Optical Wireless Communication for the Internet of Things: Advances, Challenges, and Opportunities

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***Abstract*—The continuous development of the Internet of Things (IoT) calls for innovative solutions and technologies to realize the IoT vision efficiently. One of the rising connectivity technologies that can potentially benefit the IoT deployment is Optical Wireless Communication (OWC) technology. In OWC, light beams from light sources are used to modulate information. The receiver demodulates the received light and processes the signal. The broad unlicensed spectrum of the OWC technology, along with its potential high bit-rate and increased physical link security, motivated researchers to consider OWC for IoT solutions. In this paper, we survey the existing literature related to using OWC technology in the IoT domain. We present the background and preliminaries of the IoT and OWC domains to understand how the OWC fits in the IoT architecture. Then we perform a comprehensive survey of literature related to the use of OWC technology in IoT applications. We highlight and summarize the major papers and experiments in the literature to provide researchers a jump-start to tap into the domain of OWC in IoT using the systemic and detailed survey presented in this paper.**

***Index Terms*—Classification, Free Space Optical (FSO), Interent-of-Things (IoT), LED-ID, LED, Optical Camera Communication (OCC), Optical Wireless Communications (OWC), Survey, Wireless Communications.**

I. Introduction

THE *Internet of Things (IoT)* is the growing global network of identifiable *things* (e.g., sensors, actuators, smartwatches, smartphones, and other "smart" devices) connected to the internet. The interconnection of devices creates ecosystems where one device can serve as an access point to others. A hierarchy of devices can collectively operate to inform connected device behaviors and provide insights to users using the continuous data collection by the system. Emerging IoT solutions promise to advance business verticals, impacting different aspects of our daily life, such as health, safety, productivity, and entertainment. As a result, the IoT market is proliferating at a striking rate and the number of *things* being connected to the Internet is continuously on the rise. Out of the 17B devices connected to the Internet as of 2018, seven billion devices are contributing to the IoT market [1]. By 2025, the number of devices connected to the Internet is expected to be 34.2B devices, with 21.5B devices being IoT devices (see Figure 1). As the IoT market continues to grow, so does the interest of academia and industry vis-à-vis the IoT domain and solutions.

Wireless communication is usually the technology of choice in IoT access networks to provide the users and things the full flexibility and mobility needed. According to the visual networking index (VNI) forecast developed by Cisco [2], it is anticipated that the number of public Wi-Fi hotspots and home spots will grow 4-fold to become 549.2 million by 2022 as compared to that of 2017. Moreover, global mobile data traffic is expected to increase seven-fold between 2017 and 2022 to become 77.5 exabytes.

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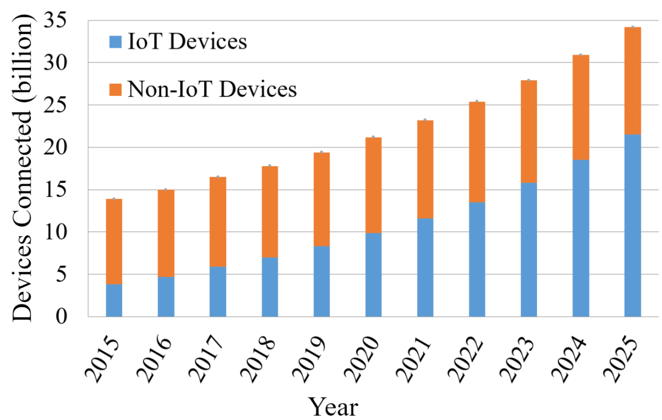


Fig. 1: Total number of active devices connected to the Internet [1]. Non-IoT includes all mobile phones, tablets, PCs, laptops, and fixed line phones. IoT includes all consumer and business-to-business (B2B) devices connected.

Figure 2 depicts the electromagnetic (EM) spectrum with different frequency ranges (and the corresponding wavelengths) for different wireless technologies. An appropriate carrier frequency is selected based on the application needs. At low carrier frequencies, the long-wavelength allows radio frequency (RF) signals to penetrate walls and windows, diffract over obstacles, and propagate for long-distance due to the low signal attenuation. These advantages of low carrier frequencies, however, come at the cost of the lower bandwidth and thus data rates. On the other hand, increasing the carrier frequency and decreasing the wavelength leads to higher bandwidth and data rates at shorter link range and limited penetration and diffraction.

Most, if not all, IoT wireless access networks currently deployed are utilizing RF communication technologies [3]. The demand for higher data rate communication links is steadily increasing with the development of IoT data-centric applications. To meet these demands, researchers must increase the efficiency of the available congested RF spectrum. A major challenge and the most significant limiting factor of developing higher data-rate RF communication links is

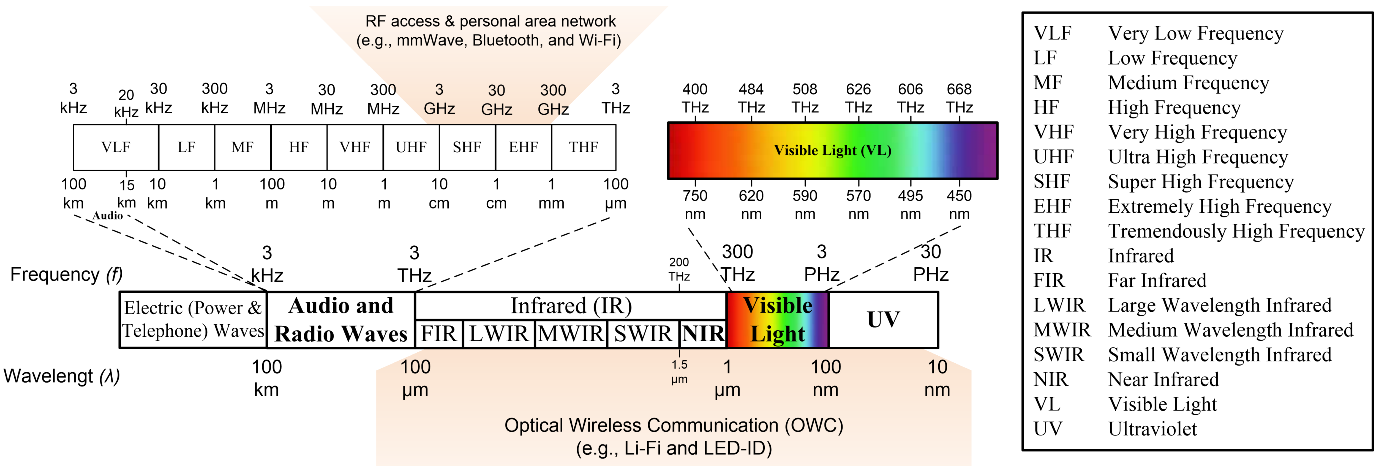


Fig. 2: Abstract overview of a portion of the EM spectrum showing the frequency (and wavelength) ranges for each band. Ranges utilized by both RF and OWC technologies are also indicated. Exact frequency bands allocated for each technology may vary depending on international and national regulatory agencies.

interference [4]. Therefore, the main focus of RF research is on stretching the capability of existing wireless technologies by alleviating interference through coordination.

Nevertheless, RF technologies are being pushed to their limit as we move towards the 5th generation (5G) cellular wireless system, one of the major enabling technologies for the IoT vision [5]. This is evident by the 2.5 GHz and portions of the mm-Wave band (30 GHz - 3 THz) being cleared and auctioned by the Federal Communication Commission (FCC) for prospective 5G service providers to allow them to deliver high data rate connections for their customers [6], [7]. The recent advances and development of cost-effective electronics and high-gain steerable antennas operating in the mm-Wave frequency bands, in addition to the higher bandwidth, are the reasons that motivated researchers to explore mm-Wave technology for 5G [8]–[10]. However, at high frequencies, such as in the mm-Wave band, diffraction and reflection of waves barely apply, and the links become limited in range and require higher directivity and Line-of-Sight (LOS). These challenges are currently limiting the wide outdoor deployment of mm-Wave links in 5G networks, and thus are being addressed by the research community [11]. The limitations on the mm-Wave technology outdoor-deployment are considered the motivations for exploring the deployment of indoor short-range high data rate mm-Wave links in other applications such as inter-rack communication in data center networks (DCNs) [12].

Optical Wireless Communication (OWC) is a wireless technology in which a light beam (visible/invisible) is modulated and transmitted to propagate in an unguided medium. It operates in a broad license-free spectrum (see Figure 2) spanning the Infrared (IR), Visible Light (VL), and Ultraviolet (UV) bands. The OWC technology has been gaining increasing attention over the last few decades due to the latest advances in its enabling technologies (light sources and modulation), as well as the fact that it combines the high-bandwidth of fiber optics communications and the flexibility of wireless technologies. As a result, OWC technology continues to find its place in many applications [13] including indoor [12], terrestrial [14], space [15], and underwater [16] applications.

OWC is being considered as a complementary, and sometimes a viable alternative technology to other communication technologies. This encourages the development of hybrid systems in which OWC is joined up with other technologies to improve the overall system performance. For example, OWC can be utilized along with acoustic communication in underwater (UW) wireless sensor networks (WSNs), also referred to as UWSNs [17], [18]. In UWSN, an uncrewed UW vehicle travels between UW sensor nodes to collect data. The vehicle utilizes acoustic signals for long-range localization and accurate ranging. Once the vehicle is aligned with the UW sensor, a high data rate OWC link is established to transfer the data collected by the sensor to the vehicle.

RF communications and OWC are orthogonal mediums, therefore using OWC can help declutter the RF spectrum, reducing interference as more devices are connected. OWC can be combined with RF technology in interference-sensitive applications such as in hospitals and in personal entertainment systems on commercial aircraft that could interfere with navigation and avionics systems [19]. Another important example is the promising role of OWC in the future of access networks in 5G [20]. In a recent study [21], Zhang et. al., propose a hybrid OWC and RF software-defined small-cell networks. Simulation results show improved throughput as a result of the reduced interference in the hybrid system.

The ever-increasing number of IoT devices will require hybrid access network solutions. OWC is a promising technology that is considered as a viable enabling technology for the IoT domain [22]. For example, light sources in OWC transmitters operating in the visible light (VL) band, such as Light Emitting Diodes (LEDs), have the added benefit of serving as illumination sources [23]. This dual-functionality means that the growing abundance of LED sources used worldwide can serve as network access points. On the other end of the OWC link, a high-resolution complementary metal-oxide-semiconductor (CMOS) camera, such as the built-in cameras in smartphones and devices can be used to capture the light from the LEDs to establish low data-rate links. The camera-based VLC communication is also referred to as Optical Camera Communication (OCC) which is part of the IEEE 802.15.7-2018 standard developed for Short-Range Optical Wireless Communications [24].

In the context of integrating OWC technologies in IoT networks, some challenges come along with the many advantages OWC technology has to offer. The challenges facing the deployment of OWC in IoT depend on many factors including the specific OWC technology used, application requirements, and the environment in which the system is deployed, i.e., indoor, outdoor, space, or underwater [12]. For example, due to the absence of the penetration and the limited reflection at the high OWC EM bands, OWC requires direct connection via LOS between communication modules to achieve high data rate links. For mobile applications, misalignment becomes a challenge when maintaining a LOS link. On the other hand, the LOS nature of OWC adds a layer of physical security not provided by RF. Other challenges that will be discussed throughout this paper are limited frame rate, synchronization, and ambient light [25]. These challenges have to be addressed to unleash the full potential of OWC technologies in IoT networks.

A. *Motivation and Contribution*

It has been noticed that most existing surveys focus on RF technologies when the connectivity technologies in IoT are discussed. On the other hand, technologies such as OWC are rarely discussed and are usually mentioned as a possible technology. This trend is reasonable since RF is widely used, and its enabling technologies are readily available and under continuous research and development. Nevertheless, OWC technology is experiencing rapid development and gaining significant interest in the IoT community. Therefore, we argue that the literature on IoT lags behind OWC development. In this paper, we aim to fill this gap and keep the research community current with the recent advances in OWC technology deployments in the IoT domain.

