 1970, Lerner and Holland [251], and Kennedy [252] analyzed the characteristics of atmospheric optical scattering channel laying the foundation for OSC. In [253], Reilly proposes the single scattering model and investigates the pulse broadening effect of T/CC/NLOS/Long OSC. In [250], Shaw et al. develop a simulation model to analyze the performance of the T/CC/NLOS/Long UV link and compare it to conventional RF links.

The last two decades have witnessed an upsurge of research on T/CC/NLOS/Long OSC [8], [146]–[168]. Modeling T/CC/NLOS/x OSC channel is more challenging than modeling traditional LOS links [149]. Therefore, most of the research in OSC is directed towards the modeling of OSC channels assuming single-scatter [165], [167], [254], multiple scattering [154], [157], [158] which is essential when the transmitter's beam axis and the receiver's FOV axis are not coplanar, and most recently, considering the inhomogeneity of the atmosphere to achieve a more accurate model [168]. Other researchers focus on deploying new modulation schemes to improve the performance and the bit rate of the link such as M-ary Spectral-Amplitude-Coding [162], and frequency-shift keying modulation scheme [166]. As a result of the evident interest in the OSC systems, recent survey papers [16], [255]–[257] summarize and survey major experimental and modeling research on OSC.

B. Impairments of Terrestrial FSO Links

The exposure of the terrestrial FSO links to the turbulence caused by atmospheric variations can lead to severe link performance degradation. Several publications have discussed the impairments of terrestrial FSO links in detail [17], [29], [54], [258], therefore, in this subsection, we only briefly discuss the different impairments, causes, and mitigation techniques.

A terrestrial FSO link can be affected by sunlight, beam misalignment due to building sway, attenuation (due to fog, rain, and snow) and atmospheric turbulence [218]. Fog, rain, snow, dust, or any various combination of them can lead to absorption, refraction, and scattering resulting in signal attenuation and link performance degradation [22], [54]. Atmospheric turbulence can be caused by scintillation, beam wanders and beam spreading. Atmospheric scintillation is the spatiotemporal change of light intensities at the receiver due to variations of air index of refraction.

There is a wide range of atmospheric turbulence impairment techniques that can be applied at the physical layer, such as; aperture averaging, adaptive optics, diversity, relay transmission, and hybrid systems. Other recent approaches explore

TABLE VI: Terrestrial FSO Link Impairments.

Impairment	Causes	Effects	Solutions
Ambient Light	Sunlight	Reduced SNR	- Increase transmitted power - Highly directional links
Swaying Buildings	Winds and seismic activity	Loss of signal	- Beam diverging - Active tracking - Spatial diversity
Attenuation	Fog, rain, snow, dust or a combination of them.	Absorption, refraction and scattering	- Increase transmitted power. - Diversity. - Efficient modulation
Atmospheric Turbulence	Refractive index variations	Beam wandering and heat dependency.	- Adaptive optics. - Aperture averaging - Temporal and spatial diversity - Relay transmission - Hybrid Links - Reconfiguration and re-routing

atmospheric turbulence mitigation at higher layers including retransmission and Reconfiguration and re-routing [17].

Aperture averaging relies on the idea that more light can be collected by a receiver with wider aperture and thus, it is possible to average out relatively fast fluctuations. However, increasing the aperture of the receiver has its limitations in terms the available real-state. Similar to RF wireless communication, space, spatial, and temporal diversity techniques can improve the link availability and help mitigate atmospheric impairments. In adaptive optics, the conjugate of atmospheric turbulence that is estimated to impact the beam to be transmitted is added before the transmission. Relay transmission is another form of spatial diversity in which the transmitters are distributed over a network instead of being co-located at the sending node location. This can help utilize links that are not undergoing the same impairments as the direct link between the source and destination nodes. Another approach to mitigate atmospheric turbulence is to switch to a technology that is not affected with such impairment (e.g., RF). Such a system is referred to as hybrid FSO/x system and we discuss it in detail in Section X-B. Since RF is the most mature wireless technology in the terrestrial setting, FSO/RF hybrid systems are usually used. To overcome atmospheric turbulence, retransmission of data can also be used. In this approach, protocols that guarantees reliable delivery of messages, such as; automatic repeat request (ARQ), go-back-N ARQ, and selective repeat ARQ (SR-ARQ) are used. In case of FSO networks, reconfiguration and rerouting of the path that a signal takes can be very useful to avoid links that are affected by severe atmospheric turbulence. This approach is also useful for avoiding node failures and building robust and fault-tolerant networks.

A possible approach to overcome the atmospheric scintillation is to operate at a higher wavelength (e.g., 2000-2200 nm) [259]. However, the development of optical components operating in this range are not as widely commercially available since this range is unsuitable for fiber optic technology which is more mature than the FSO technology. Recent attention, however, has been directed towards this band due to its advantages when used in FSO technology. Currently, sources operating in this range are available using Fabry-Perot and Discrete Mode Fabry-Perot (DFB) technologies [260].

Recent advances in the domain of Quantum Cascaded Laser (QCL) [261] have enabled the development of FSO links operating in the infrared ranges (2.5-10 μm). Nevertheless, most of these links are experimental [262] with an exception of a very few commercial products [263]. In [264], [265], a survey of recent advances in the domain of QCL and its use in the development of FSO systems.

Although most terrestrial FSO links may be affected by the same impairments, link distance, day, and time during the day may influence the severity of the impairment. For example, an FSO link is affected by the sunlight which induces a shot noise at the receiver reducing the SNR. This impact is the highest during the sunrise and dawn when the Sun is co-linear with the FSO link (also called solar conjunction) [54], [266], [267].

The sway of tall buildings due to wind or seismic activity can result in a link misalignment which in turn causes a reduction of received power. The effect of building sway and deviation can be compensated for by diverging the transmitted beam so that it covers a large area around the receiver and hence the beam is received. However, this technique results in a lower SNR as the beam power is distributed over a larger beam spot size. On the other hand, for high capacity, long range links APT systems can be used to compensate for the effect of building sway [22], [218].

The major limitation of OSC is the intensity attenuation due to the scattering of the transmitted beam. Since the performance of an OSC link is dependant on the geometry of the transmitter and receiver beams [268], one of the approaches to improve the received intensity in OSC is to apply beam shaping techniques using freeform lens. In [268], Zou et al. investigate the use of elliptical and rectangular beam reshaping instead of the conventional cone-geometry. It is found that both shapes can significantly improve the received signal with different degrees depending on the Tx-Rx angle pair.

Table VI tabulates different impairments of terrestrial FSO links, causes, effects and solutions.

C. Terrestrial FSO Standards and Recommendations

The standards by IrDA, IEEE (802.11 and 802.15.7), and JEITA are mainly designed to address indoor OWC links. On the other hand, the International Telecommunication Union (ITU) is interested in standards and recommendations related to terrestrial OWC links. In particular, the ITU has released the Recommendations ITU-R P.1814-0 [266], ITU-R P.1817-1 [267], and ITU-R F.2106-1 [259]. Recommendations ITU-R P.1814-0 and ITU-R P.1817-1 are related to the propagation prediction methods for planning terrestrial FSO links operating in VL and IR regions of the spectrum, whereas ITU-R F.2106-1 is more focused on the planning of fixed service terrestrial FSO link.

