CSOWC: A Unified Classification Framework for Standardizing Optical Wireless Communications

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***Abstract*—Free space optics (FSO) or optical wireless communication (OWC) technology has regained a great interest over the last decade as an attractive alternative or complementary technology for existing technologies, such as radio frequency (RF), that have been pushed to their limits in order to serve the needs of emerging applications. Accordingly, FSO technology is being widely deployed in various indoor, terrestrial, space, and underwater systems. As the application portfolio of FSO/OWC technology grows, so does the need for a clear classification for FSO/OWC link configurations. An efficient classification can serve as a unified language to link different entities involved in the standardization process. This is particularly important during the early stages of standard development which require discussions and exchange of ideas between different standardization entities, including: academic, industry, and regulatory. Most existing classifications, however, focus on indoor OWC systems. Less attention has been paid to terrestrial, space, and underwater OWC systems. Moreover, most classifications for the indoor OWC are not inclusive enough to accommodate recent and emerging developments of indoor link configurations.**

In this paper, we present a most-inclusive scenario-oriented (or function-based) classification, *CSOWC*, that can be used to classify existing and future indoor, terrestrial, space, and underwater OWC links using common and simple unified notation. We believe that, CSOWC can serve as a unified framework for standardization bodies to identify potential needed standards and to deliver efficient standards that meets the emerging market needs. Moreover, we use the proposed classification to briefly review existing standards and recommendations related to OWC.

I. Introduction

Emerging business applications and systems, such as, big data analytics and Internet-of-Things (IoT) are characterized by being bandwidth intensive and performance sensitive. Thus, a pressing need is being mineralized to evolve the communication infrastructure beyond the core to avoid the foreseen bottleneck, as such applications and systems rapidly move closer to the end users. As we move towards the end users, wireless communication systems, such as Radio Frequency (RF), are the favored technologies as these technologies allow for mobility and flexibility. Wireless technologies also avoid most of the inherit complexities encountered by wired technologies, such as, long setup time, right of the way for laying cables, and the sunk cost once the cables are laid [1]. RF is a mature technology and is being widely deployed in many indoor, terrestrial, and space communication systems, however, the congested RF spectrum, as well as interference pose real challenges that limit the RF system performance [2].

Free space optical (FSO) communication, also known as optical wireless communication (OWC), combine advantages of both wireless and optical communication systems. FSO modulates light beam which propagates wirelessly from one point to another. OWC is being extensively investigated over the last few decades as an attractive technology that provides flexibility and high-bandwidth. The next generations of wireless communication systems (e.g., 5G) incorporate several complementary access technologies along with the RF technology, including OWC [3]. OWC has already found its place in many applications, such as, mobile networks backhaul [4], space communication [5], underwater sensing [6], wireless sensor networks [7], indoor local area networks [8], data centers (DCs) [9] and many other applications.

As a result, large number of research papers on OWC has been published over the last decade. This motivates our thought process to develop a classification that presents current advances in OWC in a systematic fashion. The classification is capable of expressing existing, emerging, and future OWC link configurations in a non-confusing and unambiguous fashion. This classification is proposed as a unified framework for researchers in different standardization organizations to help them identify emerging needs for standards and to exchange ideas and knowledge during standardization process. Therefore, in this paper, we propose a set of notation that can be easily used to classify various OWC link configurations for indoor, atmospheric, non-atmospheric, and underwater environments, based on their structure and operation.

The remainder of the paper is organized as follows. In Section II we review existing classifications of OWC and discuss the motivation for developing the Classification for Standardizing Optical Wireless Communication (CSOWC). We dedicate Section III to present the proposed CSOWC. Existing standards and recommendations are briefly discussed in Section IV followed by conclusions in Section V.

II. Related Work and Motivation

OWC technology can be deployed in four different environments: indoor, atmospheric, space, and underwater. Out of the four different scenarios, indoor OWC has the largest share of surveys and classifications [10]–[16]. In this section, we briefly review existing classifications and discuss the motivations for developing the proposed CSOWC scheme.