Being a relatively untapped research space, the scope and boundaries of OWC in IoT are yet to be fully explored. As the application portfolio of OWC technologies in the context of IoT grows, so does the need for a systematic survey. We believe that there is a need for a survey for existing and emerging applications of OWC technologies in the IoT domain. Accordingly, in this paper, we classify and survey all existing work in the area of the OWC in IoT. We aim to give researchers a jump-start to tap into the domain of OWC technology in IoT networks. 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 provide a brief overview of the IoT with a focus on the related work such as existing classifications and surveys

TABLE I: Acronyms and Abbreviations

Acronym	Description
6LoWPAN	IPv6 over Low Power Wireless Personal Area Networks
AMI	Active Medical Implant
AMQP	Advanced Message Queuing Protocol
BER	Bit Error Rate
BLE	Bluetooth Low Energy
CCD	Charge-coupled device
CMOS	Complementary metal-oxide-semiconductor
CoAP	Constrained Application Protocol
CSK	Color Shift Keying
DDS	Data Distribution Service
ECG	Electrocardiogram
EEG	Electroencephalogram
EM	Electromagnetic
FCC	Federal Communications Commission
FPS	Frames Per Second
FSO	Free Space Optics
GSM	Global System for Mobile Communications
HS-PSK	Hybrid Spatial Phase Shift Keying
IIoT	Industrial Internet of Things
IoT	Internet of Things
IP	Internet Protocol (IPv4: version 4, IPv6: version 6)
IR	Infrared
LD	Laser Diode
LED	Light Emitting Diode
LED-ID	Light Emitting Diode Identification
LOADng	Lightweight On-demand Ad-hoc Distance-vector Routing Protocol - Next Generation
LiFi	Light Fidelity
LLN	Low-Power Lossy Networks
LoRA	Long Range
LoRaWAN	Long Range Wide Area Network
LOS	Line of Sight
LPWAN	Low-Power Wide-Area Network
LR-WPANs	Low-Rate Wireless Personal Area Networks
LTE-A	Long Term Evolution - Advanced
M2M	Machine-to-Machine
MQTT	Message Queuing Telemetry Transport
MQTT-SN	Message Queuing Telemetry Transport for Sensor Network
NFC	Near Field Communication
NLOS	Non Line of sight
OCC	Optical Camera Communication
OOK	On-Off Keying
OSC	Optical Scattering Communication
OSI	Open Systems Interconnection
OWC	Optical Wireless Communications
PAN	Personal Area Network
PCM	Pulse Code Modulation
PD	Photodiode/Photodetector
PIN-PD	Positive Intrinsic Negative Photodiode
PLC	Powerline Communication
RF	Radio Frequency
RPL	IPv6 Routing Protocol for Low-Power and Lossy Networks
SBC	Single Board Computer
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UV	Ultraviolet
UW	Underwater
UWSN	Underwater Wireless Sensor Network
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VL	Visible Light
VLC	Visible Light Communication
VPPM	Variable Pulse Position Modulation
WBFM	Wide Band Frequency Modulation
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
XMPP	Extensible Messaging and Presence Protocol

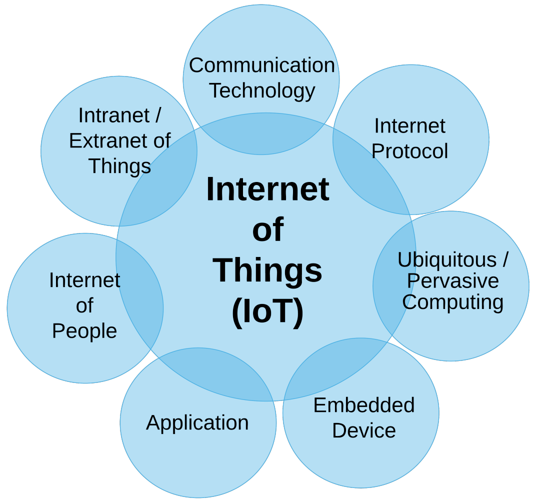


Fig. 3: Scope of the Internet of Things and its relation to other research fields [26]. This figure emphasizes that IoT is not any of these technologies, but rather a overlaps with all of them.

on the IoT. Section III focuses on the preliminaries and basic concepts related to the generic OWC link components, including light sources, photodetectors, and modulation schemes. We dedicate Section IV to classify and review major work in the area of OWC in IoT. Research directions and open problems for OWC in IoT are discussed in Section V. Summary is given in Section VI.

II. IoT Preliminaries and Basic Concepts

In this section, we cover the preliminaries related to the IoT. This section is necessary to understand how OWC technology can fit into the IoT model. In particular, we discuss the definition of IoT, followed by a brief review of existing taxonomies and surveys.

A. IoT Definition

Despite the vast body of work in the IoT domain, there is not a definitive agreed-on definition of the term [26]. Different definitions of the IoT exist because each of the defining individuals, organizations, and businesses tend to project their visions and motivations [26]–[28].

In [26], the IEEE IoT Initiative shared a living document with the title *"Towards a Definition of the Internet of Things (IoT)"* in an attempt to develop an all-inclusive definition of IoT collectively. In this shared document, the collaborators comprehensively survey and review all existing definitions for the term IoT in standards, research projects, national initiatives, white papers, books, and industrial activities. This review did not result in a formulated final definition for the IoT term; instead, the authors recommended a definition that was established by Uckelmann et al. in their edited book entitled *"Architecting the Internet of Things"* and published in 2011 [28]. For the sake of completeness and to improve the readability of this paper, we include and discuss the definition of IoT presented in [28], which reads as follows:

> "The future Internet of Things links uniquely identifiable things to their virtual representations in the Internet containing or linking to additional information on their identity, status, location or any other business, social or privately relevant information at a financial or non-financial pay-off that exceeds the efforts of information provisioning and offers information access to non-predefined participants. The provided accurate and appropriate information may be accessed in the right quantity and condition, at the right time and place at the right price. The Internet of Things is not synonymous with ubiquitous/pervasive computing, the Internet Protocol (IP), communication technology, embedded devices, its applications, the Internet of People or the Intranet/Extranet of Things, yet it combines aspects and technologies of all of these approaches."

What makes this definition stand out is that in addition to defining what IoT is, Uckelmann et al. also highlight what IoT is not. Figure 3 [26] depicts the relation between the IoT and other technologies discussed in their definition. Moreover, the definition emphasizes the "rightness" of the different aspects of IoT. The large quantity of data is not the goal; instead, it is the ability to filter and process the data to extract the right amount of data. Data availability does not need to be real-time, but rather at the right time when the data is needed, which implies that it could also be near real-time or even asynchronous. The amount and timing of data must lead to the extraction of the right information appropriate to the user (machine or human) at the right place. The right price for this system is not necessarily the lowest as long as the price is higher than the cost of attaining the information and the possible market price leading to an appropriate revenue margin.

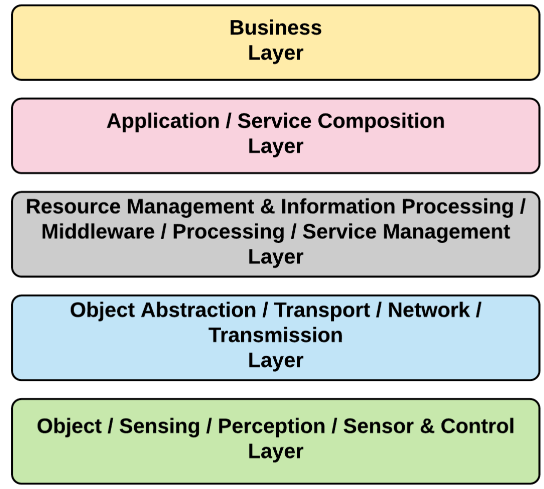


Fig. 4: Five-layer stack-based IoT architecture.

B. IoT Architecture

Several layered models have been developed to describe the architecture of the IoT as a result of the different visions and

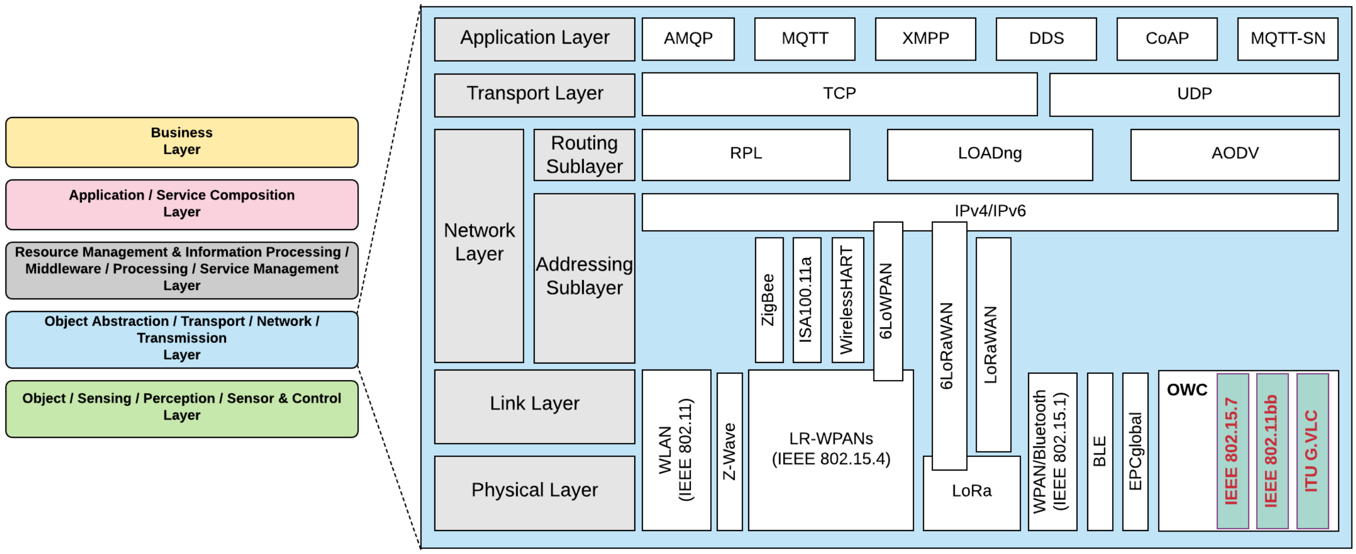


Fig. 5: This figure depicts a partial high-level view of a stack representing the IoT Object Abstraction Layer. Inter-layer protocols' interactions are complex and cannot be demonstrated in a single figure. Therefore, order, size, and alignment of boxes do not signify relationship or importance. Overlapping boxes indicate adaptation layers (i.e., protocols specifically created to adapt two inter-layer protocols.)

objectives of stakeholders [3], [29], [30]. After inspecting the variety of models developed and presented in the literature, we find that the five-layer model (see Figure 4) is the most commonly used model to represent the architecture of the IoT with slight variations from one paper to another. In Figure 4, we list all name variations mentioned in the literature for each layer. In the following, we discuss each layer in detail.

IoT Object Layer

This is the layer of "things". Since the concept of IoT relies heavily on the sensing and perceiving the surrounding, the layer is often referred to as the "Sensing" or the "Perception" Layer. However, part of the IoT is to take action and actuate [31]. Therefore, we use the name "Object Layer" to refer to this layer [3] since the term object refers to an end-node, i.e., a managed device in the system, whether it is a sensor, actuator, or a hybrid. Dorsemaine et al. present a taxonomy of IoT objects from the attributes prespective [32]. Based on their discussion, an IoT object can be described based on the following attributes; communication, energy, functional attributes, hardware and software resources, and local user interface. In [33], Rozasa et al. present a detailed taxonomy of IoT sensors. They classify IoT sensors into six types, namely; motion, position, environment, mass measurement, and biosensor. An object may or may not be equipped with a connectivity module [34]. Some scenarios in which a sensor performs no communication is when the device is deployed in an environment that requires offline recording and later recovery (e.g., dosimeter). On the other hand, an object equipped with a connectivity module, such as Single Board Computers (SBCs), will transfer the data collected to the higher layer in the architecture through the Object Abstraction Layer.

IoT Object Abstraction Layer

This layer is responsible for networking the Object and the Middleware layers. The Object Abstraction Layer enables the cross-domain connectivity in which heterogeneous devices are connected to facilitate Machine-to-Machine (M2M) and collaborative interaction [35]. The layer is also responsible for abstracting the output of the object layer and then transmit/transport it up the stack for further processing and vice versa. Depending on the system architecture (Cloud or Fog-based), the task of the Network layer is either to relay the data to a local smart gateway for pre-processing at the edge, or to the cloud where a Middleware performs centralized processing and makes decisions [36].

To relate to conventional networking concepts, we can think of the IoT Object Abstraction Layer as a stack of communication protocols that is partially or fully implementing the Open Systems Interconnection (OSI) model. This layer has its Application, Transport, Network, Link, and Physical layers, which should not be confused with the layers of the IoT architecture. It is worth pointing, however, that large number of technologies and protocols are used in the IoT model. Therefore, one-to-one mapping of all the IoT technologies and protocols to the OSI model is not straight-forward or even possible sometimes. Figure 5 depicts a non-exhaustive overview of the IoT Network Layer with some of the existing protocols, standards, and technologies. The layers in the IoT Network Stack are divided as follows:

1) Application Layer: The various energy, memory, and processing constraints imposed by the IoT objects necessitate the development of more convenient Application Layer protocols as compared to that of the conventional Web application layer protocols. To this end, several IoT-compatible protocols have been developed, namely, Constrained Application

TABLE II: Comparison of RF protocols for IoT [3], [37], [38].

Technology	PHY Protocol / Standard	Frequency Band	Theoretical Data Rate (bps)	Transmission Range	Energy Consumption	Cost	Spreading Technique	MAC Access	Scalability
WSN	IEEE 802.15.4	902-928 MHz	20-250 K	20-100 m	High	High	NA	NA	NA
Wi-Fi	IEEE 802.11 a/c/b/d/g/n	5-60 GHz	1 M - 6.75 G	20-100 m	High	High	NA	NA	NA
WiMAX	IEEE 802.16	2-66 GHz	1 M-1 G (fixed) 50-100 M (Mobile)	<50Km	Medium	High	NA	NA	NA
LPWAN	LoRA	868/900 MHz	0.3-50 K	<30 Km	Very Low	High	NA	NA	NA
LR-WPAN	Zigbee	868/915/2400 MHz	20/40/250 K	10-20 m	Low	Low	DSSS	NA	65K nodes
	IEEE 802.15.4								
	Z-Wave [3]			NA	NA	NA	NA	CDMA/CMA	232 nodes
Bluetooth	IEEE 802.15.1	2.4 GHz	1-24 M	8-10 m	Medium	Low	FHSS	TDMA	5917 slaves
	BLE		1024 K		Very Low		NA	NA	NA
RFID	EPCglobal	860-960 MHz	5 640 K	NA	NA	NA	DS-CDMA	ALOHA	NA
	ISO/IEC 15,693	860-960MHz 2.4GHz	106 k-424 K	<100m	Medium	Medium	NA	NA	NA
Mobile Communication	LTE-A 2G-GSM,CDMA 3G-UMTS,CDMA2000 4G-LTE 5G	865 MHz 2.4 GHz 3.5 GHz 26 GHz	2G: 50-100 K 3G: 200 K 4G: .1-1 G 5G: .25-10 G	Entire Cellular Area	Medium	Medium	Multiple CC	OFMDA	NA

Protocol (CoAP) [39], Message Queue Telemetry Transport (MQTT) [40], Extensible Messaging and Presence Protocol (XMPP) [41], Advanced Message Queuing Protocol (AMQP) [42], Data Distribution Service (DDS) [43], and Web Socket [44], [45]. Al-Fuqaha et al. discuss different IoT Network Application Layer protocols in detail [3]. In [45], Karagiannis et al. present a comparison of different Application Layer protocols with respect to different metrics: Transport protocol, Quality of Service options, Architecture, and Security.