1) ITU-R P.1814-0 and ITU-R P.1817-1: In [266], the power budget of generic LOS FSO link and the means of calculating the terms forming the power budget equation. The recommendation emphasizes the importance of the location selection taking into consideration different factors such as the weather conditions, physical obstructions, surface type along the path, and the transceiver mounting arrangements. Several sections are dedicated to discuss different weather factors that must be taken into consideration as the FSO link is planned. One of the factors to be considered while calculating the FSO link margin is the impact of the solar conjunction which occurs when the Sun is parallel to the optical link and the Sun projects high power inside the receiver that can override the transmitted signal of the link. To avoid this effect, the FSO link transceivers must be arranged such that the sun is always off-axis. Due to the significant importance of the weather impact and impairments on the terrestrial FSO links, the ITU discusses different weather factors in the Recommendation ITU-R P.1814-0 and also dedicates the Recommendation ITU-R P.1817-1 to discuss different weather impairments in detail.

2) ITU-R P.1817-1: Recommendation ITU-R P.1817-1 provides a comprehensive discussion regarding the methods for predicting the propagation parameters required for planning FSO links. First, basic definitions and causes of atmospheric impairments such as; frequency selective absorption, scattering, and scintillation are explained and discussed. These basics are then followed by the a detailed discussion including equations, parameters, and variables of different factors that must be taken into consideration during the design of an FSO link such as; Molecular absorption and scattering, aerosol absorption and scattering, scintillation, rain attenuation, snow (wet and dry) attenuation, and ambient light effect. The recommendation also discusses the visibility measurement at the maximum intensity of the solar spectrum (i.e., around 550 nm).

Appendix 1 of the Recommendation ITU-R P.1817-1 lists available computer modeling programs that can be used to determine the atmospheric transmission coefficient useful for the planning of the terrestrial FSO links such as LOWTRAN from ONTAR [269] which contains models of optical signal attenuation by aerosols.

3) ITU-R F.2106-1: In [259], the ITU recommendation sector released the report number F.2106-1 (2010) in which recommendations related to the fixed service applications using FSO T/PC/LOS/F/x links are discussed. Link ranges can vary from a few tens of meters to several kilometers depending on the equipment used and other factors such as weather conditions; clear-sky propagation, the effect of fog, rain, snow attenuation, ambient light attenuation, and scintillation.

Laser diodes (LD) are used with transmission power in the order of 10 mW. Wavelengths in the 1300-1500 nm and 780-800 nm ranges are used for FSO applications. These ranges are selected due to their small atmospheric absorption and the commercial availability of the corresponding devices from the optical fiber technology.

The wavelength range 2000-2200 nm that is part of the Short-wavelength Infrared (SWIR) band is another convenient FSO transmission window due to the minimal aerosol scattering and molecule absorption as well as the reduced sensitivity to optical beam bending caused by atmosphere temperature variation [259]. Unlike the 1300-1500 nm and 780-800 nm bands, transceivers in this range were not widely and commercially available at the time this recommendation was released. This can be attributed to the fact that the enabling technology used in FSO was mainly adopted from the mature optical fiber technology [270]. Therefore, researchers were inclined to use off-the-shelf and readily available components used in fiber optics. Due to the limitations of the 2000-2200 nm band in fiber optics technology with respect to fiber absorption, optical components operating in this band were not widely used. However, as discussed in Section VI-B, recent advances in the enabling technologies have allowed the development of FSO transceivers operating in the SWIR (2000-2200 nm), as well as MIR [270] and LWIR [271] using the QCL technology.

VII. Space FSO Links

FSO is an attractive alternative to RF inter-satellite-link (ISL) including intra- (e.g., LEO-LEO) and inter-orbit (e.g., LEO-GEO) links. In addition to the wide bandwidth and high data rate an FSO system can provide, FSO systems have lower antenna weight and size especially in the absence of atmospheric effects in space. Most of the space FSO links are of the type S/PC/x/x/ULong with link distances ranging from 15,000 to 85,000 km [206].

A. Space FSO Link Configurations

1) S/PC/LOS/M/x: An example of an S/PC/LOS/M/ULong ISL link is the Semiconductor Inter-satellite Link Experiment (SILEX) conducted by the European Space Agency (ESA) [169]. The development phase of an FSO system for an in-orbit demonstration started in 1991. In 1998, an Optical link between two geostationary (GEO-GEO) satellites was established at 50 Mbps [170]. Moreover, since 2003, SILEX system has routinely used a 50 Mbps LEO-GEO S/PC/LOS/M/ULong link twice a day [170].

Another example is the project Laser Communication Terminal on Terra-SAR-X (LCTSX) conducted by Tesat-Spacecom with funding support from the German Space Agency (DLR) [172]. In this experiment, a LEO-LEO coherent optical inter-satellite link with data rate up to 5.65 Gbps was demonstrated.

2) S/PC/NLOS/M: A good candidate for this FSO link configuration is the deep-space communication. Instead of transmitting the data using a direct link that goes from the probe to the ground station, a link can be relayed from the deep space probes to the ground station through data relay

TABLE VII: Space FSO Link Impairments.

Impairment	Causes	Effects	Solutions
Ambient Light	- Sunlight - Sunlight reflection from planetary surfaces. - Integrated starlight. - Zodical light.	Reduced SNR	- Increasing transmitted power. - Using optical filters.
Link Misalignment	- Narrow beams - Moving terminals - Terminals disorientation.	Link loss	- Automatic tracking system - Using optical filters.

satellite system using FSO links. This allows the systems to exploit the low mass, power consumption and volume of the FSO systems as compared to that of RF technology which is the dominant technology [205], [272].

B. Impairments of Space FSO Links

Compared to the terrestrial scenario, space FSO links experience lower noise and impairments (Table VII). However, the space links are still susceptible to shot noise due to ambient light interference. There are several sources of external light such as the sunlight, sunlight reflected off of planetary surfaces, integrated starlight, and zodiacal light.

As mentioned earlier, ISL distances can vary from 15,000 km in case of LEO-LEO links to 85,000 km in case of GEO-MEO links [206]. The ultra long range of the links is another critical impairment for ISL FSO links. This is because the longer the range, the higher the transmission power, size, mass, and cost. Moreover, alignment of the transmit and receive antennas must be maintained within 1μrad despite the vibration and the continuous movement of satellites and probes [273]. To this end, tracking servo loop must be used at both ends of the FSO link for laser beam *Acquisition, Pointing, and Tracking (APT)*. Control loops maintain the alignment using optical beacons using a dedicated laser beam or using the communication signal. In [17], Kaushal and Kaddoum present a detailed discussion of the challenges and mitigation techniques for OWC in space.

C. Space FSO Standards and Recommendations

1) IOAG.T.OLSG.2012.V1A: An Optical Link Study Group (OLSG) was established by the Interagency Operations Advisory Group-14 (IOAG-14) to assess the viability of a cross support in the FSO space communication domain. Various mission scenarios, including, Low Earth Orbit (LEO), Moon, Lagrange, Mars Space-to-Earth, and Earth relay, are defined and analyzed taking into account the effect of weather (clouds, optical turbulence, and other atmospherics) and aviation interference using 1550 nm and 1064 nm wavelengths. The aim is to determine the requirements for the ground terminal solution that maximizes the data return for the mission. However, since the number of ground stations required can be a substantial cost burden for a single agency, OLSG recommended the cross support among agencies.

The highest priority for standards development was given to the standards for core services under development, core services that will lead to significant benefits (operational and/or financial), and for capabilities or services that were planned to be committed to flight operations or tracking networks starting September 2015.