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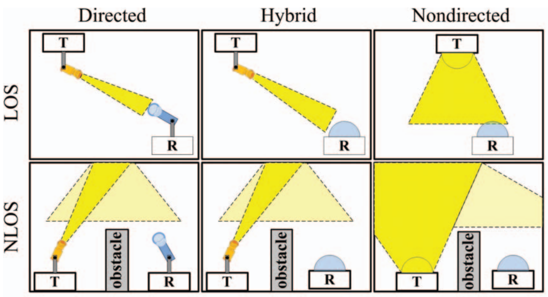

Fig. 1: Classification by Kahn and Barry [10].

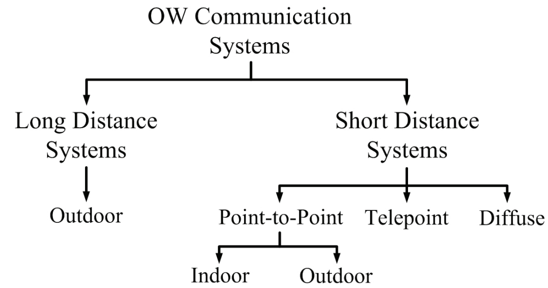

Fig. 2: Classification by Heatley et al. [12].

A. Existing Classifications

In [10], Kahn and Barry proposed one of the most popular and widely used classifications of indoor OWC systems in the literature to date. 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 into a total of six different OWC link configurations (see Figure 1).

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

In [11], Street et al. presented a tutorial review for indoor OWC systems. Four link configurations were used to classify OWC 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 [10], respectively. In a tracked system, a base station produces several narrow spotlights simultaneously. Each spotlight is used to illuminate only a single user station as a LOS link. The spotlights produced by the base station are steerable, therefore, they provide high data rate LOS link and support mobility by tracking the mobile user stations as they move around within the coverage area (cell).

In [17], [18], Wisely et al. proposed tracked OWC 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 element to the adjacent one in the array such that the LOS link is maintained. This process continues until the user station becomes again stationary or leaves the cell.

In 1998, Heatley et al. published a paper which can be considered as the first attempt to present a classification that is not limited to the indoor OWC systems [12]. In this classification (see Figure 2), OWC systems are classified as long 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 [10] and cellular in [11]) 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 since it does not belong to any of the classes in their classification.

In [19], 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 OWC links helps reducing the channel power loss as compared to that of in 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.

Since conventional classifications were not designed to adapt to emerging OWC link configurations, researchers had to use a subset of OWC link configurations from previous classifications, and add new link configurations as separate classes [14], [15]. For example, in [14], Elgala et al. chose Directed/LOS, Nondirected/LOS, and diffuse links from previous classifications and added the quasi diffuse links as a separate, fourth class, whereas, Borah et al. picked point-to-point and diffuse links from previous classifications and added multi-spot diffuse as a separate class [15].

In a recent survey, Khalighi and Uysal classify OWC links *only* based on the link distance into ultra-short, short, medium, long, and ultra-long range OWC [4]. In [20], Johnson et al.

present a brief survey and classification of underwater (UW) OWC. Similar to [14], [16], the authors classify UW OWC links into four link configurations, LOS, non-directed LOS, non-LOS, and add retro-reflector as a separate class.

B. Motivation for CSOWC

The life cycle of a standardization development process starts with identifying the need for standardizing a technology. For technologies with broad portfolio such as OWC technology, tracing the progress and the advances in the technology can be difficult. As a result, identifying the market needs for standards maybe constrained.

A well-designed classification, however, can help organize and systematically present the progress in the research for OWC technology such that the identification of needed standards becomes easy. However, most classifications in the literature refer to the same OWC link configuration using different titles. This may affect the integration of knowledge reported in the literature. Moreover, most of the reported classifications are meant for simply reviewing and differentiating existing OWC systems without considering future development of new OWC links. Therefore, it might be difficult to fit some of the emerging and future configuration classes into existing classification schemes. Accordingly, many classifications needed to introduce new classes, which makes the overall classification scheme inconsistent and nonsystematic in its expansion. A clear example is considering quasi (multi-spot) diffuse systems as a sperate class despite its similarities to diffuse systems. This reveals the rigidity in the existing classifications.