2) Transport Layer: This layer provides host-to-host communication services for the applications used. These services include connection-oriented communication, reliability, flow control, and multiplexing. The two most popular Transport Layer protocols are adopted from the Internet protocol suite, namely, Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). TCP is a connection-oriented protocol that provides reliable transmission, whereas UDP is a connection-less protocol with no guarantees of data delivery. For example, MQTT, XMPP, and AMQP Application Layer protocols utilize TCP. On the other hand, the CoAP protocol is a UDP protocol. A different specification for MQTT protocol for Sensor Networks (MQTT-SN) was developed to map the MQTT to operate with UDP. The DDS protocol is designed to operate with both TCP and UDP [46].

3) Network Layer: This layer is responsible for addressing objects and routing data between different entities in the network. It was envisioned that the IPv6 would help solve the challenges related to the addressing of a large number of objects in the IoT model. However, as the constraints of IoT objects continue to propagate through the stack of the IoT Object Abstraction Layer, utilizing IPv6 could prove cumbersome for some of the IoT objects. To address the limitation of using IPv6 with low-power devices, a modified version of the IPv6 in which overheads are removed has been developed as part of the Low-Rate Wireless Personal Area Networks (LR-WPANs). This modification has led to the development of IPv6 for Low power Wireless Personal Area Networks (6LoWPAN) protocol [47]. Other LR-WPANs protocols include Zigbee [48], ISA100.11a [49], and WirelessHART [50]. Long Range Wide Area Network (LoRaWAN) protocols are being developed for IoT. The protocols are operating on top of the Long Range (LoRa) Physical Layer protocol. An adaptation of LoRaWAN has been developed to allow for IPv6 transmission, referred to as 6LoRaWAN [51].

Routing protocols operate on top of the addressing protocols to forward data from one node to another. Depending on the network segment responsible for forwarding the data, different routing protocols will be used. For example, the ZigBee network utilizes the Ad hoc On-Demand Distance Vector (AODV) Routing protocol [52].

Routing protocols developed for IoT Low-Power Lossy Networks (LLNs) can be classified as proactive or reactive. In proactive routing protocols, gateways construct routes between nodes in the network even without data routing requests [53], making these routing protocols suitable for applications with periodical data collection. A famous example of proactive routing protocols used for is the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [54]. On the other hand, a reactive routing protocol establishes on-demand routes when a node has data to transmit. Therefore, a reactive routing protocol is most suitable for applications with infrequent data traffic. An example of a reactive routing algorithm for LLNs is the Lightweight On-demand Ad hoc Distance-vector Routing ProtocolNext Generation (LOADng) [55] and LOADng-IoT [53].

4) Link Layer: This layer is responsible for taking the data formatted by the Network Layer and prepare it for the single-hop node-to-node transmission through the Physical Layer. Protocols at this layer are directly related to the protocols and technologies used in the Physical Layer. Therefore, for most of the conventional wired and wireless technologies utilized by the IoT network, the corresponding Link Layer protocols, including logical link control (LLC) and media access control (MAC) sublayers, are pre-defined. New technologies developed are being defined and usually protocols for Link and Physical Layers are jointly defined.

5) Physical Layer: The Physical Layer (PHY) is responsible for the bit-level transmission of data over the physical medium. The medium used in this layer can be wired or wireless. Wired medium provides high capacity; however, it

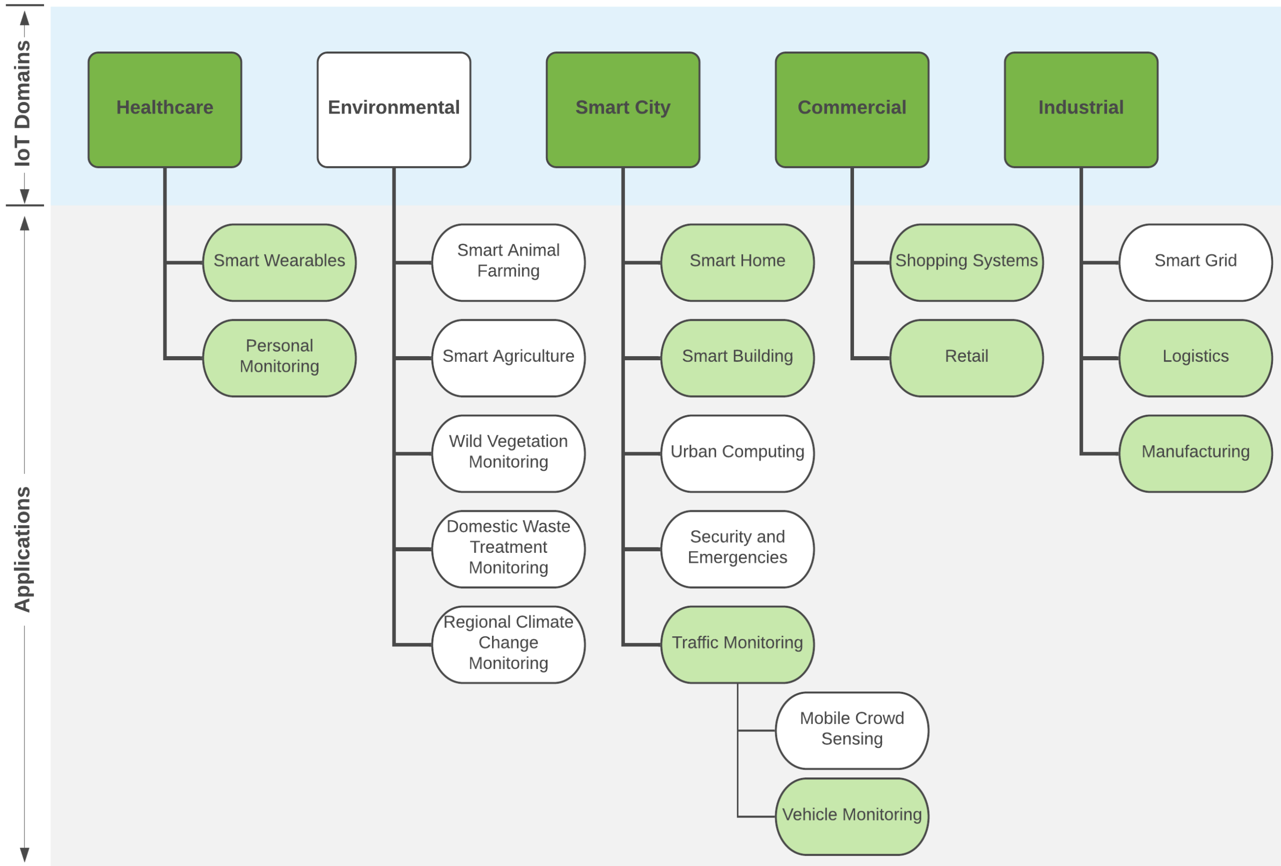


Fig. 6: A taxonomy of IoT domains and applications adopted from [56] with some modifications. Highlighted blocks indicate domains and applications for which at least one paper that discusses an OWC link is found and surveyed.

has limited flexibility and can be costly. On the other hand, wireless communication provides flexibility and mobility.

There is a wide range of RF Wireless technologies, and thus, considerations for range, reliability, bandwidth, security, cost, energy consumption, and environmental factors influencing which protocol to use [3], [37], [38], [56]. Table II summarizes different wireless protocols and technologies used in the Physical Layer of the IoT. The IEEE 802.15.4 and IEEE 802.11 standards are the basis for several Object Abstraction Layer protocols that utilize IP routing. IEEE 802.15.4 focuses on the Personal Area Networks (PANs) with short-range, lower power, and lower data rates as compared to the IEEE 802.11. WiMAX (IEEE 802.16) is a standard similar to Wi-Fi but has access to lower frequencies that are better at penetrating obstacles. The Cellular network is a widely used network with worldwide coverage and an ability to maintain the connection in highly mobile applications. LoRa and Z-Wave are low data rate, low power consumption RF protocols that operate over a large coverage area using sub GHz frequencies commonly used in Wireless Sensor Networks (WSNs). Bluetooth is used to create PANs while utilizing management features not present in other protocols using the same frequency band. Bluetooth Low Energy (BLE) is a lower energy implementation that operates around the same range but at a lower data rate. RFID is suitable for identifying objects since it facilitates a low-power one-way connection that sends only a single message called a tag or ID to a nearby receiving device.

OWC technologies, which are the focus of this survey, span the three lower layers (Physical, Link, and Network Layers) in the IoT Object Abstraction Layer with varying degrees depending on the specific OWC technology. Therefore, in the rest of this paper, our discussion will focus on the Object Abstraction Layer. The most significant OWC standard that is related to the IoT is the IEEE 802.15.7, which defines the protocols for the Physical and Link Layers. The standard will be discussed in detail in Section III as we present the preliminaries and basic concepts for the OWC domain.

IoT Middleware

The scale of diversity at the lower layers of the IoT architecture and thus the accompanying challenges become more apparent as we move up the stack. One such difficulty is the fact that no common standard can be developed and used with the variety of devices deployed in different IoT domains [57]. To develop a meaningful business model, various applications from different domains must utilize the data sent from the perception layer. To this end, data must be abstracted and adapted to be ready for different applications [29]. The Middleware IoT layer is the layer responsible for performing this abstraction to interface the diverse and heterogeneous components and services at lower layers and the IoT Application layer [3], [29], [57]. The Middleware layer performs its tasks by storing in databases, analyzing, and processing the massive scale of data collected by the sensors and relayed by the object abstraction layer. Data collected is then used to develop services through mashup tools. The mashup tools provide the users at the IoT Application layer with application programming interfacing (API) to utilize the services. The degree of sophistication in the mashup can range from putting data together in a manually prewired fashion to using semantics and ontology leading to Semantic Mashup [58].

IoT Application Layer

This layer is the layer at which services from IoT's infrastructure along with the industry needs converge to realize the intellectualized industry; that is, the conventional industry with the added value of processed data from the IoT Middleware [29]. Applications can be in a wide range of sectors and domains such as healthcare, smart city, commercial, environmental, telecommunications, and industrial, among others. In the following, we briefly summarize the major IoT domains discussed in this paper:

- **Healthcare:** IoT connected devices used by healthcare providers to monitor and manage patient health with rapid, accurate, low-cost solutions are increasing. The Healthcare domain comprises any application that is related to maintaining or monitoring patient health.
- **Smart City:** Applications involve both public and private sector applications that do not pertain to sales or production. Managing resources for a building, transportation, or public area constitute a general goal for Smart City applications.
- **Commercial:** Applications aim to attain economic goals. Usually involves improving user experience in facilities and areas such as shopping centers and museums.
- **Environmental:** Applications pertain to agricultural and natural spaces and resources such as water, energy, and mining.
- **Industrial:** Includes applications related to manufacturing, production, and efficient distribution of resources, like running factory equipment or managing a supply chain for a warehouse.

Figure 6 depicts a summary of IoT domains and applications. It is worth pointing out that the domains and applications taxonomy presented in Figure 6 is non-exhaustive and is not based on standard classification. Therefore, there may be overlaps between different applications. It is also possible that one application can be thought of from different perspectives such as provider and consumer. As a result, the same application can be listed under two different domains.

IoT Business Layer

At this layer, the services provided by a business or a vertical converge with the needs of the business customers (individuals or other businesses). Among others, the responsibility of the IoT Business layer is to develop a profitable business model [29], [30] taking into consideration the cost of collecting, relaying, and processing data in the underneath IoT layers. The cost of developing market analysis reports, application and business services, marketing, and managing and securing users' data are also considered at this layer.

C. Existing IoT Taxonomies and Surveys

The lack of a unified IoT definition has led to the existence of several IoT taxonomies and classification schemes in the literature, none of which is inclusive nor agreed-upon. Most existing taxonomies either list different classes at each of the layers in the IoT stack [34], [36], [59], [63] or focus on one or a subset [32], [33], [56], [57] of the layers in the IoT architecture. In this paper, we follow the former approach of using the full stack of IoT layers to describe a surveyed system from the literature in Section IV.

In [33], Rozsa et al. present a taxonomy of sensors at the Object Layer based on the domains at the Application Layer. In [32], Dorsemaine et al. present a more generic taxonomy that can fully characterize any connected object in the IoT Object layer. An object is characterized by its communication, functional attributes, hardware and software resources, local user interface, and energy. A taxonomy of networking technologies used in the Object Abstraction layer is presented by Sethi and Sarangi in [36]. In this paper, the authors classify networking into Wireless Sensor Networks (WSNs), Near Field Communication (NFC), RFID and WSN integration, Internet Protocols for Smart Objects, and Low-Power Technologies. Multiple surveys focused on the Middleware layer [57], [58], [64]. General Application layer domains are classified in [56].

Similarly, there is a significant number of survey papers on the IoT. Some of the surveys in the literature review IoT architectures [37], security [58], protocols [3], middlewares [57], [64], general applications [56], or specific applications such as, smart cities [62] and IoT in healthcare domain [38]. Table III tabulates major and most related IoT taxonomies and surveys in the literature.

Al-Fuqaha et al. conducted a survey on IoT protocols, with a limited discussion about specific use-cases. The Object Abstraction layer protocols examined for use in IoT networks were all lightweight RF link layer protocols [3]. IEEE 802.15.4, BLE, EPCglobal, Cellular, and Z-Wave were examined across five characteristics to compare feasibility in IoT systems. From these specifications, the authors determined that the efficient communication and scalability of these protocols were the most attractive link layer protocols to use in IoT and M2M environments [3].

In [37], Ray surveys 130 research papers to identify characteristics of IoT architecture. This included use-cases, protocol stacks, and grouping these into application domains to discover trends. With regards to RF in IoT, the author assessed that

TABLE III: Chronological Summary of Major and Related IoT Taxonomies and Surveys in the Literature.