VIII. Underwater FSO Links

Propagation of mechanical waves in the acoustic frequency band experiences less absorption in the underwater environment compared to other frequencies on the spectrum [274]. Consequently, acoustic technology became the dominant communication technology for UW communication systems. Underwater acoustic (UWA) can be used to realize long-range communication links. Recent research efforts aim to improve UWA communication links [275]–[278]. Despite recent advances, UWA links can experience significant latency due to the slow speed of sound in water (approximately 1500 m/s) [279]. Moreover, the propagation of UWA experiences multipath fading that leads to long delay spreads (10-100 ms). The delay spread, in turn, leads to significant ISI and thus UWA links have very limited data rates (less than 100 Mbps).

The need for higher data rates has pushed the researchers to consider other technologies for underwater communication. Although it seems reasonable to turn to RF communications given its maturity and advances in the terrestrial and space applications, RF propagation in the UW environment is severely limited compared to that in air and space due to the opacity of water with respect to electromagnetic radiation. The most popular example of UW RF communication link is the link used to communicate with naval submarines. In this system, the link operates in the extremely low frequency (ELF) band (30-300 Hz). Using RF in the ELF range makes it possible for the signal to penetrate the water. However, this system has a very limited functionality as the data rate is very low that it cannot modulate voice, moreover, it requires extremely high transmission power and large antenna that cannot be installed on a submarine for a full-duplex operation. Therefore, such system is usually used to transmit basic messages from terrestrial bases to submarines. On the other hand, for a submarine to establish a reliable terrestrial RF communication link, the submarine must surface to use frequencies in the High Frequency (HF), Very High Frequency (VHF), or UHF bands.

There has been, however, a pressing need for even higher data rate UW communication links to fulfill the performance requirements by emerging applications such as UW wireless sensor network (UWSN). In UWSN, a network of distributed sensor nodes that can perform real-time spatiotemporal sampling and monitoring of climate change, biological, and ecological processes. The huge amount of data sampled and stored by the distributed nodes are then collected using unmanned UW vehicles [280], [281]. Data acquisition by the unmanned vehicles must be fast beyond the capabilities of acoustic and RF communication technologies.

On the other hand, the visible spectrum is less affected by the opacity of the water as compared to other EM frequencies. Moreover, recent advances in the OWC enabling technologies have triggered the re-evaluation of OWC as a solution for UW applications. This, in turn, led to the development of underwater OWC links at data rates up to 4.8 Gbps [180], [181], [185], [186]. This technology is widely referred to as *Underwater Optical Wireless Communication (UOWC)*. In this section, we discuss existing and recent research efforts in the UOWC domain.

A. Underwater FSO Link Configurations

It is found that, different water bodies have different turbidity levels, and thus different characteristics and impact on the light beam. There are different water bodies with different turbidity level. Therefore, it is crucial to investigate the properties of the water in which an UOWC system is to be deployed. This helps in the selection of the link parameters, including light source wavelength, modulation scheme, transmit power and link configuration. Good overviews of the properties of UOWC channels can be found in [83], [282]–[286].

In the following, we discuss different UOWC link configuration and summarize corresponding experiments. For each experiment, we highlight the type of water used.

1) UW/PC/LOS/F/x: Even though visible spectrum is less affected by the opacity of the water as compared to other EM frequencies, light penetration in the visible band is limited to a few hundreds of meters in clear waters (e.g., deep water) and even less in turbid water. Fixed LOS links can help overcome this limitation by avoiding losses and allowing maximum collection of incident light by the PDs resulting in high data rate transmissions. Therefore, UW/PC/LOS/F/UShort [11], UW/PC/LOS/F/Short [173]–[187], and UW/PC/LOS/F/Medium [188]–[193] are the most common UOWC link configurations.

We chronologically summarize the major UW/PC/LOS/F/x UOWC studies in Table VIII. We summarize the highlight for each study, the type of light source and modulation technique used. We also list the type of water in which the experiment is conducted and the achieved data rate and link length.

2) UW/PC/LOS/M/x: The success of the terrestrial modulating retro-reflectors (MRR) T/PC/LOS/M links have motivated researchers to consider deploying the technology in the UW environment [194]–[197]. As mentioned earlier in Section VI-A2, MRR can help relax the pointing and tracking requirements which is essential for a link with a mobile transmitter and/or receiver. Moreover, MRR helps reduce the payload and power requirements at one of the link ends. This can be utilized in UW applications such as UWSN where SNs are of limited power, or in UW exploration with moving divers to communicate with a submarine.

Similar to all UOWC links, the quality (range and capacity) of an MRR link depends mainly on the type of water in which the link is deployed. In clear water, the link quality depends on the number of photons collected by the detector. To maximize the link range and capacity, relatively finer pointing and tracking is required. On the other hand, in case of turbid water, backscattering is the major limitation of the link quality. In [194] and [195], Mullen et al. present polarization discrimination technique to alleviate the impact of backscatter on UW/PC/LOS/M/Short MRR links. Experimental results show significant reduction in the backscatter component in an MRR channel.

A MEMS-based blue/green Fabry-Perot modulator for MRR link is proposed by Cox et al. [196]. Experiments are performed in a 7.7 meters long water tank. The turbidity of the water is varied by adding Maalox. UW/PC/LOS/M/Short MMR links at 1 Mbps and 500 kbps data rates are achieved at 2.7 and 5 attenuation lengths, respectively. On the other hand, error-free MRR links are realized at 6.5 and 3.8 attenuation lengths for 500 kbps and 1 Mbps, respectively, after deploying Reed Solomon error control code (ECC).

In [197], Rabinovich et al. present a theoretical UOWC MRR link budget in natural waters. The authors also perform experimental tank measurements to verify the theoretical model.

3) UW/CC/LOS/x: As mentioned earlier, to achieve high data rate in UOWC, UW/PC/LOS are preferred. Therefore, less attention has been directed towards UW/CC/LOS as compared to UW/PC/LOS UOWC links.

In [198], Cochenour et al. present an experiment in which a diffuser is used to diffuse the light of a 532 nm LD to establish a UW/CC/LOS/Short link. A 20° full angle beam in 7.72 meters long water tank was realized and impulse response measurement at different modulation frequencies up to 1 GHz are performed. It is found that, in clear waters, the diffuse link requires > 30 dB more optical power than the collimated source to achieve a similar signal level at the receiver. Although, they used a single receiver, the experiment description suggests that other receivers can be deployed in the coverage area of the diffused transmitted beam allowing a cellular coverage link.

In [199], Pontbriand et al. demonstrate one-way broadcasting UW/CC/LOS/Medium UOWC links. Two different receiver configurations are used; large omnidirectional and small with flat window. Multiple experiments are performed in deep clear water (in Bermuda at depths of 1-2 km) and in the shallow turbid water off a dock. For the experiments in Bermuda, only the large receiver arrangement is used. Link distance is varied from 75 m to 200 m. The clarity of the water resulted in a clear channel with high SNR and a 5 Mbps is established despite the background light from bioluminescence and Cerenkov Radiation. Links with data rates ranging from 1 to 4 Mbps are realized during dock tests.

4) UW/CC/NLOS/x: An UW/CC/NLOS/x link can be used to establish a link in the absence of a LOS link due to obstructions, misalignment, or random orientation of the transceivers. In UW/CC/NLOS/x, a transmitter emits a wide beam in the upward direction. As the light reaches the water-air surface, an annular area is illuminated and the light partially bounces off of the water surface. A careful selection of the incidence

TABLE VIII: Summary of Major UW/PC/LOS/F/x UOWC Link Experiments.