Motivated by the discussion above, we propose CSOWC to address the shortcomings in existing classifications. We believe that CSOWC will be useful in:

1) Tracing the progress in different link configurations of OWC. This will make the task of understanding the market needs for standards easier and more effective.
2) Serving as a unified language to close the loop of collaboration among standards experts from academia, industry, and other standardization bodies, during the piecemeal standard development process.
3) Alleviating the redundancy and enhancing the transition of knowledge between standards for different links that share some attributes.

III. Proposed CSOWC Classification

After analyzing various existing classification schemes for OWC link configurations, 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 paper, we develop a function-based (scenario-oriented) classification of OWC link configurations. The proposed classification abstracts the implementation details of the various configurations, such that configurations with different implementation details but perform the same function are combined into a single class.

A. Elements of the CSOWC 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 CSOWC 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 the OWC links realized in 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 does 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.
- **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 communicate 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.).
- **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 mechanical steerable optics or solid-state multi-element transmitter and receiver arrays.

- **Link Distance (δ):** Depending on the environment and the application, OWC links can be of different link distance (range). For example, an OWC link can be used in optical interconnects within integrated circuits, outdoor inter-building links, and deep-space communications. Based on the transmission range, OWC can be studied in five categories [4]: Ultra-short range [e.g., chip-to-chip communications], Short range [e.g., wireless personal area network (WPAN) applications, and underwater communications], Medium range [e.g., indoor IR and wireless local area networks (WLANs)], Long range [e.g., inter-building connections], and Ultra-long range [e.g., inter-satellite and deep space links].

B. CSOWC Classification

Based on the above discussion, an OWC link configuration can be expressed using the $(\varepsilon/\kappa/\alpha/\mu/\delta)$ tuple, where, $\varepsilon \in$ {I, T, S, UW}, $\kappa \in$ {PC, CC }, $\alpha \in$ {LOS, NLOS}, $\mu \in$ {F, M}, and $\delta \in$ {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 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.

An NLOS OWC link can be realized using an active repeater or diffusely/specularly reflected light beam off of a passive reflector. In particular, (x/PC/NLOS/F/x) links can be realized using both methods, whereas, (x/PC/NLOS/M/x) links can only be realized using active repeaters, such that, the downlink of the repeater is (x/PC/LOS/M/x). This is because using an active repeater, each of the uplink and downlink can be independently mobile, while in specular reflection, both transmitter and receiver need synchronized motion in order to maintain the link which adds to the complexity of the link. This problem, on the other hand, does not exist in the (x/PC/NLOS/F/x), because, once the link is aligned and established, it does not change.

Even narrow beams have large spot size at the receiver for all non-indoor OWC environments because the beam proportionally diverges with distance traversed. Therefore, it is hard to use passive repeaters or reflectors (e.g., mirrors) to realize ({T,S,UW}/PC/NLOS/F/x), and thus ({T,S,UW}/PC/NLOS/F/x) are mainly realized using active repeaters, where, a signal is received first by an intermediate station and then retransmitted. This makes the link a set of consecutive ({T,S,UW}/PC/LOS/F/x) links.

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.

In (x/CC/NLOS/x) links, wide beams or a set of narrow beams are diffusely reflected off of surfaces in the vicinity such as walls, ceiling, floor, and furniture. Receivers deployed have wide field of view (FOV) or multiple receivers with narrow FOV in order to capture the reflected beams from different angle in addition to the LOS (if existed).

We define a *heterogeneous OWC link* as a link that traverses different environments. In real life, there are applications in which an OWC link may encounter different environments. In the following we discuss briefly few examples of heterogeneous OWC links:

- Inter-Building Terrestrial Links: Due to the small size of OWC system components, transceivers of a terrestrial OWC link connecting two buildings can be mounted behind windows in offices instead of on building rooftop [21]. This can save the operators the cost of acquiring a permission to place transceivers on the rooftop of a building. In the case of rooftop, the link is considered purely terrestrial. On the other hand, placing OWC transceivers behind windows means that a small segment of the link is indoor while the main part of the link is terrestrial. We refer to this heterogenous link as {I-T}/PC/LOS/F.
- Space-Ground Links: Space-earth OWC link is another example of heterogenous OWC links. The link from satellites in the geostationary orbit (GEO) is fixed w.r.t the ground station and can be referred to as {S-T}/PC/LOS/F/ULong, on the other hand, satellites or stations in different orbits will establish a link that supports mobility and is referred to as {I-T}/PC/LOS/M/ULong.
- Space-Air Links: Many commercial airlines started to equip their fleets with real-time high-speed Internet access using RF links from ground stations (e.g., US provider GoGo) or satellites (e.g., Lufthansa's FlyNet system). Since most aircrafts have cruise altitudes above the cloud layer, OWC links from satellites can be used to provide high speed Internet service without any at-