Reference	Year	Type	IoT Layer	Focus	RF	OWC
Bandyopadhyay et al. [57]	2011	Classification & Survey	Middleware	Role and building blocks	✓	✗
Zhao et al. [59]	2013	Survey	Multi	Security	✗	✗
Xu et al. [60]	2014	Survey	Multi	Survey of technologies and applications	✓	✗
Dorsemaine et al. [32]	2015	Taxonomy	Object	Classification of objects	✓	✗
Al-Fuqaha et al. [3]	2015	Survey	Multi	Protocols	✓	✗
Kadam and Dhage [61]	2016	Literature Review	NA	Modulation techniques	✗	✓
Rozsa et al. [33]	2016	Taxonomy	Application & Object	Classification of sensors based on applications	✗	✗
Ray [37]	2016	Survey	Multi	Domain-specific IoT Architectures	✓	✗
Arasteh et al. [62]	2016	Survey	Application	Smart Cities	✗	✗
Yaqoob et al. [63]	2017	Taxonomy	Multi	Multi-layer classification	✓	✗
Sethi and Sarangi [36]	2017	Taxonomy & Survey	Multi	Multi-layer survey	✓	✗
Ngu et al. [64]	2017	Survey	Middleware	Survey of Middlewares	✓	✗
Ahmadi et al. [38]	2018	Survey	Application	Healthcare	✓	✗
Teli et al. [22]	2018	Literature Review	NA	General Applications and Challenges	✗	✓
Boyes et al. [34]	2018	Classification Framework	Multi	Industrial Internet of Things	✗	✗
Asghari et al. [56]	2019	Taxonomy & Survey	Application	Survey of domains and applications	✗	✗
Hou et al. [65]	2019	Survey	Multi	Security	✗	✗
Turan et al. [66]	2019	Survey	Application	VLC technology & future directions	✗	✓
Chowdhury et al. [67]	2020	Classification and Survey	Application and Object Abstraction	Review of Connectivity Technologies	✓	✓

the most common communication protocols within the surveyed use-cases were WiFi, WiMAX, IEEE 802.15.4, Cellular, Bluetooth, RFID, and LoRa. The surveyed IoT architectures were classified across domains including RFID, WSNs, Supply Chain Management, Healthcare, Smart society, Cloud services, Social computing, and Security.

In [56], Asghari et al. selected 72 research studies in IoT applications then focused on categorizing the domain of IoT applications and identifying a standard taxonomy amongst them. Out of that sample, the authors determined the evaluation environments for the IoT application and found that 24% were implementations, 58% contained data from simulations, and 14% had neither. However, there was a lack of focus on protocol stacks, with only 11 Object Abstraction protocols identified and five Application Layer protocols listed. Out of the Object Abstraction protocols, all were RF standards and included 3G, BLE, ZigBee, GSM, WiFi, RFID, 802.15.4, and Narrowband RF.

Ahmadi et al. surveyed 60 research papers that focused on IoT applications within the Healthcare domain to find the effects and challenges of IoT in healthcare [38]. The paper included 3 Application layer protocols, and 8 Object Abstraction layer protocols in the overview and detailed which protocols used within all surveyed Healthcare applications.

Despite being incomprehensive, Table III shows that the majority of existing IoT survey papers addressing the wireless communication in the IoT Object Abstraction layer focus on the RF technologies. The focus on RF technologies is justifiable since RF technologies are the most widely used wireless technologies and have been under continuous development for many decades. On the other hand, very few papers have surveyed the deployment of optical communication technologies in general, and the OWC technology in particular, in the IoT domain. Even within the optical communication research community, papers discuss the deployment of fiber optics in the backbone of the IoT infrastructure [68] with no or limited discussion of the OWC technology. On the other hand, the papers that address the OWC technology in IoT are limited to the enabling technologies of the OWC itself or high-level discussions of the potential of the OWC in IoT.

In [61], Kadam and Dhage present a literature review of VLC and hybrid VLC/RF setups in general used to advance the VLC domain. Two of the surveyed papers are related to IoT applications. Surveyed papers are discussed with a focus on identifying modulation techniques that are most suited for indoor applications, including IoT. However, papers that used OWC in IoT specific applications were not reviewed.

In [22], Teli et al. present a high-level discussion of the advantages and the potential role of the VLC technology in different applications that can fall under the IoT domain, referring to it as the Optical Internet of Things (OIoT). The authors review five papers discussing enabling technologies for VLC in IoT, including protocols, localization, and modulation. The paper, however, does not get into the details of specific applications and implementations.

In [66], Turan et al., provide a summary of the role of VLC in the Industrial Internet of Things (IIoT). Similar to the work in [22], the majority of the book chapter focuses on the VLC domain and its enabling technologies. The paper then highlights the potential of the OWC in future IoT applications. A total of three papers related to the OWC in IoT were reviewed by the authors.

In [67], Chowdhury et al. present a visionary discussion of the anticipated role of the OWC technologies in the 5G/6G and IoT solutions. The paper reviews the 5G, 6G, and IoT systems and requirements followed by a short review of existing OWC-Based 5G and IoT Systems, out of which four reviewed papers are related to the IoT.

In a more recent paper [69], Ding et al. review connectivity technologies and applications in IoT. This paper is the first paper to discuss OWC as an integral part of the connectivity in the Object Abstraction Layer in the IoT. The paper, however, had a minimal review of OWC deployments in the IoT domain in which the work by Teli et al. [22] is referenced.

There is an abundance of publications in general, and surveys in particular, discussing the IoT. Limited survey papers focus on OWC technology in the context of IoT. None of the OWC-centric survey papers discuss OWC as an enabler of a complete IoT solution with a clear understanding of the object, object abstraction, middleware, and application layers. Instead, the majority of the publications focus on the VLC as an OWC technology, high-level visionary discussions of VLC in IoT, and VLC enabling technologies such as modulation and localization.

III. OWC Preliminaries and Basic Concepts

Based on the IoT five-layer model discussed in Section II, we can see that the OWC fits in the Object Abstraction layer with other RF technologies and standards, such as RFID, 5G, WiFi, Bluetooth Low Energy, etc. Unlike RF, OWC has fewer standards with the most notable standard being the IEEE 802.15.7-2018 [13], [70]. Therefore, in the case of OWC application in IoT, we cannot only mention the standard as is the case for RF. Instead, we believe that a detailed and more specific classification must be used to distinguish OWC implementations in different IoT systems.

In this section, we present a brief background related to OWC technology. This background is necessary to understand the technical contents of the papers surveyed in Section IV.

A. OWC Frequency Bands and Link Configurations

OWC is the use of a modulated fast switching light emitter such as a Light Emitting Diode (LED) or Laser Diode (LD) to send data that can be received by image sensors (e.g., camera) or photodetectors [13]. The three frequency bands of Infrared (IR) 3 THz-300 THz, Visible Light (VL) 380 THz-790 THz, and Ultraviolet (UV) 790-3000 THz are commonly used to break up the large OWC bandwidth into frequencies with similar characteristics. Similar to fibre-optic systems, Near IR (NIR) band is used in OWC applications in almost all environments indoor [12], underwater [71], terrestrial, and space [72]. UV is also invisible and can be physiologically damaging because of its high energy [13], therefore, UV is proposed to be used in terrestrial and underwater OWC systems using back-scattering links which is referred to as *optical scattering communication (OSC)* [73]. VL is the only visible band to the naked eye and is utilized widely to illuminate living quarters, work spaces, and businesses. It is proposed to utilize the growing LED-based illuminating infrastructure to perform communication along the primary illumination functionality leading to the VL Communication (VLC) that is widely used in indoor [74], terrestrial [75], and underwater [16].

An OWC link can be classified based on the following five criteria [13]:

- **Environment (ε):** OWC technology can be used in four different environments, namely: *Indoor (I)*, *Terrestrial (T)*, *Space (S)* and *Underwater (UW)*.
- **Coverage Type (κ):** An OWC link can be either point-to-point, i.e., *Point Coverage (PC)* or point-to-multipoint, i.e., *Cellular Coverage (CC)* link.
- **LOS Availability (α):** An OWC link can be achieved using *LOS* or non-LOS (*NLOS*) link configuration. In case of the NLOS OWC link, the the light can either reflect of off a *specular* surface (e.g., mirrors, beam splitters) or a relayed using an active repeater that receives a signal from the transmitter and re-transmits the signal to the intended receiver. Due to the limited reflectivity of the high-frequency OWC waves, the NLOS model adds challenges to the modeling and practicality of the OWC applications.

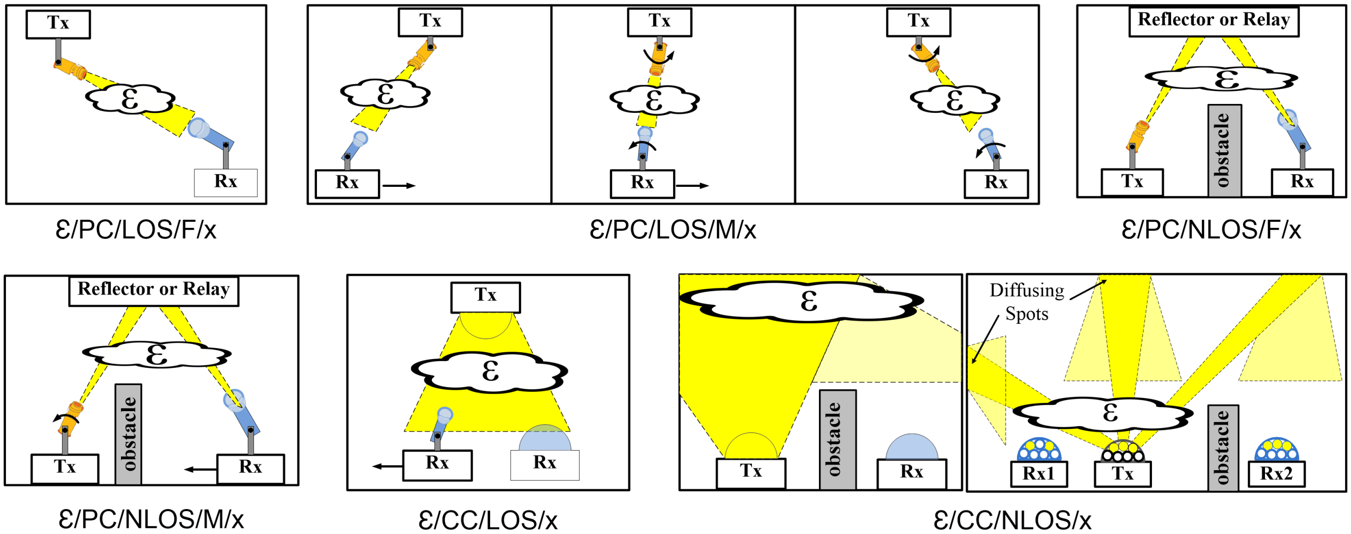


Fig. 7: Different OWC link configurations based on the classification in [13]. The cloud symbol represents the environment (ϵ) in which the link is implemented. The ϵ can represent Indoor (I), Terrestrial (T), Space (S), Underwater (UW), or anay combination of these environments. We use the notation *Tx* and *Rx* to refer to a transmitter and a receiver, respectively. Arrows represent mobility of the transmitter and/or receiver in any direction.

- **Mobility** (μ)**:** Depending on the mobility of the transmitter and receiver, an OWC link can be either a *fixed (F)* or *mobile (M)* link.
- **Link Distance** (δ)**:** The range of the OWC link can be Ultra-short range [$\leq$ 5 cm e.g., chip-to-chip communications], Short range [$\leq$ 50 m e.g., underwater communications], Medium range [$\leq$ 500 m e.g., indoor wireless local area networks (WLANs)], Long range [$\leq$ 500 km e.g., terrestrial connections], and Ultra-long range [$\geq$ 500 km e.g., deep space links].

Using these five criteria, an OWC link configuration can be expressed using the tuple $(\varepsilon/\kappa/\alpha/\mu/\delta)$, such that:

$$
\begin{aligned}
&\varepsilon \in \mathcal{P}\left(\{\ I, T, S, UW\ \}\right) \setminus \{\emptyset\}.\\
&\kappa \in \{\ PC, CC\ \}\\
&\alpha \in \{\ LOS, NLOS\ \}\\
&\mu \in \{\ F, M\ \}\\
&\delta \in \{\ UShort, Short, Medium, Long, ULong\ \}
\end{aligned}
$$

where $\mathcal{P}(.)$ is the power set. For example, an indoor, point-to-point link that is established between two fixed terminals that are few meters apart and utilizes a LOS model can be described as $I/PC/LOS/F/Medium$. Figure 7 depicts different link configurations that result from the classification adopted in the generic environment ε.

The choice of the transmitter, receiver, and modulation technique depend heavily on the application requirements and constraints. In the following, we briefly describe different types of transmitters, receivers, and modulation schemes to familiarize the reader with the OWC technology.

B. Transmitters

An OWC link can utilize a single or an array of light sources at the transmitter. A light source can be either a Laser Diode (LD) or a Light Emitting Diode (LED). In the following, we briefly discuss both light sources.

LD: an LD emits high-bandwidth coherent and focused beams with low divergence. Therefore, LDs are usually used for high data rate specialized indoor and long-distance outdoor applications. The high-power focused beams from LDs, however, can be harmful to the eyes, and therefore regulations for operating power are in place. A possible approach to comply with the restrictions when operating using LD is to deploy a beam diffuser to reduce the intensity and spread the beam.

LED: Compared to LDs, LEDs are usually cheaper to produce and more stable. LEDs are also less hazardous to humans than LDs since they are extended sources with larger emitting areas and beams. The diffused LED beam, however, leads to lower signal strength, and thus relatively shorter achievable distance and data rate [76]. Recent research efforts aim to increase the data rate of LEDs recent studies show that Organic LEDs (OLEDs) can help achieve high data rates up to 1.13 Gbps [77]. Another study by Tsonev et al. demonstrates a 3 Gbps FSO link utilizing a single 50-μm gallium nitride LED and Orthogonal frequency division multiplexing (OFDM) modulation scheme [78].