Reference	Year	Experiment Highlights	Light Source	Modulation	Data Rate	Link Length (m)
Snow et al. [188]	1992	Lab experiments to measure the spatiotemporal properties of the laser pulses using large freshwater tanks, natural ponds, and coastal seawater.	LD	-	50 Mbps	18
Bales and Chrissotomidis [189]	1995	Two FSO communication links in clear dark waters. The first is between an Autonomous UW vehicle (AUV) and its docking station. The two units are mechanically attached facilitating an aligned (UW/PC/LOS/F) FSO link. The second link is established between two AUVs in the water.	LED (450 nm and 660 nm)	-	10 Mbps	20
Farr et al. [190]	2005	A 91 m link is realized in a 15 m deep pool using mirrors. And a dock experiment that is performed at night to minimize ambient light in slightly turbid water is performed to realize a 10 m vertical link.	LD	-	10 Mbps	100
Hanson and Radic [173]	2008	Error-free UOWC link in a laboratory water pipe with up to 36 dB of extinction.	LD (532 nm)	IM/DD	1 Gbps	2
Doniec et al. [175], [176]	2010	AquaOptical, an UOWC system with three optical communication sub-systems: long-range optical modem (AquaOpticalLong), short-range optical modem (AquaOpticalShort), and a hybrid optical modem (AquaOpticalHybrid).	LED	Discrete Pulse Interval Modulation (DPIM)	1.2 Mbps (pool) 0.6 Mbps (Harbor)	30 7
Simpson et al. [177]	2010	A small, low-cost platform for UWSN is used in a lab experiment in which Maalox is used to vary the turbidity of the water.	LED	RS RZ	5 Mbps	3-7
Gabriel et al. [191]	2012	Realistic Monte Carlo simulator that takes into account the medium, transmitter and receiver characteristics is used to evaluate UOWC link. Results shows that the channel time dispersion is negligible for data rates up to 1 Gbps in most practical cases.	LED	OOK	1 Gbps	31 (deep sea) 18 (clear ocean) 11 (coastal)
Cossu et al. [179]	2013	Three error-free UOWC links were tested. BER is measured over several hours during the day.	LED	16-QAM	6.25 Mbps (Manchester coding) 12.5 Mbps (NRZ 8b/10b) 58 Mbps (Discrete Multitone (DMT))	2.5
Nakamura et al. [180]	2015	A lab experiment that involves an acrylic water tank and tap water.	LD (405 nm)	IM/DD-OFDM	1.45 Gbps	4.8
Oubei et al. [181]	2015	A $1m \times 6cm \times 6cm$ water tank is used. A link of 7m is realized using mirrors. High sensitivity Si APD is used to realize high data rate.	LD (520 nm)	16-QAM-OFDM	2.3 Gbps	7
Ren et al. [184]	2016	Orbital Angular Momentum (OAM) is employed to spatially multiplex optical channels.	LD (520 nm)	-	4 Gbps	
Xu et al. [185]	2016	Orbital Angular Momentum (OAM)	LD (red)	128-QAM-OFDM 32-QAM OFDM	1.324 Gbps (PIN) 4.883 Gbps (APD)	6
Baghdady et al. [186]	2016	Dual-channel parallelism is demonstrated using Orbital Angular Momentum (OAM).	LD (445 nm)	NRZ-OOK	3 Gbps	2.96
Shen et al. [192]	2016	Multiple experiments for video streaming, data transmission, and remote control are performed. The authors use LDs and APDs to achieve a 12 and 10 m links with data rates of 2 and 1.5 Gbps, respectively.	LD (450 nm)	NRZ-OOK	1.5 Gbps	20
Kong et al. [193]	2017	WDM experiment in which RGB LD sources are used for transmission. The RGB sources achieved data rates of 4.17, 4.17 and 1.17 Gbps, respectively.	RGB LDs	32-QAM	9.51 Gbps	10
Lee et al. [11]	2017	The authors present a near-ultraviolet (NUV) phosphorescent white light LD and establish a 15 cm link at data rates up to 1.25 Gbps.	LD (410 nm)	NRZ-OOK	1.25 Gbps	0.15
Al-Halafi et al. [187]	2017	A series of lab experiments to stream a high-quality video using a 5 m link in different water qualities.	LD (520 nm)	PSK and QAM	1.2 Gbps	5

TABLE IX: UOWC Link Impairments.

Impairment	Causes	Effects	Solutions
Ambient Light	The Sun near water surface	Reduced SNR	- Increase transmitted power - Using optical filters
Attenuation	intrinsic absorption and scattering	- Reduced SNR - Intersymbol Interference (ISI)	- Experimentally select appropriate wavelength for minimum absorption. - Higher transmitted power - Spatial Diversity - Equalization - FEC
Scintillation	Water turbulence and temperature variation	NA	NA

angle along with the fact that the refractive index of water is higher than that of air can lead to total internal reflection. A turbulent sea surface forms a challenge for this link model since light can reflect back to the transmitter instead of the intended receivers.

UW/CC/NLOS/x UOWC links can be used for underwater ranging and imaging [200]–[202]. For example, a transmitter can detect the water quality by detecting the backscattered light from its own transmission without the need for a back-channel [201] enabling the transmitter to change its operating parameters such as transmit power, data and code rates.

In [200], Alley et al. propose an UW/CC/NLOS/Short imaging system. In the proposed system, a 7.7 m diameter water tank is used. An LD illuminator (488 nm or 530 nm) is placed close to the target object to eliminate the majority of the forward and backscatter that occurs on the way to the target. Water turbidity is varied from very clear water to most turbid by adding Maalox to the tank. Images from both LDs have high contrast and SNR in case of clear water. As the turbidity increases, the contrast and SNR degrades. In the most turbid water, images based on both LDs maintained the resolution. However, the 530 nm images have better contract and SNR as compared to those of 488 nm. This is because the tank water had a higher attenuation coefficient at 488 nm. Compared to conventional LOS imaging systems, the UW/CC/NLOS imaging system proposed by Alley et al. demonstrated improvements with respect to the SNR.

UW/CC/NLOS/x links can also be used to establish communication between separate transmitters and receivers. In [203], Arnon et al. analyze the use of UW/CC/NLOS/Medium links in the context of UWSNs. In this scenario, the LOS links between a transmitter and a set of distributed WSN nodes are not available.

B. Impairments of UOWC Links

An UOWC link is affected by three main impairments, namely; ambient light, attenuation (due to intrinsic absorption and scattering), and turbulence [29], [287]–[291]. The impairments of UOWC links are summarized in Table IX. Near the surface, sunlight can result in a strong background signal that needs to be filtered [274]. Moreover, the amount of wave action can have significant effects on the performance of the UOWC link.

UW environment imposes some constraints on the used wavelength. For example, it is found that red and IR parts of the spectrum suffer higher light absorption in *clear* water, whereas blue light (400-450 nm) experience minimal absorption. However, this is not necessarily true in all cases since aquatic particles like chlorophyll, algae, or plankton can alter the absorption patterns leading to minimal absorption at different wavelengths. Therefore, experiments must be conducted to determine the optimal wavelength for the given application [292].

A light beam in the UW environment suffers *Attenuation* when it loses its intensity due to intrinsic *absorption* and *scattering* [288]. Attenuation in shallow water can be severe as compared to that of deep clear ocean water. In pure seawater, attenuation is dominated by absorption. Closer to land, scattering dominates the attenuation coefficients due to the organic matters. Scattering is the redirection of incident photons into new directions preventing the forward on-axis transmission. This in turn, reduces the light intensity and leads to reduced SNR and ISI [287].