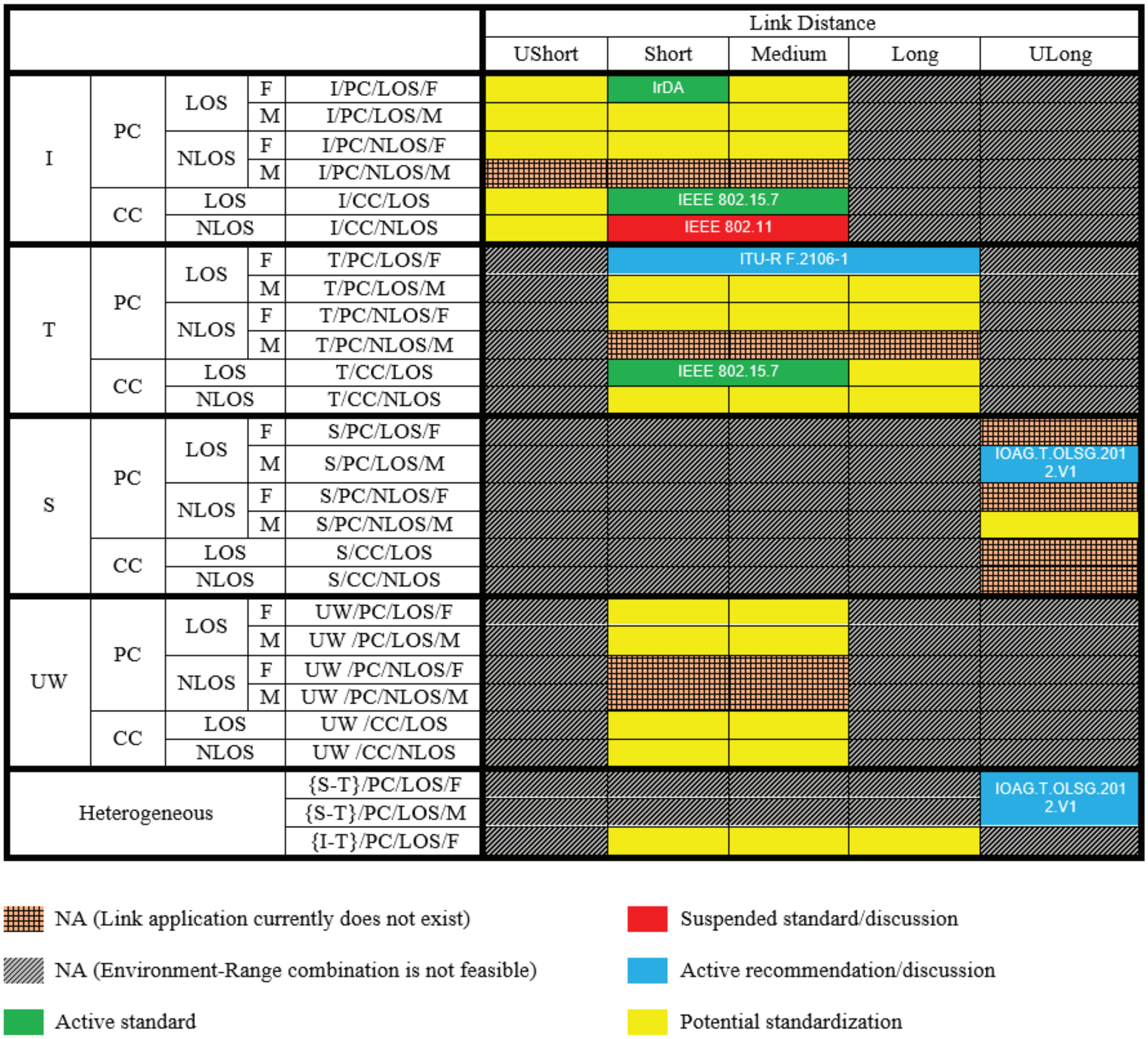

Fig. 3: Proposed CSOWC classification.

tenuation by clouds and with little atmospheric turbulence. This link can be classified as a variation of {S-T}/PC/LOS/M/ULong link.