In the context of IoT, an OWC link will more likely utilize an LED over an LD [79]. This is because LEDs are cheaper and more reliable as compared to LDs. Moreover, LDs emit narrow beams leading to lower coverage and stringent alignment requirements. On the other hand, LEDs are extended sources with large-area emitters leading to broader coverage areas and safe operations at relatively high power. Using an LED light source, a transmitter can send data that is processed *LED*, or unprocessed *LED Identification (LED-ID)*. With that said, there is not a technical reason that hinders the use of the LD in the IoT domain. At the other end of the IoT OWC link, the data transmitted can be received using photodiodes (PDs) or with cameras which is called Optical Camera Communication (OCC).

C. Receivers

Receivers in OWC systems can utilize photodiodes (PDs), also referred to as photodetectors, or cameras to detect transmissions. In the following, we briefly discuss both types of OWC receivers.

Photodiodes (PDs): The two most common PD receivers are Positive-Intrinsic-Negative (PIN) diodes and Avalanche photodiodes (APDs). All PDs absorb photons and generate a current in proportion to the absorption with different degrees. Because of the fast switching of the generated current, PDs are desirable for high bit rate transmissions [95].

PINs are low-cost PDs that can operate at low bias and are tolerant to wide temperature fluctuations [96], [97]. Therefore, PIN PDs are preferred in low-cost and low data rate OWC links. APDs are PIN PDs operating at very high reverse bias. As a result, APDs experience high internal electrical gain and Signal-to-Noise Ratio (SNR) at the receiver [96], [98]. The additional gain generated in the APDs makes them excellent candidates for applications with limited ambient light noise and in high data rate and high-performance OWC links. APDs, however, are more expensive, and their gain is temperature-dependent. In [97], Ghassemlooy et al. analyze different noise sources impacting PINs and APDs.

Researchers are exploring technologies such as graphene, two-dimensional materials, and (nano)materials, such as plasmonic nanoparticles, semiconductors, quantum dots to develop faster PDs capable of meeting the demands for higher data rate links [99]–[101].

Recent research, also, explores replacing or integrating the PDs with solar panels [102]. In this scenario, solar panels will simultaneously serve as energy harvester and PD, leading to a prolonged operation lifetime. The extended operation time is a useful feature for IoT applications. To distinguish regular PDs and those equipped with solar panels, we refer to the latter as Photodiode-Solar Panel (PD-S) receivers.

Image Sensors: A typical example of image sensors is the complementary metal-oxide-semiconductor (CMOS) camera that is built-in most of the consumer-grade electronic devices. Such cameras can be used as receivers in OWC links [13]. If a camera is used, the OWC link is referred to as an Image Sensor Communication (ISC), or more commonly as an Optical Camera Communication (OCC) link. OCC is more practical for most consumer-specific applications because it allows consumer-grade devices, that are not specialized in OWC, to receive data through a CMOS camera with rolling shutter. OCC technology offers several advantages such as the larger field of view (FOV), spatial separation of light, and wavelength separation [103]. We refer readers interested in OCC technology to the recent work by Saeed et al. [104] in which they present a comprehensive survey of the technology. Other related work can be found in [105]–[108].

A camera shutter can be either a rolling shutter (RS) or a global shutter (GS). The difference between the two shutter types is how the camera captures an image. Rolling shutter develops an image by capturing one row of pixels at a time, working across the frame, depending on the shutter speed. A global shutter camera develops the entire array at the same time. Although Rolling shutter and Global shutter cameras interact with modulation schemes differently, the receivers can still be designed to decode the same transmitted signal.

An OCC link typically has a lower bit rate as compared to that of a system utilizing a photodetector. The bitrate limitation is because the bitrate is dependant on the camera's frame rate. The typical frame rate of 30-60 frames per second (fps) leads to slower camera sampling rates as compared to that of photodiodes. Therefore, OCC links are more suitable for lower bitrate links such as in many IoT applications.

Modulating Retroreflector (MRR): In the late 1990s, the U.S. Naval Research Laboratory (NRL) started conducting experiments on modulating retroreflector (MRR) FSO communication links [109]. An MRR link comprises an interrogator with ample power at one end and a small passive corner cube or a cats eye optical retroreflector coupled to an optical modulator at the other end. The interrogator transmits a beam light beam towards the retroreflector, which modulates and reflects the beam back to the interrogator. The limited duplex MRR link has been successfully used in Terrestrial shore-to-shore, boat-to-shore, and sky-to-ground links. Minimal indoor application of the MRR links has been discussed in the literature [110], [111].

D. Modulation

Based on the application requirements, a modulation scheme with appropriate transmission reliability, energy, and spectral efficiencies. The most straight forward and commonly used OWC modulation scheme is On-Off keying (OOK) modulation. In OOK, a light beam is switched on and off based on the data bits. Despite the simplicity of OOK, it can be inefficient in high bitrate applications. More sophisticated modulation schemes are needed for high bitrate applications such as Pulse Width Modulation (PWM) [112], Pulse Position Modulation (PPM) or one of its variations, e.g., Variable-PPM (VPM) [97], [113], [114]. The higher efficiency of PPM-based modulation schemes, however, comes at the cost of a more complex time-domain equalization. This additional complexity can pose a challenge for OWC links with low-quality channels [115].

A modulation scheme is either a single-carrier, such as OOK and PPM, or a multi-subcarrier modulation scheme. Single-carrier modulation schemes have lower bandwidth efficiency, and therefore, at higher bitrates, they experience higher inter-symbol interference (ISI) and become inefficient [116].

Subcarrier Intensity Modulation (SIM) and Multiple SIM (MSIM) such as Wavelength Division Multiplexing (WDM) and Orthogonal Frequency-Division Multiplexing (OFDM) offer better bandwidth efficiencies and can help mitigate OWC channel impairments [117]. In SIM-based modulation schemes, a pre-modulated RF signal drives the optical source. A DC bias is added to the pre-modulated signal to obtain an all positive amplitude [118].

More subcarriers must be used to achieve a higher bitrate. However, as the number of subcarriers increases, so does

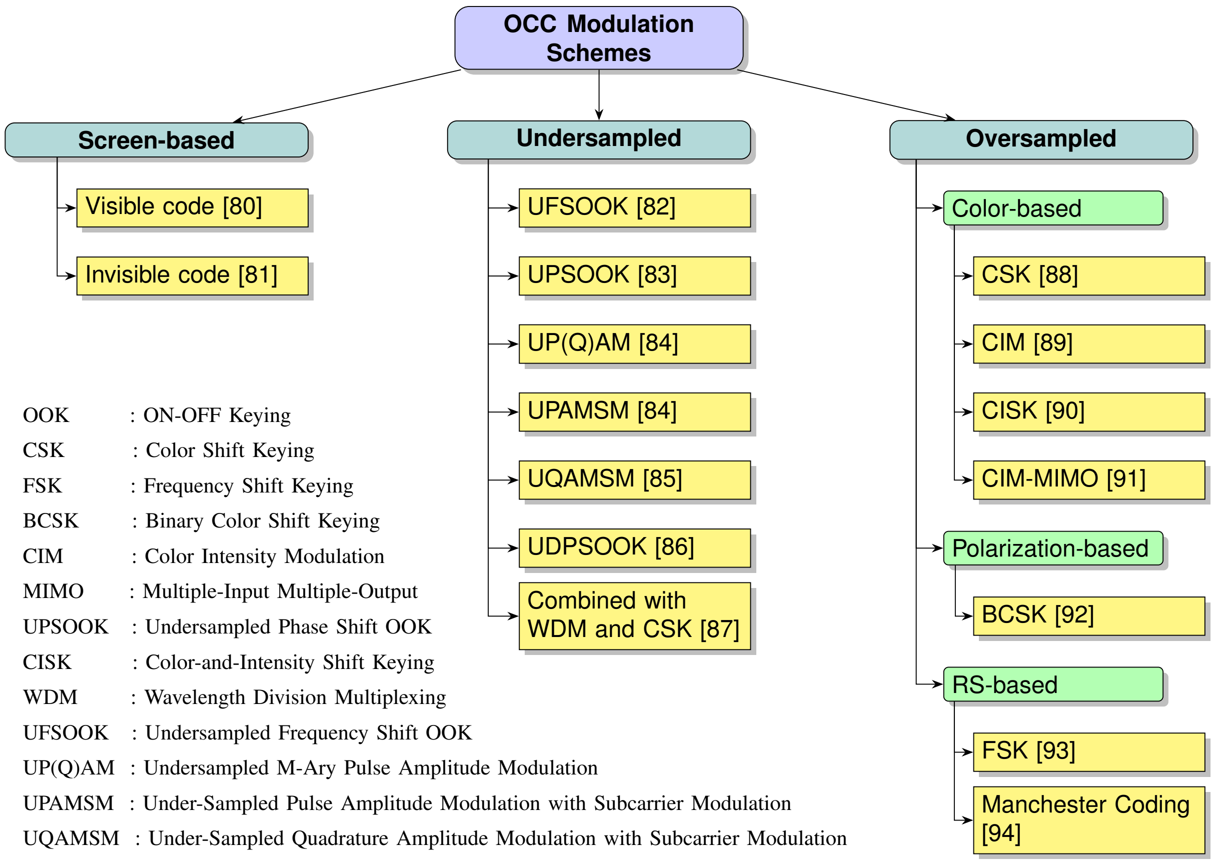


Fig. 8: Summary of main OCC modulation scheme categories and examples

the required non-information DC bias, which can lead to a higher peak-to-average power ratio (PAPR) and worsens the power efficiency [117]. PAPR can be mitigated using reduction techniques and pre-distortion or post-distortion nonlinearities-compensation methods [119]–[121]. Moreover, the light source nonlinearity causes interference among the subcarriers and broadening of the signal spectrum resulting in mixed signals and Inter-Modulation Distortion (IMD) [118], [122]. The effect of the nonlinearity can be mitigated by using fewer subcarriers at the cost of reduced bitrate, or utilizing spatial diversity, with increases to overall system cost [123].

We refer readers, interested in SIM modulation techniques, to the survey conducted by Hassan et al. in which they discuss the advantages and challenges of SIM/MSIM [117].

Although most of the modulation schemes discussed above can be used for OCC links, most of these modulation schemes modulate faster than the camera frame rate. If the modulation frequency was reduced to be closer to the frame rate, the frequency would be less than the critical flicker frequency (CFF) of the human eye. Any human will be able to distinguish this flickering visibly, making the OCC link inconvenient. Since the camera cannot receive the data as quickly as PD receivers, new schemes that are specific to rolling shutter cameras or global shutter cameras were created [103], [104], [124].

In [103], Luo et al. classify OCC modulations into three categories, namely, screen-based, oversampled, and undersampled modulation schemes. In screen-based modulation schemes, a visible (QR-like) or invisible (embedded) code is used to modulate a 2D array of LEDs. In oversampled modulation techniques, the received signal is oversampled during the demodulation. In an undersampled modulation, which is a form of SIM, a signal is transformed from baseband to passband and then used to modulate light source at a frequency higher than the CFF. The three modulation categories can achieve flicker-free modulation; however, undersampled modulation schemes are more suitable for low data rate, long-range transmission, oversampled schemes are high data rate, but shorter distance. Screen-based modulation can achieve similar data rates as an array of transmitters using undersampled schemes.

We include Figure 8 to depict and familiarize the reader with the different existing OCC modulation categories and schemes. The details of different modulation schemes, however, are beyond the scope of this survey paper. Therefore, we refer interested readers to the recent comprehensive surveys on OCC modulation schemes [103], [104], [124]. Nonetheless, as we review the papers from the literature in Section IV, and if the details of a specific modulation scheme are deemed necessary to understand the paper under consideration, we will provide the reader the details of that specific modulation scheme.

E. Standards

The ever increasing interest in OWC technology has motivated several initiatives to standardize the technology (see

TABLE IV: Summary of Existing OWC Standards and Recommendations

Standard/Recommendation Name	Type	Environment	Status	Focus
IrDA [125]	Standard	Indoor	Active	Short-Range IR Links
JEITA CP 1221-1223 [126]	Standard	Indoor	Active	VLC
IEEE 802.11 [127]	Standard	Indoor	IR Suspended (1997)	LAN RF and IR Links
IEEE 802.11bb [128]	Project	Indoor	Active	IEEE 802.11 MAC Changes to use Light as a Medium
IEEE 802.15.7-2011 [129]	Standard	Indoor & Terrestrial	Superseded by IEEE 802.15.7-2018	Short-Range OWC
IEEE 802.15.7-2018 [129], [130]	Standard	Indoor & Terrestrial	Active	Short-Range OWC
IEEE 802.15.7m [131]	Standard	Indoor & Terrestrial	Active	OCC
ITU G.VLC [132]	Standard	Indoor	Active	High-Speed VLC Transceiver
IEEE P802.15.13 [133]	Project	Indoor & Terrestrial ($\leq$ 200 m)	Active	Multi-Gbps OWC with Ranges up to 200 meters
ITU-R F.2106-1 [134]	Recommendation	Terrestrial	Active	Fixed FSO LD-based Links
IOAG.T.OLSG.2012.V1 [135]	Recommendation	Space	Active	Inter-organization Standard for Space FSO Communication

Table IV). Among the four environments comes the Indoor environment with the most significant standardization efforts, followed by Terrestrial, then Space, and complete absence of standardization in the Underwater environment [13]. We believe that understanding the existing OWC standardization efforts will help us better understand the papers to be reviewed in Section IV. We focus our discussion on short and medium-range indoor and terrestrial OWC systems.

1) IEEE 802.11: In 1997, IEEE released the standard IEEE 802.11 in which two data links, 1 and 2 Mbps, are specified [127]. The first link operates in the 2.4 GHz frequency in the Industrial, Scientific, and Medical (ISM) band, which is now known as the WiFi. The second link operates in the IR band (850-950 nm) and has a range of 10 m. Two modulation schemes, 16 and 4 PPM, are used for the two data rates 1 and 2 Mbps, respectively. The limitation of the enabling technologies in 1997 prevented the broad deployment of the IR link, and the development of the standard for the IR link was suspended.