Similar to atmospheric OWC links, UOWC links require the development of efficient transmission techniques to overcome environmental challenges such as turbidity. Therefore, the physical and data link layers must be equipped with energy-efficient modulations and powerful channel codes [29]. Moreover, localization and beam alignment can be challenging in the UW scenario and require careful design consideration.

From the above discussion, it is obvious that the limitation of the acoustic and FSO technologies does not qualify any of them as an efficient standalone technology. Therefore, and as we will discuss in Section X, FSO, and acoustic communication technologies are usually operated in a complementary (or hybrid) fashion.

C. Underwater FSO Standards and Recommendations

There are no initiatives or standardization efforts related to the FSO technology in the underwater environment, to the best of our knowledge. In 2015, Yeong Jang, the chairman of IEEE 802.15.7r1, presented a discussion with the title: "Current Status of IEEE 802.15.7r1 OWC Standardization" in the "International Conference and Exhibition on Visible Light Communications 2015" [293]. In this discussion, Jang discusses the different aspects of the OWC Technology and different related applications/use cases including; A5-Underwater Communication using image sensor communications and C1-Underwater/Seaside Communication using low-rate PD communications.

IX. Heterogenous FSO Links

An FSO communication link may traverse multiple environments in some applications. In this case, we refer to this optical link as a *heterogenous FSO link*. In a heterogenous FSO link, different segments of the link experience different impairments based on the environment, however, the overall link is affected by all of these impairments. In the following, we discuss few examples of hybrid FSO Links:

A. Inter-Buildings Links ($\{I-T\}/PC/LOS/F/x$)

The transceivers of a terrestrial FSO link connecting two buildings can be mounted either on rooftops or behind windows [218]. There are additional costs to rent or acquire a permit to place links on top of buildings. Moreover, directing received signals on top of the building to the desired floor can be a tedious process. However, the small-sized and light weights of FSO system components as compared to that of equivalent RF technology allows for housing the transceivers in buildings.

In the case of the rooftop, the link is considered purely terrestrial. On the other hand, placing FSO transceivers behind windows means that a small segment of the link is indoor while the main part of the link is terrestrial. Therefore, in addition to the atmospheric impairments, the indoor part of the link may have an impact on the overall link performance. For example, the receiver might be affected by artificial ambient light or losses due to the propagation through the windows.

B. Space-Air/Ground Links ($\{S-T\}/PC/LOS/x/ULong$)

FSO communication links between earth stations and spacecraft or satellites in the space is one of the most popular FSO link configurations. A chronological summary of successful heterogenous (space-ground) FSO demonstrations between 1992 and 2016 is listed in Table X.

Most existing ground-space FSO demonstrations utilize ground-based transceivers. Therefore, a portion of the link must propagate through the atmospheric channel and the designers of the link must take this into consideration [206]. Communication system from low earth orbit (LEO) military satellite to mobile troops using Acquisition, Pointing, and Tracking (APT) systems are discussed in [204].

It might be noted that there are different considerations and design requirements for the uplink (i.e., ground-to-space) as compared to that of in downlink (i.e., space-to-ground). For example, similar to RF systems, a power on a space terminal is limited, whereas, a power on the ground is relatively unlimited. Another example that is more specific to the FSO systems is that in the downlink, a beam starts in a space environment where there are no impairments until the last 30 km where the beam is affected by the terrestrial impairments. On the other hand, in uplink, a beam starts in terrestrial (or atmospheric) environment which affects the beam until it cuts the first 30 km. This distorted beam will cut the longer distance in the space to get to the station [295]. The turbulence and the quality of the wavefront that is propagating in the atmosphere is characterized by the atmospheric coherence length [206]. The atmospheric coherence length depends on several factors, including, aperture area and resolution of the telescope, location, time during the day (nighttime is preferred). Analysis shows that in a space-ground FSO link the satellite (uplink) experiences large atmospheric coherence length whereas ground station receiver (downlink) has smaller atmospheric coherence length and severe phase distortion [206]. The smaller coherence length and severe phase distortion experienced by the downlink beam can lead to large received signal spot size at the focal plane of the ground receiver. To be able to capture most of the signal photons, large surface photodetector must be used. However, using large photodetector limits the electrical bandwidth of the receiver, and thus, the ability to detect high data rate signals. To overcome this problem, adaptive optics or array detectors [17], [206].

Currently, many commercial airlines started to equip their fleets with real-time high-speed Internet access using RF communication systems. Most of these services are provided using ground-based access network. For example, US provider GoGo [207] has built a network of 3G ground stations all across the US, and planes communicate with these stations as they fly over. Although GOGO's system is simple to implements, the system has a very limited bandwidth of 3.1 Mbps per plane. Since most aircrafts have cruise altitude above the cloud layer, it is possible that FSO links from satellites provide high-speed service avoiding severe atmospheric impairments [205]. The legacy L-band technology is slow and relatively expensive. On the other hand, higher-frequency Ku-band (12-18GHz) satellites are relatively economical and more efficient. Lufthansa's FlyNet system [208], for instance, claims download speeds to the aircraft of up to 50 Mbps.

X. Classification of FSO Systems Using the Proposed Framework

In previous five sections, we discuss indoor, terrestrial, space, and underwater FSO links. We also discuss "heterogenous FSO links" in Section IX. In this section, we focus our discussion on two types of FSO systems, namely; *Heterogenous* FSO systems, and *Hybrid FSO/x* Systems.

Before we discuss FSO systems in details, we need to understand the difference between "heterogenous FSO links", "heterogenous FSO systems", and "hybrid FSO systems". We use Figure 10 to understand the difference between heterogenous FSO systems and links.

In heterogenous FSO links, a single FSO link spans multiple environments. For example, in case of Space-Air/Ground FSO links discussed in Section IX-B, a single transmitted FSO beam will propagate through a terrestrial channel, and then propagate through a space channel (or vice versa). In Figure 10, horizontal axis represents the different environments an FSO link can propagate through, whereas the vertical axis shows different configurations of FSO links in the four environments. We can see several examples of heterogenous FSO links that span two environments.

A heterogenous FSO system is a system that operates in a single environment, however, utilizes multiple link configurations to realize a more efficient system that could not be

TABLE X: Summary of Major Space and Heterogenous (Ground-Space) FSO Link Experiments.