Figure 3 depicts a summary of the proposed classification with its 24 different OWC link configurations in addition to few examples of heterogenous OWC links. 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 a new OWC link configuration that might be developed as the OWC technology continues to develop and advance. Moreover, it is also possible that the environment-range combination of an OWC link is not valid. For example, an ultra short OWC link can only be realized in an indoor environment, whereas, an ultra long link can only be realized in space communication. We also list related active/discontinued standards and current active discussions which will be briefly discussed in the next section.

IV. Existing Standards and Recommendations

In this section, we briefly discuss existing standards and recommendations related to OWC. The original version of the standard *IEEE 802.11* released in 1997 specifies two data rates of 1 and 2 Mbps to be transmitted via infrared (IR) signals or RF at 2.4 GHz [22], [23]. The peak-power wavelength of the transmitter is in the 850-950 nm band, while a typical link length is limited to 10 m. The IEEE 802.11 specification was developed for I/CC/NLOS/{Short,Medium} links [22], however, the drawbacks exhibited by IR communication prevented its implementation.

Infrared Data Association (IrDA) developed six standards focusing on low cost, I/PC/LOS/x/Short OWC links mainly for handheld devices [23], IrDA standards include, Serial Infrared

(SIR) with data rates ranging from 2.4 to 115.2 kbps, Fast Infrared (FIR) supporting 4 Mbps, and Gigabit Infrared (Giga-IR) which currently supports 512 Mbbs and 1.024 Gbps [23].

Visible light communication (VLC) is another rapidly emerging technology in which light emitting diodes (LEDs) are used to provide VLC data links as well as illumination. In 2006, members of VLC Consortium (VLCC) [the predecessor of VLCA] proposed the standards, CP-1221 (VLC System), and CP-1222 (Visible Light ID System) of Japan Electronics and Information Technology Industries Association (JEITA) [24]. On the other hand, in response to the advances in the VLC technology, IEEE proposed the *IEEE 802.15.7* standard. This standard defines PHY and medium access control (MAC) layers for {I,T}/CC/LOS links to support audio and video multimedia services. In 2013, JEITA proposed the CP-1223 (Visible Light Beacon System), which is a simplified and improved version of CP-1222, to TC-100 of the International Electrotechnical Commission (IEC) and was approved as IEC 62943 in 2014.

In [25], the recommendation sector of the international telecommunication union (ITU) released the report number *ITU-R F.2106-1* in which recommendations related to the fixed service using T/PC/LOS/F/{Medium,Long} OWC links are discussed. 1 or 1M class terminal based on IEC 60825-1 normative reference are recommended using two wavelength ranges; 1300-1500 nm and 780-800 nm.

An Optical Link Study Group (OLSG) is established by the Interagency Operations Advisory Group-14 (IOAG-14) to assess whether there is a business case for cross support in the OWC 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 consideration 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 maximize the data return. However, since the number of ground stations required can pose a substantial cost burden for a single agency, OLSG recommended the support across agencies. The highest priority is given to standardization of core services under development, especially core services that will lead to significant operational and/or financial benefits and for capabilities or services that will be committed to flight operations or tracking networks by September 2015.

V. Conclusions

We present CSOWC, a simple, yet powerful, classification scheme for standardizing OWC. In this scheme, an OWC link can be classified as a combination of five different criteria, namely: Environment (ε), Coverage Type (κ), LOS Availability (α), Mobility (μ), and link distance (δ). An OWC link can be deployed in an indoor, terrestrial, space, or underwater 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 and it can span various distance ranges based on the application. Using the discussed five criteria, we develop a most-inclusive classification that can be used to categorize different OWC links as a $(\varepsilon/\kappa/\alpha/\mu/\delta)$ tuple, including recently evolving schemes in which other classifications in the literature fall short. We also review existing standards and recommendations related to OWC and classify their scope using CSOWC.

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