2) IEEE 802.15.7 and IEEE 802.15.7m: In 2011, the IEEE 802.15.7-2011 standard for VLC was released, defining the PHY and MAC layers for short-range OWC using VL for Local and metropolitan area networks [13]. In 2014, the Short-Range Optical Wireless Communications Task Group was tasked to revise the IEEE 802.15.7-2011 to broaden the scope of the standard to include IR and near UV as well as including other communication techniques such as OCC. As a result, the revision IEEE 802.15.7-2018 was released in 2018. The standard defines three classes of VLC devices:

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

The three VLC devices can be arranged in one of three network topologies:

- Star: Supports communication between several devices and one coordinator assigned a unique optical wireless personal area network (OWPAN) identifier not used within the coverage area.
- 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 without forming a network.

Three PHY layers were defined in the 2011 version of the standard such that they can co-exist but not interoperate. The revised version of the standard slightly modified the original three PHY types and added three new PHY types with a list of modulations schemes for each new PHY type.

- PHY I: Low data rate outdoor applications (11.6 to 266.6 kbps). Employs OOK and VPPM.
- PHY II: Moderate data rate indoor applications (data rate in the tens of Mbps). Employs OOK and VPPM.
- PHY III: Designed to support systems with multiple light sources/detectors at different frequencies (colors). Employs Color-Shift Keying (CSK) with data rate in the tens of Mbps.
- PHY IV: For the use of discrete light sources with data rates $\leq$ 22 kbps.

TABLE V: Overview of Recent OWC in IoT Research Efforts Based on IoT Domain and Transmission-Receiver Pair

Domain	Number of Publications	LD/PD	LED-ID/PD	LED-ID/OCC	LED/PD	LED/OCC	LED/PD-S
Healthcare	9	NA	NA	NA	[136]–[141]	[142]–[144]	NA
Smart City	19	[145]	NA	NA	[146]–[151] [158]–[162]	[147], [152]–[156]	[157]
Commercial	5	NA	[147], [163]	NA	[147]	[147]	NA
Industrial	4	NA	NA	[164]	[165]–[167]	NA	NA

- PHY V: For diffused surface light sources with data rates $\leq$ 5.71 kbps.
- PHY VI: For video displays with data rates in kbps.

The IEEE 802.15.7m TG focused on the OCC operation which uses PHY IV, V, and VI. The IEEE 802.15.7-2018 standard includes tables listing different operating modes for OCC using different PHY types. For each mode, a modulation scheme, optical clock rate, Forward Error Correction (FEC) scheme, and achievable data rate are also listed.

3) IEEE 802.11bb: In July 2017, the Light Communication (LC) Topic Interest Group (TIG) was created within the IEEE 802.11 Working Group (WG) to explore the viability of utilizing the light as a medium for wireless communications. As a result of the LC TIG's efforts, an LC Study Group was formed, which worked on developing the Project Authorization Request (PAR) and Criteria for Standards Development (CSD). The IEEE 802.11 WG approved the PAR and CSD in March 2018, followed by the IEEE Standards Association's Standards Board in May 2018, and the new Light Communications amendment to the IEEE Std. 802.11 was created.

The IEEE 802.11bb LC Task Group on Light Communications focuses on introducing necessary changes to the MAC of the base IEEE 802.11 Stds and reuse of associated services to enable communications using light. Moreover, new PHY mechanisms will be defined to operate using a wide range of light sources developed by different vendors and operating at different modulation bandwidths. The project aims to standardize communication links operating in the range of 380-5,000 nm with a single-link throughput of 10 Mbps and at least one mode of operation of at least 5 Gbps. Security issues related to the interoperability of the new LC PHY and the existing 802.11 PHYs as a device transitions from one PHY to another will be considered.

4) IEEE 802.15.13: This standard defines a PHY and MAC layer using light wavelengths from 10 μm to 190 nm. The standard aims to develop links capable of achieving data rates up to 10 Gbps at distances in the range of 200 m with unobstructed LOS under varying channel conditions. The standard considers point-to-point, coordinated, and non-coordinated point to multi-point communication links. The coordinated point to multi-point communication is similar to a base station and users in cellular communication. The connectivity must be maintained as a device is moving within the coverage area of a coordinator, and handover as it moves from one coordinator's coverage area to the coverage area of an adjacent coordinator.

F. Putting it All Together

Pairing a transmitter (LD or LED) and a receiver (PD, PD-S, camera) can lead to different OWC links with varying properties and performance. Using the proper modulation scheme can also help improve the bitrate of the link. With standards being developed, complete networking OWC solutions can be realized.

One of the existing OWC networking solutions is LiFi technology. LiFi is a high-speed bidirectional local area OWC access network that operates in the VL and IR spectrum bands and builds on the VLC technology [23], [168]. In a LiFi network, LED light fixtures are used for illumination and data communication, simultaneously [169], [170]. This is achieved by equipping each LED with a LiFi chip or modem making the LED fixture an Access Point (AP).

Communication links in LiFi networks are full-duplex (bidirectional). However, several LiFi systems only include a unidirectional OWC link. Typically this involves a stationary infrastructure transmitter such as an overhead light fixture and a user equipment (UE) that utilizes RF to communicate back to the overhead LED and with other devices in the network [151]. This hybrid receiver may be to lower alignment requirements on the user's device as RF requires less attention to transmitter orientation. Other reasons may include the specific hardware required for OWC transmission in a user's device. The device would require a powerful enough transmitter that utilizes a band outside of visible light to prevent user discomfort. Nevertheless, several examples are found of mobile devices capable of duplex LiFi that used the IR band for the uplink channel [141], [150], or where the high rate transmission of OWC in the VL band made bidirectional LiFi desirable [147]. An experiment featuring a 4.5 mW LED in which data at a speed of 1.1 Gbps was successfully transmitted over a distance of 10 m [168]. If IR is used for the uplink from the UE, the AP must be equipped with an IR receiver. As the LiFi technology continues to develop, it is being designed to comply with the IEEE 802.11bb and ITU G.VLC standards [168].

IV. Survey of OWC Technology in IoT

In this section, we review and summarize papers in the domain of OWC in IoT.

Table V gives an overview of the recent major research performed in the domain classified based on the IoT domain on one dimension, and the six possible transmission/receiver pairs on the other dimension. The table also shows the number of publications in each domain. It is clear that the domain of Smart Cities is leading the OWC in IoT research. An extended and more detailed chronological summary of the major OWC in IoT studies is tabulated in Table VI. We breakdown this section into subsections based on application domains. Highlighted boxes in Figure 6 represent the areas in which we found OWC-related papers. Therefore, the following subsections will only focus on the healthcare, smart city, and commercial domains.

It is worth pointing that, we distinguish between papers related to general OWC in IoT aspects, and general OWC papers. There is a large number of papers that focus on improving the performance of OWC links in general and not in the specific context of IoT. Although developed approaches can eventually be used in the IoT domains, we believe that surveys focusing on OWC technology are more appropriate for such papers and we consider them out of the scope of our survey. A few examples of such papers are papers focused on LED-ID transmission that did not include an application, but instead gave implementations for localizing a receiver without IoT application context [171]–[175]. Other papers discussing LED/PD implementations that showcase transmission speeds and link distance, but did not extend to application of the link beyond showing connectivity [176]–[179].

A. Healthcare

The earliest example of an LED/PD OWC link in IoT is the work presented by Miller et al. [136]. In this work, IR-LEDs are utilized to transmit data to and from a ventricular heart assistance device through an implanted PD. The application is capable of maintaining an error-free link of 9600 bps at 150mm. This paper's main focus was to have the LED/PD transceiver implanted in the patient to allow a wireless link with the heart assistance device.

Using an LED/PD link Abita and Schneider created a link that sent data through porcine skin samples at 1 Mbps [137]. They used an IR LED and PD transceiver to send and receive data with an Active Medical Implant (AMI) at a distance of 24 mm. The AMI can be used in many different situations and can allow care providers to receive patient health information after the AMI is implanted quickly. The authors did not discuss higher-level applications, such as aggregating patient data over time. However, the AMI devices used were capable of storing up to 512 Kb so that longer-term data could be given to the care provider or wearer regularly.

Another example of transcutaneous LED/PD communication was found in [138]. In this paper, Okamoto et al. tested both IR and VL LEDs. They found that both IR and VL were able to transmit unhindered at 9600 bps, but the IR LED transmitted without error at a distance of 45mm while the VL-LED was capable of transmitting error-free up to 20mm.

In [142], Rachim et al. created an experimental LED/OCC setup for transmitting electroencephalogram (EEG) data. This study used a single 3-watt white LED to transmit over LOS to a smartphone on a tripod stand within the same room. They achieved error-free transmissions with an upload speed of 2.4 Kbps at a distance of 4 meters as shown in Figure 9. They proposed that this type of data transfer may replace common RF protocols used by wearable devices as a physiologically safer alternative. Even though the authors discussed no application protocol, the transmitted EEG data could be wrapped in an IoT application protocol to enable aggregation and automated healthcare monitoring to further its utility in IoT.

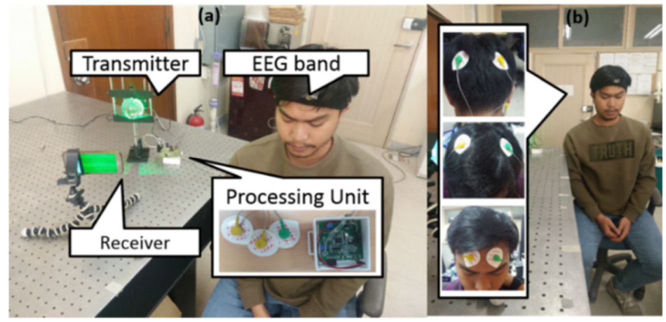


Fig. 9: Experimental setup created by Rachim et al. in [142]

In [139], Dhatchayeny et al. simulated an LED/PD link that sent vital sign measurements to a gateway. The simulation did not mention bit rates or distances but instead focused on Signal to Noise (SNR) ratio versus Bit Error Rates (BER). The team found that they were able to transmit four different signals to the same receiver with a minimal error rate when the SNR value was 12 dB, showing that the MIMO healthcare data aggregation is reliable under the correct conditions.

In another experiment by An et al., an LED/PD link was used to transmit data from multiple electrocardiograms (ECGs) to a custom made dashboard for monitoring the heart health of patients [140]. By using lenses with the LEDs, the authors were able to send data at 40 Kbps at two different distance ranges. The longest distance with a Packet Error Rate of less than 1 was at 8 m. This implementation explored Time hopping as a way to send multiple signals to the same PD receiver. The authors also considered using RF technology to supplement the link when LOS is broken.

Dhatchayeny et al. expand their previous work in [139] and offer a scenario in [141] for biomedical sensors to transmit via IR LED to reduce crowding of the RF spectrum within hospitals and allow high data rate transmission in RF sensitive environments. They propose and implement an LED/PD link for multiple health sensors to transmit patient biomedical data to a single overhead receiver. This allows multiple patients to be monitored in the same room by using a scheduling scheme for transmissions. An IR LED's choice means that there is no visible light to disturb patients or providers, but retains high data rate, LOS secure communications while not causing RF interference. The real-time information can be monitored by a server and send alerts to providers when coupled with an IoT application protocol. The experimental setup enabled transmission at 1.5m at 6.4Mbps, but no IoT Object Abstraction Layer application protocol was tested in the research.

In [144], Hasan et al. simulate a hybrid OWC/RF link system to improve the reliability of the signal from healthcare devices, while lowering the amount of RF transmission. The OWC link simulated is an LED/OCC link, and the main

TABLE VI: Chronological Order of Major OWC in IoT Studies

IoT Business Domain	IoT Application Layer	Year	Study Type	IoT Middleware Layer	IoT Object Abstraction Layer							
					OWC						RF	Application Layer
					Topology	Tx Type	Rx Type	Data Rate	Distance	Protocol		
Healthcare [136]	Heart Monitoring	1992	Implementation	N/A	P2P	LED	PD	9.6 Kbps	150 mm	FSK	N/A	N/A
Healthcare [137]	Health Monitoring	2004	Implementation	N/A	P2P	LED	PD	1 Mbps	24 mm	IrDA	N/A	N/A
Healthcare [138]	Heart Monitoring	2005	Implementation	N/A	P2P	LED	PD	9.6 Kbps	45 mm	N/A	N/A	N/A
Smart City [158]	WSN Management	2011	Implementation	N/A	Star	LED	PD	115.2 Kbps	60 cm	N/A	Ethernet/PLC	N/A
Smart City [159]	Indoor Localization	2017	Implementation	N/A	Broadcast	LED-ID	PD	120 bps	4 m	N/A	N/A	N/A
Smart City [160]	Automated Lighting	2015	Simulation	N/A	Star	LED	PD	1 Kbps	1 m	OOK Manchester	N/A	N/A
Smart City [152]	Temperature Monitoring	2016	Implementation	N/A	Broadcast	LED	OCC	150 bps	12 m	UOOK	N/A	N/A
Smart City [146]	Airport Communication	2016	Theoretical	Data Comm	P2P	LED/LD	PD	N/A	N/A	N/A	Wireless	N/A
Healthcare [142]	Wearable Monitoring	2017	Implementation	N/A	Broadcast	LED	OCC	2.4 Kbps	4.5 m	OOK	N/A	N/A
Healthcare [139]	Vital Sign Monitoring	2017	Simulation	N/A	Broadcast	LED	PD	N/A	N/A	OOK	N/A	N/A
Healthcare [140]	Multiple ECG Monitoring	2017	Implementation	Custom	Broadcast	LED	PD	40 Kbps	8 m	OOK	Wireless	N/A
Smart City [161]	Vehicle Identification	2017	Implementation	N/A	Star	LED	PD	DL: 5 Kbps UL: 1 Kbps	N/A	N/A	N/A	N/A
Smart City [161]	Parking Detection	2017	Implementation	N/A	Star	LED	PD	DL: 5 Kbps UL: 1 Kbps	N/A	N/A	N/A	N/A
Smart City [162]	Building Management	2017	Implementation	N/A	Star	LED	PD	1 Kbps	3 m	N/A	RF/PLC	N/A
Smart City [153]	Temperature Monitoring	2018	Implementation	N/A	Broadcast	LED	OCC	N/A	4 m	N/A	N/A	Hadoop
Smart City [147]	Office Network	2018	Case Study	N/A	Star	LED	PD	42 Mbps	4 m	N/A	N/A	N/A
Smart City [147]	Public Localization	2018	Case Study	N/A	P2P	LED	PD	1 Mbps	4 m	N/A	N/A	N/A
Smart City [148]	Ambient Light Sensing	2018	Implementation	N/A	Broadcast	LED	PD	120 bps	N/A	OOK	N/A	N/A
Smart City [149]	Home Automation	2018	Implementation	KNX	Broadcast	LED	PD	5 Kbps	10 m	N/A	N/A	N/A