Program's Name	Year	Performing Organization(s)	Experiment Summary
Airborne Flight Test System (AFTS)	1980	McDonnell Douglas, and U.S. Department of Defense (DoD).	Laser communication link established between an aircraft and a ground station receiver at data rates of 500 Mbps and 1 Gbps [209].
Relay Mirror Experiment (RME)	1990	Ball Aerospace & Technologies Corp. (led a team of seven government agencies and private firms during the design, fabrication and operation).	A 1.064-micron laser beam emitted from a ground site to a mirror orbiting at 450km altitude, and reflected to a 3-meter ground-based target [210].
Semiconductor Inter-satellite Link Experiment (SILEX)	1991	European Space Agency (ESA).	Started the development phase of an optical communication system for an in-orbit demonstration [169].
Galileo Optical Experiment (GOPEX)	1992	California Institute of Technology Jet Propulsion Laboratory (JPL).	Uplink optical communication to Galileo spacecraft by Earth-based transmitters. A 532 nm laser was used [212].
Advanced Satellite Communications Experiments using ETS-VI	1993	Communications Research Laboratory (CRL).	Space-Ground FSO communication experiment conducted using the satellite ETS-VI. Two different wave lengths were used, 0.83 μm for the downlink and 0.51 μm for the uplink. The transmission rate was 1.024 Mbps [211].
Laser Communication Experiment (LCE)	1995	CRL and JPL	A space-to-earth bi-directional link was established from the GEO ETS-VI and a ground station outside of Tokyo [58], [213].
Semiconductor Inter-satellite Link Experiment (SILEX)	1998	ESA	LEO-LEO and GEO-LEO FSO links were established. 800-850 nm wavelength range, 2 Mbps modulation capability on forward link 50 Mbps data rate on return link [169].
Geosynchronous Lightweight Technology Experiment (GeoLITE)	2001	U.S. DoD	A successful Multi-Gbps link from GEO orbit [213]. GeoLITE mission details are classified [58].
Mars Laser Communication Demonstration	2004	NASA's Goddard Space Flight Center (GSFC), JPL, and Massachusetts Institute of Technology Lincoln Laboratory (MITLL)	The project demonstrated at rates in the order of 1 to 80 Mbps [213]. This proves that FSO can improve NASA's ability to communicate with astronauts and planetary sensors, in the future, at high data rates [171].
European Data Relay System (EDRS)	2008-2014	European Space Agency (ESA)	The first gigabit space FSO communication [294]. An FSO LEO-GEO link was established over a distance of 45,000 km and data rate of 1.8 Gbps [172].
European Data Relay System (EDRS)	2008-2014	European Space Agency (ESA)	The first gigabit space FSO communication [294]. Laser Communication Terminals are used, where each terminal is designed to transmit 1.8 Gbps across 45,000 km, the distance of a LEO-GEO link. Such a terminal was successfully tested during an in-orbit verification using the German radar satellite TerraSAR-X and the American NFIRE satellite [172]. Further system and operational service demonstrations were carried out in 2014. Data from the Sentinel-1A satellite in LEO was transmitted via an optical link to the Alphasat in GEO and then relayed to a ground station using a conventional Ka band downlink. The new system can offer speeds up to 7.2 Gbps in the future.
Lunar Reconnaissance Orbiter (LRO)	2013	NASA	The first one-way laser planetary distance communication demonstrated by NASA to beam an image of the Mona Lisa to the LRO over a 385,000 km FSO link. The Lunar Orbiter Laser Altimeter (LOLA) instrument on the LRO received and reconstructed the image. Reed-Solomon error correction code is used to overcome the atmospheric impairments [214].
Lunar Laser Communications Demonstration (LLCD)	2013-2014	NASA	First two-way space communication by NASA using FSO instead of RF. An error-free uplink at 20 Mbps from an Earth ground station to LADEE in Lunar orbit was demonstrated [215]. For the downlink, LLCD transmitted data on the Lunar Atmosphere and Dust Environment Explorer (LADEE) over a 385,000 km between the Moon and Earth using pulsed laser beam and data rate of 622 Mbps.
Optical PAyload for Lasercomm Science (OPALS)	2014	JPL	NASA transmitted "Hello, World!" high-definition video from the International Space Station (ISS) using FSO on Thursday, June 5. The transmission was at rate of 175-megabit [216], [217].
Laser Communications Relay Demonstration (LCRD)	2016	GSFC, JPL, and MITLL	NASAs first, long-duration FSO mission. The aim of the mission is to mature concepts and technologies for future near-Earth and deep space communication network missions [30]

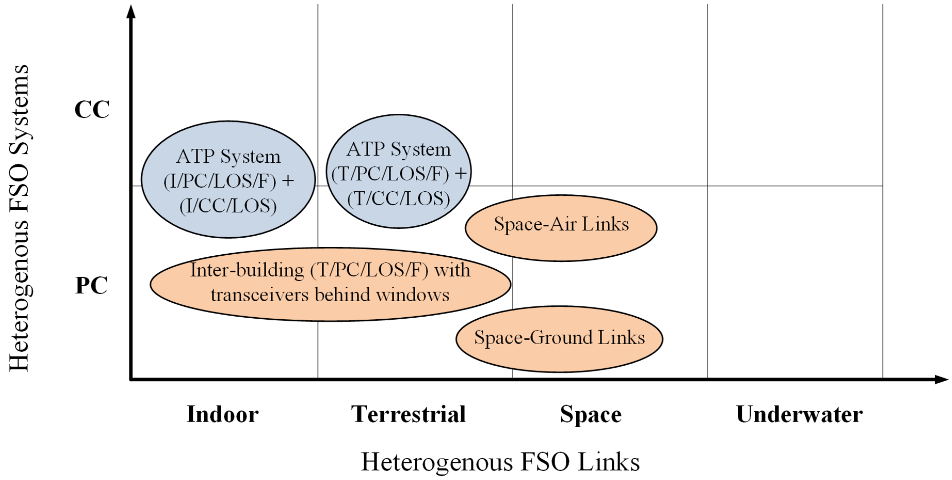

Fig. 10: Difference between heterogenous FSO links and heterogenous FSO systems.

TABLE XI: Classification of Heterogenous and Hybrid FSO Systems Using the Proposed Framework.

Application	FSO System Type	Classification of Links	
		FSO Link	Non-FSO Link
Indoor Tracking Systems	Heterogenous	I/CC/LOS/Short I/PC/LOS/M/Short	-
Outdoor Tracking Systems for HSTs [296]	Heterogenous	T/CC/LOS/Long T/PC/LOS/M/Long	-
Relay-assisted network using UAVs [297]	Heterogenous	T/PC/LOS/F/Long T/PC/LOS/M/Long	-
card-to-card FSO/optical [298]	Hybrid	T/PC/LOS/F/UShort	Fiber
Backhaul RF/FSO Links	Hybrid	T/PC/LOS/Long	RF
Underwater Sensing	Hybrid	UW/CC/LOS/Short	Acoustic
Loon [299]	Hybrid	T/CC/LOS/Long T/PC/LOS/M/Long	RF
Internet.org [300]	Hybrid	T/PC/LOS/M/Long	RF

achieved using only one of the link configurations. Figure 10 depicts an example of a heterogenous FSO system which we will discuss in more details in the next section. As we can see, there is a system that operates entirely in the indoor environment. However, the system utilizes two link configurations; I/PC/LOS/F and I/CC/LOS.

It is important to note that although the environment is consistent, and the link configurations are different, the heterogenous FSO system employs only FSO technology. Unlike heterogenous FSO systems, hybrid FSO/x systems are systems in which FSO is used with another technology (x) together to realize an improved communication system.

Table XI summarizes the examples of the FSO systems to be discussed in this section.

A. *Heterogenous FSO Systems*

As mentioned earlier, x/PC/LOS/F/x FSO links provide high bit rate links for fixed users. If a high bit rate link is to be established for a mobile user x/PC/LOS/M/x links are used. However, establishing and maintaining a PC/LOS link with a mobile user can be challenging. On the other hand, x/CC/LOS/x links utilize wider beams and can cover a wide area which can help to relax the pointing and tracking requirements. However, this usually comes at the cost of reduced bit rate.

One of the most common examples of heterogenous FSO systems is the use of x/PC/LOS/M/x and x/CC/LOS/x together to establish a high bit rate link with a mobile user. This approach is one of the Acquisition, Tracking, and Pointing (ATP) mechanisms used to establish FSO link with mobile users [18]. ATP can be used for indoor, terrestrial, space, and can also be used for heterogenous FSO links.

In [301], Wang et al. have utilized an I/CC/LOS/Short link for user localization and I/PC/LOS/F/Short link for high bit rate with the user. In particular, when a user moves, localization steers the mirror and high bit rate is maintained.

In Section VI-A4, we discuss the application high speed trains (HSTs) in which OWC-enabled BSs along the side of the railway tracks are used to provide the coverage and Internet access for passengers onboard the HST. The BSs are deploying wide beams that cover a long distance of the railway tracks leading to a simple implementation of the system that does not require sophisticated pointing and tracking mechanisms. A different approach to achieve the same objective is to employ ATP to maintain the LOS link between the BSs and the transceivers on the train. In [296], Urabe et al. present an OWC heterogenous system in which I/CC/LOS/Long and

I/PC/LOS/M/Long links are used to achieve 1 Gbps links to HSTs with a handover time in the order of 100 ms.

In [297], Fawaz et al. present relay-assisted network using UAVs equipped with buffers. In the proposed network, in addition to existing regular T/PC/LOS/F/Long relayed links, a UAV that is either stationary or flying between the sender and receiver can be used to establish T/PC/LOS/F/Long or T/PC/LOS/M/Long sender-UAV and UAV-receiver links. The links range from 1.5 and 3 km. The results showed the improvement in the performance with respect to packet delivery.

B. Hybrid FSO Systems

Different communication systems can be integrated together yielding an improved system that utilizes the advantages of both integrated systems. For example, in [302]–[304], Wang et al. incorporate high bandwidth I/PC/LOS/M/Short FSO links with RF system that is mainly used for user localization within the room.

In [298], Wang et al. demonstrate a high-speed reconfigurable card-to-card optical interconnect architecture that utilizes an I/PC/NLOS/F/UShort FSO links along with multimode fiber (MMF). The authors realized 3×10 Gbps optical interconnects despite the air turbulence from the fans cooling the board.

FSO links can be independently deployed in several terrestrial applications including last-mile access and back-haul networks [305]. Combining FSO and RF technologies to realize heterogeneous RF/FSO links can lead to higher-rate and more reliable communication. Single-hop RF/FSO systems consisting of two separate RF and FSO links are widely investigated [306], [307]. In this type of systems, A T/PC/LOS/F/Long FSO link is used for high-bit rate transmission as long as the weather permits, in case of severe weather, RF link acts as a backup. In other cases, both links can operate simultaneously to improve the overall performance of the system and in case of severe weather, the system performance degrades to the lower-bound of single RF link system. Similarly, multi-hop RF/FSO systems are also being investigated [308].

Acoustic communication system dominates the UW communication, therefore, it is possible that acoustic systems are used along with FSO in order to utilize the outreach of the acoustic system, and high bit rate of the optical systems. For example, since acoustic signals are capable of long-range low data rate communication, they can be used in UWSNs for localizing sensor nodes. Moreover, distance between nodes can be accurately determined due to the slow speed of sound which leads to accurate signal timing. Several experiments in the literature demonstrate heterogeneous communication systems where acoustic communication is used side by side to FSO communication systems [309], [310]. Short-range LOS FSO link is usually used for data transfer at high data rates, whereas, the acoustic signal is used for signalling and transmission of short messages. In [311], Vasilescu et al. presented a heterogeneous system with mobility along the transmitters LOS. UW/CC/LOS/Short FSO communication link is realized within a 90° cone with a range of 2-8 m. The acoustic link used for broadcast at lower data rates of 330 kbps and distances over 400 m.

Other examples of hybrid FSO/RF systems are the Loon project by Google [312] and Facebook's Internet.org project [300]. The objective of both projects is to provide Internet connectivity to people having no (or limited) Internet connectivity in unreachable and underdeveloped regions [18]. To this end, High Altitude Platforms (HAP) located 20 km above the earth's surface on the stratosphere are to be used. At this altitude, LOS connections can be established. Moreover, the atmospheric impairments at this altitude are minimal.

In case of Loon project, the HAPs are balloons. The balloons are designed to endure the harsh conditions in the stratosphere [299]. At the stratosphere, winds can blow over 100 km/hr, the balloons are not protected against UV radiation and must endure temperature swings of 150° and temperature going as low as -90° [313]. Balloons are launched using a special launcher capable of launching a balloon every 30 minutes [313]. To control the balloons movement, the altitude of the balloon is controlled to utilize the stratified winds in the stratosphere. As the balloon enters different strata, the balloon will be carried at different speed and direction as desired and designed using specialized algorithms that can navigate the balloons. For the communication purposes, each balloon is equipped with three modules; an LTE module and two FSO modules. The LTE modules is used to communicate with the terrestrial base station that is connected to the internet. The LTE module is also used to connect with and carry the data to/from the mobile users in the unreachable and underdeveloped regions. To relay the data to/from the balloon that is connected to the base station, balloons utilize the FSO modules to communicate with each other. Loon system deploys a heterogenous FSO system in which a wide beacon beam T/CC/LOS/Long along with T/PC/LOS/M/Long are used for the realization of ATP for the moving balloons.

Unlike Loon project, Internet.org project deploys high-altitude solar-powered drones, LEO, and GEO satellites. All terminals are equipped with RF and FSO transceivers. Similar to Loon project, RF modules are used to communicate with the terrestrial base station, and communicate with the mobile users. FSO T/PC/LOS/M/Long links are used for inter-drone links that relays the data between the base stations and the mobile users. LEO and GEO satellite serve the same purpose of covering unreachable regions.

C. Case Study: LiFi-Based Systems

Hybrid FSO system is expected to be the working model of the 5G and next-generation wireless systems since RF is falling short in fulfilling the requirements of such next-generation networks alone. LiFi is a network that is based on VLC communication. LiFi offers dual-functionality to transmit data using optical sources (illumination concurrent with data communication) [122].

In [314], Ayyash et al. present general characteristics of heterogeneous (LiFi + WiFi) network and develop a framework in which LiFi and WiFi technologies coexist. The network consists RF macrocells, RF small cells (RF-SCs), and optical small cells (O-SCs). The system discussed in [314] is a *hybrid FSO/RF* system. Each of the LiFi luminaires (lights) is an *I/CC/LOS/Short* link model. It may be noted that *I/PC/LOS/F/Medium* FSO links can be used to form the backhaul network and connect different BSs in a large room instead of wires. A network of nodes equipped with the LiFi receivers can be supported by this network which makes this network very suitable for the IoT model.

XI. Research Directions and Open Problems for OWC systems

We discussed different OWC link configurations and systems throughout this paper. As we discuss the applications for the OWC links and systems, we pointed out future directions of research related to each OWC subdomain, system, and application. From previous sections, we can see that researchers are continuously finding new applications for OWC technology. This continuous expansion of OWC technology application portfolio makes the task of predicting the future of OWC technology challenging. In this section, we will shed the light on a few of the future OWC technology research directions and applications.

A. OWC and the Internet of Things (IoT)

To realize the IoT vision, in which 34 billion things (people, devices, and objects) will be connected to the Internet by 2020, different types of networks forming the infrastructure of the IoT paradigm must evolve to accommodate the data volume and transmission speed requirements. Moreover, the emerging practical deployments for the IoT trigger a need to integrate and inter-operate a variety of hybrid connectivity technologies to realize real business values. Several applications require the integration of technologies, such as Wireless Sensor Networks (WSNs) and RFID, using WiFi, Bluetooth, and/or ZigBee connectivity technologies into one single hybrid network. As the RF spectrum gets more congested, there is a need to explore other connectivity technologies to be used in such networks. One of the key candidate technologies to complement RF is OWC since it does not interfere with the RF technology. Moreover, the possibility of developing a communication module that is small in size and weight, consumes lower power, has low cost, and on top of that, operates in an unregulated spectrum, leads us to envision that OWC will play a key role in the future of IoT.