IoT Business Domain	IoT Application Layer	Year	Study Type	IoT Middleware Layer	IoT Object Abstraction Layer							
					OWC						RF	Application Layer
					Topology	Tx Type	Rx Type	Data Rate	Distance	Protocol		
Smart City [150]	Smart Vehicle	2018	Implementation	N/A	Broadcast	LED	PD	N/A	1.5 m	WBFM	IEEE 802.11OCB	N/A
Smart City [151]	5G Access	2018	Simulation	N/A	Star	LED	PD	N/A	3 m	16-QAM	N/A	N/A
Smart City [157]	Building Automation	2018	Implementation	N/A	Star	LED	PD-S	N/A	N/A	OOK Manchester	N/A	MQTT
Smart City [145]	Energy Conservation	2018	Simulation	N/A	Broadcast	LD	PD	2.5 Gbps	3 Km	N/A	N/A	N/A
Commercial [147]	Smart Retail Aswaaq	2018	Case Study	N/A	Broadcast	LED	OCC	N/A	N/A	N/A	N/A	N/A
Commercial [147]	Smart Retail Carrefour Lille	2018	Case Study	N/A	Broadcast	LED	OCC	N/A	N/A	N/A	N/A	N/A
Commercial [147]	Smart Retail E. Leclerc	2018	Case Study	N/A	Star	LED	PD	1 Mbps	4 m	N/A	N/A	N/A
Commercial [147]	Smart Museum Grand Curtius	2018	Case Study	N/A	Broadcast	LED-ID	PD	N/A	N/A	N/A	N/A	N/A
Commercial [163]	Smart Museum	2018	Implementation	OneM2M	Broadcast	LED-ID	PD	N/A	4 m	N/A	BLE/Zigbee	N/A
Industrial [165]	Mobile Industrial VLC	2018	Simulation	N/A	Broadcast	LED	PD	N/A	15 m	N/A	N/A	N/A
Industrial [164]	Smart Warehouse	2018	Implementation	N/A	P2P	LED	OCC	90 bps	N/A	PCM	LoraWAN	N/A
Industrial [166]	Smart Manufacturing	2018	Implementation	N/A	P2P	LED	PD	1 Mbps	5 m	N/A	N/A	N/A
Healthcare [141]	Patient Monitoring	2019	Implementation	N/A	Broadcast	LED	PD	6.4 Mbps	1.5 m	OOK	N/A	N/A
Healthcare [143]	Smart Wearable	2019	Implementation	N/A	Broadcast	LED	OCC	960 bps	1 m	N/A	N/A	N/A
Healthcare [144]	Patient Monitoring	2019	Simulation	N/A	Broadcast	LED	OCC	N/A	4 m	N/A	BLE	N/A
Smart City [154]	V2X Communication	2019	Implementation	N/A	P2P	LED	OCC	Varies	200 m	HS-PSK	N/A	N/A
Smart City [155]	V2X Communication	2019	Simulation	N/A	P2P	LED	OCC	N/A	N/A	N/A	N/A	N/A
Industrial [167]	Manufacturing Robot Communication	2019	Implementation	N/A	P2P	LED	PD	150 Mbps	N/A	64-QAM	N/A	N/A
Smart City [156]	Temperature Monitoring	2020	Implementation	Thingsboard	Broadcast	LED	OCC	5 bps	6 m	UFSOOK	WiFi	MQTT

component studied was the reliability of the link. When the OCC link becomes unreliable, the RF channel was utilized instead. The authors found that increasing the number of cameras in the room decreased the need to switch to the RF channel and that the OCC link was viable up to 4 meters.

Dhatchayeny et al. propose an experimental LED/OCC link in [143] that can be used to transmit vital sign data. The main consideration was that the link would have a lower bit error rate (BER) to ensure that critical health data remains accurate over the link. The setup involved a 4×4 panel of RGB LEDs to transmit 48 bits per frame and a 30 fps rolling shutter camera. The experimental setup demonstrated a low BER value transmission of 1.2×10^{-4} with a rate of 960 bps at a distance of 100 cm. The transmissions were directly translated into vital sign data, but an application protocol could be utilized over such a link to enable data aggregation.

B. Smart City

1) Smart Home, Smart Building: In [158], Lee et al. consider how an LED/PD link may be implemented to manage an indoor wireless sensor network. The authors considered LED lighting uniformly distributed throughout a building connected to Power Line Communication (PLC) to provide a secure downlink for any sensor nodes within a wireless sensor network. In their experiments, the authors used WLEDs to transmit from overhead lights to sensor nodes, while the nodes transmitted back using IRLEDs. The added benefit of PLC is that minimal infrastructure changes can be made to enable LED/PD communication in buildings. This system is a general example of how VLC may be utilized within an indoor environment to increase network efficiency over a simple RF system.

Another application is an indoor lighting system that can adjust building lights depending on the ambient light levels. In [160], Warmerdam et al. simulate an LED lighting system of overhead building lights as VLC gateways that communicate with light sensors using LED/PD links. In this example, gateways are connected through wireless RF technology or ethernet. Sensors use LEDs to send 512 bits of ambient light data at 1 Kbps over 1 meter to the overhead lights, which is then aggregated and informs the self-regulation of the overhead lighting.

In [152], Ong and Chung show the results of an LED/OCC link used to monitor indoor temperature. The system achieved 150bps at 12m using Undersampled OOK paired with color modulation of three different colored LEDs at the transmitter side. The results showed that transmission was viable at up to 15 m during the day, and extended to 25 m at night when the ambient light was low.

Mariappan et al. explore Ethernet-VLC, PLC-VLC, and RF-VLC links where all the light sources or signage in a building serve as an access point to the network for IoT end devices [162]. This type of device management system enables lighting infrastructure to integrate into wireless sensor networks to perform Building Management services with LED or LED-ID connections. The authors give some application examples of this technology, such as Heating, ventilation, and air conditioning (HVAC) monitoring, surveillance, power management, building security, and communications. The only requirement is that the end device that performs one of these functions must have a compatible OWC receiver and be within the range of the gateway. This setup works well in industrial or commercial settings where overhead lighting is available, and where the RF spectrum may be constrained if there are too many connected devices throughout the facility.

In [145], Siddique et al. propose to use an LD/PD link to send energy usage data from homes to the power substation in a smart village application to maximize energy efficiency. The simulated outdoor link had a distance of up to 3km and was tested for feasibility by finding the effects of atmospheric attenuation and scattering during rainy conditions. The key for transmitting at this distance effectively was to utilize an IR LD because the IR band of OWC is least affected by atmospheric conditions. An LD was required to ensure that the focus of the beam remained consistent for the long distance. The data transmitted using this link can ensure efficient electricity distribution by only sending energy to a home when there is demand, conserving the supply at the power station.

In [157], Reddy et al. create an LED/PD-S link and utilize MQTT to monitor and analyze data from an ambient light sensing device. They successfully obtained the data from the end node then analyzed it using machine learning to predict future ambient light levels. There is no proposed benefit by the authors for using a PD-S receiver over a PD receiver, but if the device were sufficiently low-powered, it could increase the longevity of a battery power supply. It is proposed in the paper that a similar link and application protocol with different sensor devices can be utilized for Smart Building networks.

Zhou et al. demonstrate a Temperature monitoring system in [153] that connects sensor nodes to the gateway through an LED/OCC link. The research included spreading 1000 sensors across 200 rooms on over ten floors to collect temperature data every minute. The authors utilized a single 120 fps CMOS camera per floor to gather data from multiple LED light sources which transmitted the temperature data. The maximum distance of transmission between the LED and the camera was 4m, but the rate of packet loss was not reported in this paper.

Roch and Martina give an example of an LED/PD link supplemented with PLC to create a low data rate Ambient Light Sensing system in [148]. This project's focus was to demonstrate a compact, low-cost OWC system with a that can operate as both an LED-ID or low data rate LED source. Roch and Martina utilized a single LED lamp to act as the light sensor by using a filtered photodiode, which helped prevent error when exposed to ambient light or other interfering light sources. It could then transmit the received data to another sensor or a gateway depending on network topology. Their data showed that 100-120 bps uplink was possible with the sensor node. No application layer protocols were specified in the paper. This type of OWC transceiver successfully addresses the problem with having a photodiode next to a light source, which is vital for compact OWC capable devices.

A case study of an LED/PD system capable of full-duplex communication was presented in [147]. The implementation was used in multiple offices to enable a full duplex 42 Mbps

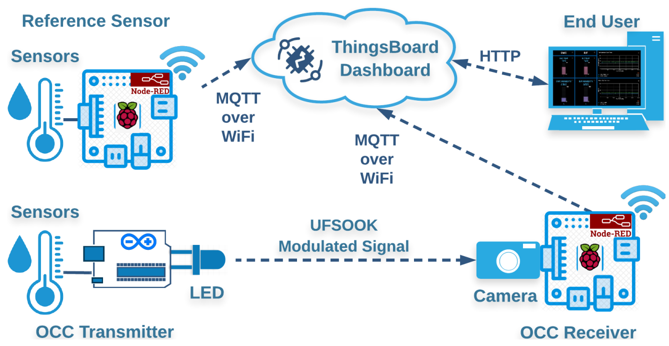


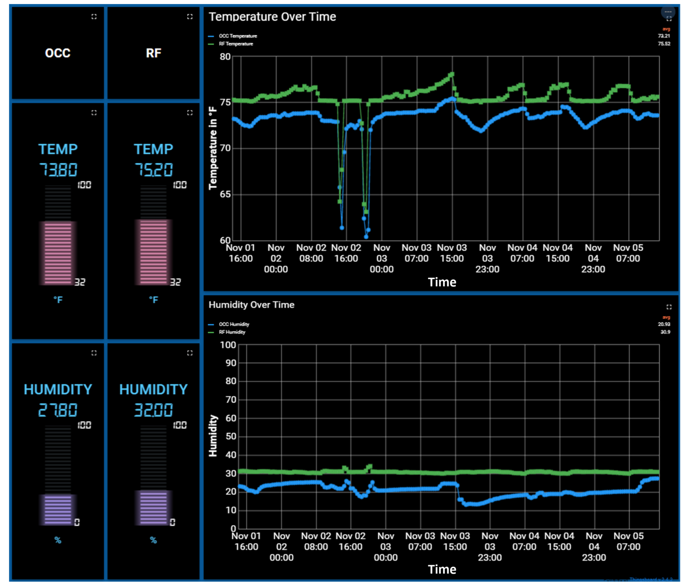
Fig. 10: Figures showing Experimental Setup and Dashboard from [156].

physical link over 4 meters. This system was utilized in a business setting to enable mobile networking with devices but required a USB dongle used as a transceiver to communicate with a gateway. The downlink channel for the end device utilized a visible band while the uplink channel utilized an infrared band to eliminate interference and user discomfort. The link was used to connect office equipment to Ethernet networks, decluttering the RF frequencies, allowing more device connections.

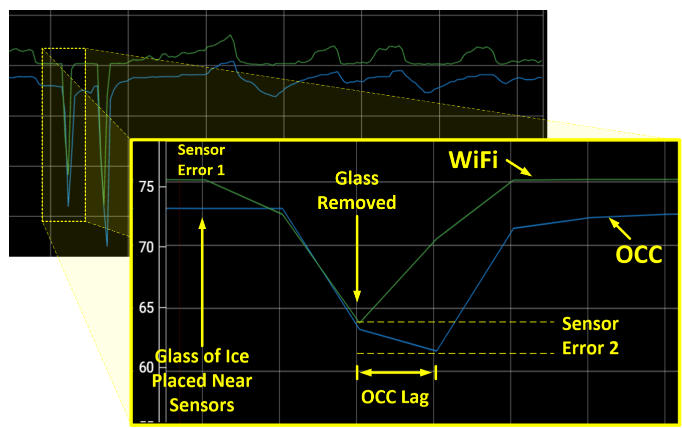
A description of indoor microcells using LED/PD links is presented in [149] where a sensor, transmitter, and overhead light are used to send data about temperature, light, and humidity in one room to a receiver that was connected to a gateway and aggregated the data. This system shows a secure, low power, and practical use of OWC in smart home automation. Sul'aj et al. used KNX as the middleware that managed and controlled devices within the LED generated microcell. This has applications throughout the home and building automation to securely control devices remotely and declutter the RF spectrum in the area.

Using a 5 mA LED and Raspberry Pi v2 Camera, the authors of [156] created an LED/OCC link, shown in Fig. 10. Sensed ambient temperature and humidity data were transmitted using UFSOOK over a distance of 4 meters to the camera. Then MQTT over WiFi was used to upload to a ThingsBoard dashboard for monitoring in Fig. 11. In 11(b), it shows a test conducted to compare the response time of the OCC link to a WiFi link. A glass of ice was placed near the sensor for a few minutes then removed. It was found that the OCC system lagged by about 5 minutes behind the WiFi link because it was not using real-time demodulation. The link had a maximum bitrate of 5 bps but showed a consistent upload link. This system is another example of how data can be transferred at low power for consistent Smart Home data.