In addition to connecting things in the IoT network, an indoor VLC network can also serve as a backbone of the OWC-enabled IoT network [315]. In [316], Hussein and Elgala a lightweight OFDM modulation scheme that is convenient for the OWC-enabled objects in the IoT network. Another research direction that can help pave the way for OWC in IoT domain is the use of OWC to recharge the battery of a an object in the IoT network [317], [318]. Such a technology can help extend the network lifetime, and also enables the objects in the network to transmit at higher power extending their reach and make them more discoverable.

B. Optical Scattering Communication

Modeling T/CC/NLOS/x OSC channel is more challenging as compared to modeling traditional LOS links [149]. The reason is that as the link range increases, so does the complexity of jointly modeling atmospheric turbulence and the multiple scattering [16]. Furthermore, the performance of the link highly depends on the geometry of the link with respect to the transmitter and receiver angles and beam shape. Developing channel and system models that capture the variables affecting the performance of OSC is of great interest especially that this link configuration can be viable for connecting distributed nodes and objects in future IoT networks.

C. Relay-Assisted FSO Networks

As mentioned earlier in Section VI-B, relay transmission can be used to overcome the atmospheric turbulence by allowing the transmitted data to use a relay node and avoid a direct link to the destination that is severely impaired by the atmospheric turbulence. There are two types of relaying configurations, namely; serial (i.e., multi-hop transmission) and parallel (i.e., cooperative diversity) relaying [319]. Multi-hop relaying is usually used to extend the range of a transmitted with limited transmission range. In this approach, the signal moves from one relay node to the other in a serial fashion. In parallel relaying, the sending node transmits the data to the receiving node and a relay node which in turn retransmits the date to the receiving node. This form of transmission acts as a distributed array of antennas and is considered as a cooperative diversity approach [29].

Since the concept of relay-assisted networks is mature when it comes to RF technology, researchers in FSO are adopting the techniques and approaches used in RF relay-assisted networks. For example, for the protocols used to forward the data using the relay nodes, researchers utilized amplify-and-forward (AF) [320]–[323], decode-and-forward (DF) [324], [325], and detect-and-forward (DetF) [326] protocols. All-optical AF relaying is introduced to avoid the requirement of optical-electro-optical (OEO) conversion at relay stations eliminating the need for high-speed circuits and delay associated with the conversion [327]–[332]. It is found that the saturated gain optical amplifier (OA) is useful to mitigate scintillation and atmospheric turbulence [330], [333]–[335]. In [330], Bandele et al. focus on cascaded FSO OA communication systems. The results show that cascaded OA FSO links are capable of suppressing scintillation even in the absence of the channel state information (CSI) and without the need of the complex adaptive decision threshold. This, in turn, leads to an extended reach of FSO links.

There are common assumptions among the aforementioned approaches that relay nodes are buffer-less and stationary. In [297], Fawaz et al. utilize moving UAVs equipped with buffers to function as a relay node in the relay-assisted heterogenous network in which fixed and moving relay nodes are used.

D. Hybrid FSO/x Networks

We discussed the application of hybrid FSO/x systems in several scenarios such as future indoor LiFi-WiFi networks, backhaul networks, underwater sensing, and providing internet access for underdeveloped regions of the globe. There are, however, some challenges that must be addressed to fully utilize the advantages of hybrid FSO/x systems. One of the main challenges is the handover and the realization of a seamless mobility of the mobile users. For example, in the discussed LiFi-WiFi network, a user should be able to seamlessly move between LiFi cells (horizontal handover) and between LiFi and WiFi networks (vertical handover) [84], [336].

With the increasing number of deployed OWC cells for coverage, inter-cell interference is inevitable. Inter-cell interference coordination (ICIC) and mitigation techniques have been studied for a long time in the RF domain [5]. The researchers in the OWC domain are utilizing the successful approached used in the RF domain [337]–[339]. Since OWC technology is becoming part of the future hybrid networks in particular to alleviate the spectrum congestion due to the interference in RF, it is critical to understand how to manage the interference in the between OWC link.

E. WDM FSO Links

The success of the WDM techniques in fiber optics has led the FSO researchers to consider the WDM to expand the capacity of the FSO links [333], [340]–[344] In [340], Chen et al. realize a 160 Gbps T/PC/LOS/F/Long WDM FSO link using sixteen 10 Gbps channels. The link uses OOK and has a distance of 2.16 km. Other T/PC/LOS/F/Long FSO link WDM FSO links were developed and experimented realizing 8 $\times$ 40 Gbps [341] and 32 $\times$ 40 Gbps [333] and using OOK modulation. Theoretical analysis and link performance of WDM FSO systems were also performed. In [342], Mbah et al. analyze the outage probability in the presence of turbulence-accentuated inter-channel crosstalk. Most recently, Zhao et al. present a 200 Gbps FSO WDM communication system. The system features integrated modules and utilizes PAM-4 modulation scheme [345]. Despite the recent advances in the WDM FSO links, more research is required to realize integrated, low-cost, and high capacity WDM FSO links in all of the four environments discussed.

XII. Summary

FSO communication links can be deployed in indoor, terrestrial, space, or underwater environments. Depending on the environment, an FSO link experiences different impairments that impact its performance. Even for the same environment, different link configurations can be affected differently by the noise and impairment source, therefore, it is crucial to be able to differentiate link configurations.

This paper presents a simple, yet powerful classification scheme of FSO technology. In this scheme, an FSO link can be classified as a combination of four different criteria, namely: Environment (ε), Coverage Type (κ), LOS Availability (α), Mobility (μ), and link distance (δ). An FSO link can be deployed in an indoor, terrestrial, space, or UW scenario. The link can be either a point or cellular coverage which can be realized using a LOS or NLOS link. Furthermore, a link can be fixed or mobile. Using the discussed four criteria, we were able to develop a generic classification that can be used to categorize different FSO links including recently evolving schemes in which other classifications in the literature fall short. In particular, the proposed classification scheme describes any FSO link configuration as a tuple $(\varepsilon/\kappa/\alpha/\mu/\delta)$.

We discuss all possible FSO link configurations in the four different environments. We provide examples for each FSO link configuration by listing selected recent references and related research efforts. Moreover, we briefly discuss the impairments experienced by each link type and their possible solutions.

We also discuss heterogenous FSO link that spans multiple environments. Several examples including the earth-space communication links have been discussed. A heterogenous FSO link experiences a combinatorial effect due to the different environments.

Unlike heterogenous FSO *link*, a heterogenous FSO *system* might incorporate two or more FSO link configurations in order to improve the system performance combining different links advantages. On the other hand, a hybrid FSO system is a system in which one or more different communication technologies are used along with FSO systems. Examples of each type of systems are provided and discussed.

We use the proposed classification scheme to review existing FSO standards and recommendations. IrDA has produced a set of standards aiming for high data rate short FSO links. JEITA CP-1221, CP-1222, CP-1223, IEEE 802.15.7, and IEEE 802.15.7r1 standards are designed for short/medium range VLC supporting low data rate links. On the other hand, limited efforts are directed towards standardizing terrestrial, space, and underwater FSO links. For example, a single recommendation for terrestrial FSO links, ITU-R F.2106-1, was proposed by ITU.

We can conclude that the FSO is increasingly becoming an attractive technology for emerging and future communication systems and applications. This holds true for either FSO as a stand-alone technology (as envisioned by NASA in its future space applications), or as a complementary technology (future wireless systems and in UW applications). This paper presents an attempt to use a simple and powerful classification system to jump-start researchers to tap into the growing and expanding the realm of the FSO technology in indoor, terrestrial, space and UW environments.

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