2) Urban Computing: Shen et al. examined the use of OWC in parking infrastructure with LED/PD links to provide three different services [161]. The services included vehicle identification, parking space detection, and positioning. The authors created a scenario where a LED-ID tag is incorporated into each parking spot, and each vehicle using the service has a tag. The parking lot overhead lights act primarily as tag readers, using filtered photodiodes. The overhead light



(a)



(b)

Fig. 11: ThingsBoard dashboard [156] (a) near real-time temperature and humidity from OCC and WiFi links over a period of five days. (b) Temperature card from the dashboard. The OCC link follows the same trend as the WiFi reference link.

also serves as a transmitter of a carrier signal for the tag that transmits with backscatter from a retro-reflector and LCD shutter combination. The communications from tags on vehicles provide identification of authorized vehicles within the parking lot. Tags placed in parking spots collect data about the lot's occupancy since any tag that is not pinging the receiver is most likely blocked by a vehicle occupying the space. The positioning application is achieved by using an LED-ID/OCC link where ID transmissions from multiple overhead lights send position information to a smart device camera.

Boubakri et al. offer a solution to expand 5G connectivity within smart cities utilizing VLC gateways in city lighting systems [151]. The authors propose to create LED/PD cells with ubiquitous public lighting and digital signage that are capable of seamless handoff between cells. Through simulations, they examined different handover methods between LED generated cells with a radius of 3 meters that were supposed to represent street light gateways. Simulating a nine-cell system showed that up to 60 devices could operate without any blocking, confirming that VLC can assist in 5G connectivity throughout a city. However, since link distance, bit rate, and error rates were not considered, this study only showed the feasibility under indoor conditions.

Another case study from [147], showcased a mobile application developer called Quartier Camille Claudel, which developed a mobile application to receive location information through public lighting. In this case, urban lights were outfitted with Oldecomm modules capable of creating LED/PD or LED/OCC. This technology can form 1 Mbps unidirectional links over 4 meters.

3) Traffic Monitoring: Li et al. implement a prototype of an LED/PD system that utilizes the light emissions from the receiver device to facilitate communication [180]. In this experiment, a tag was equipped with a solar cell to enable independent power, and a retroreflector and LCD shutter pair to enable transmission. The receiver in this communication, referred to as the ViReader, provides the carrier signal for the tag's transmissions through an LED, with which it can also send messages to the tag. The ViReader received messages from the tag through a filtered photodiode. This system was proposed as a solution for low power sensors within indoor environments to communicate without the need for recharging or adding transmission capabilities to roadside signage within a V2I network. The authors found that the tag's transmissions were effective at a rate of 10 Kbps at 2.4 meters.

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 [146]. We envision that the airport's infrastructure of lights and signages along the taxiways and runways for Data Comm can be utilized. Furthermore, OWC links can be used for aircrafts localization on the airport ground and help raise pilots' situational awareness.

Matus et al. propose a low-cost Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V) solution using LED/PD communications where RF congestion is an issue [150]. An example of V2I is a vehicle communicating with traffic lights through wireless transmissions to indicate that a vehicle is present. V2V communication includes communication between vehicles, such as sending data about the distance between them and velocities to enable automated vehicle behavior to prevent a crash. In an experimental setup, they show that LED/PD communications are achievable at 1.5 meters. They propose that this can allow for increased communication efficiency when in a dense RF environment because of the lack of RF interference. Their experiment focused on obtaining velocity and positioning information with the system and found that it was capable of maintaining accurate estimations compared with GPS velocity estimations. A benefit of this system over GPS is that it still operates when the GPS signal is out of range, allowing it to complement RF systems in adverse environments. However, the researchers noted that distance between the link and dynamic environmental factors could significantly degrade the VLC connectivity.

In [154], Thieu et al. experimented with a modulation technique called Hybrid spatial phase-shift keying (HS-PSK) meant to support V2X communications. This modulation scheme attempts to solve problems with LED/OCC links in V2X applications. The challenges indicated by the authors were the difficulty of automatically detecting the region of interest where transmission is coming from using standard computer vision. The proposed modulation scheme supports private and public communication modes, specifically to pair devices privately while still being able to transmit public information. It also ensures that the camera receivers can demodulate schemes that support dimming, long-distance, very high rate transmissions, and high-mobility transmissions, even if the receiver is low quality. The LED/OCC transmission must also enable both types of camera, global and rolling shutter, to receive the same signal from a variety of transmission sources. During the experimental analysis of the HS-PSK modulation, the authors found that they were able to demonstrate up to 200-meter connections using a pair of 30W transmitters.

Hasan et al. proposed a V2X LED/OCC system in [155] that utilizes Convolutional Neural Networks (CNN) for object recognition and tracking. The proposed idea allows the vehicle to recognize traffic signs from images and communicate through OWC simultaneously. The system requires two cameras that are tasked separately, one for object recognition, and the other for receiving OCC signals.

C. Commercial

Kim and Koh showed an example of an exhibition service in [163]. In this paper, Kim, and Koh demonstrated a broadcast LED-ID/PD link to mobile receivers. The broadcasting LEDs sent a location specific code that could be referenced by a server for information about the exhibit at the location. The uplink from the mobile receiver to the Aggregation Agent (AA) was through WLAN. The uplink was used to forward the Transmitter ID to the AA, which sent back information about a museum exhibit at the receivers location over 6LoWPAN. This is an example of how LED-ID can be utilized to provide information to receivers within LOS only, like in RFID applications, but with a smaller service area.

In [147], Albraheem et al. propose a number of case studies. The first case study was of implementation of LED/OCC in a supermarket called Carrefour Lille. The application provided location services for products within the store and advertised sales to customers. The data is streamed by overhead lighting in the store and can be received by an OCC application running on customer smartphones. No metrics were discussed within the paper about this particular link.

In another case study, [147] E. Leclerc retail stores utilized indoor positioning to monitor shopping behavior and direct customers to products. The setup utilized Oledcomm's GeoLiFi tracker, a 1 Mbps LED/PD, or LED/OCC link. The customers also received customized notifications and coupons based on their shopping habits. Although data aggregation was used in this example, the architecture was not described.

The Grand Curtius Museum is another place where Oldecomm's link technology was utilized. From the description given in [147], the system forms an LED-ID/PD link that sends a location tag to an application that uses it to show the museum visitor relevant information about an exhibit. The specifications of the link were not available within the paper.

The last case study from [147] included another example of LED/OCC links that provided customers with promotions, localization, and shopping history within the Aswaaq store in Dubai. Philips developed this application, and no specifications about the link were mentioned.

D. Industrial

In an attempt to assess the challenges facing the deployment of VLC in the industrial environment, Almadani et al. propose a modified Monte-Carlo method to investigate the VLC channel characteristics in warehouses [165]. In their proposed work, the authors study different factors that can impact the performance of VLC, such as ceiling heights, receiver's mobility, and illumination levels under different settings related to fixtures angles and output power. The authors study impulse responses, signal to noise ratio (SNR) and bit error rates (BER) for different simulated scenarios using two different commercial lights fixtures offered by OSRAM and Philips used in industrial settings. Simulation results show adequate SNR levels under 5.6, 10, and 15-meter ceiling heights. When a receiver is mobile and moves along a selected path, the simulation shows a 10.4 dB drop in the SNR.

In [164], Novak et al. demonstrate a hybrid system in which an LED-ID/OCC link is used to supply metadata about warehouse stock, can be seen in Fig. 12. The LED indicator receives status updates through LoRaWAN and then changes color and metadata depending on the status. This allows a visual cue to warehouse management and supplies additional information when queried through a camera attached to glasses, this was shown in Fig. 13. This reduces the RF network load by utilizing RF channels sporadically, while OWC links are the primary form of communication. An implemented system using this technology could automatically schedule orders to manage warehouse stock.

Berenguer et al. implemented a manufacturing robot communication application with a LED/PD system capable of establishing a 1 Mbps links at 5 meters [166]. The system was shown to be capable of transmitting to six different sensors at the same time, allowing simultaneous communication between many different manufacturing robots or other devices. The authors also propose narrowband LEDs and increased PD surface area as possible solutions to increase the transmission rate to 10 Mbps.

Another example from Berenguer et al. used an LED/PD system where six photodiode receivers were placed around the manufacturing robot, which had eight IR LED transmitters [167]. These were used to transmit and receive instructions that were also passed through ethernet connections. Berenguer et al. found that the link was capable of 150 Mbps with low BER. The distance of the transmission was not given in the paper; however, within the figure of the experimental setup, the

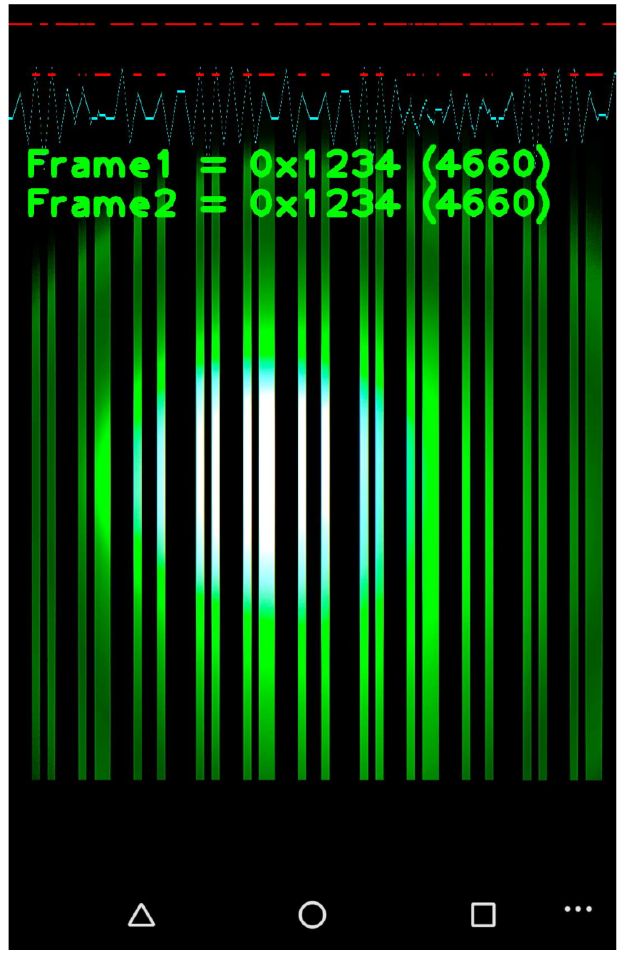


Fig. 12: Logistics Monitoring system from [164] showing the application reading a code from a single transmitter

distance is around one meter from the robot to the receivers. The authors used many transmitters and receivers to ensure that the link would be viable while the robot was able to rotate up to 190 degrees to go through a car manufacturing cycle.

V. Enabling Technologies: Open Problems and Research Directions

In this section, we cover some of the related aspects that we found to be applicable for use in IoT but were specifically OWC technologies. These aspects are not domain-related and did not include examples of how they might be used within the context of IoT. We do not cover all possible enabling technologies but provide readers with some of the main aspects that we saw during the literature review.

A. Localization

Localization is communicating a location and is an important factor within IoT ecosystems. Localization can enable IoT devices to be tracked or to receive data based on a location. For example, multiple broadcast signals from overhead lights can enable a receiver to triangulate its position. Depending on the position, local information can be received, such as an

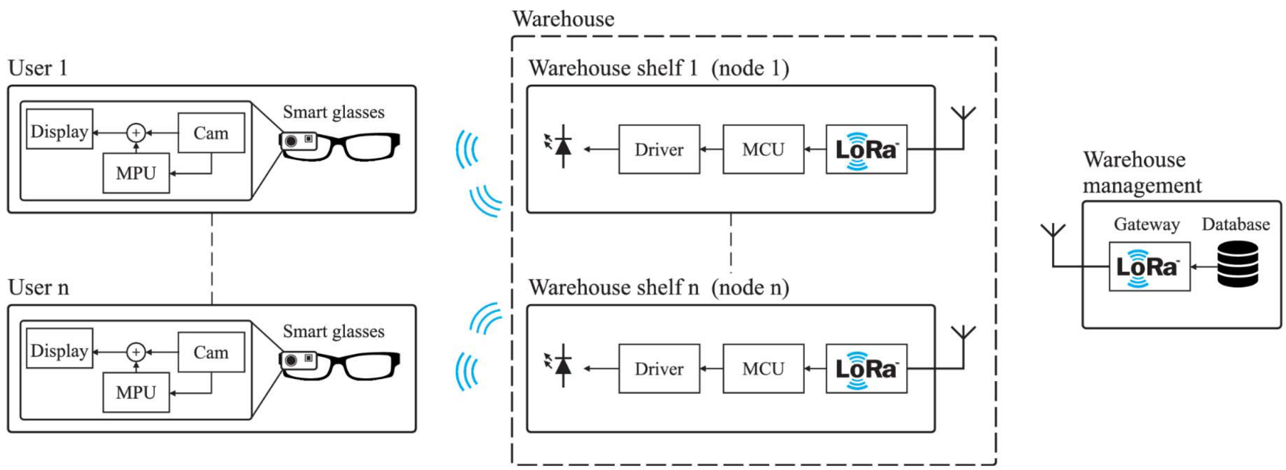


Fig. 13: Logistics Monitoring system from [164] showing the system architecture

advertisement, if the user is inside a store. Because of the much longer wavelengths (2.4 - 5 GHz are meters to centimeters long), current RF technologies for localization are not as accurate as Optical localization techniques (THz wavelengths are nanometers long). RF localization has resolutions of meters to few centimeters, while OWC localization has resolutions around millimeters or less. There are several examples that we found where OWC can reproduce millimeter or better accuracy for localizing a device [92], [95], [171], [173], [174], [181], [182].

For a better understanding of recent literature surrounding this topic, we also found some surveys that consider VLC solutions for localization [172], [183]. In these surveys, the authors acknowledge that power consumption, security, and throughput are better than RF counterparts and provide additional research done within this field. Within these surveys, there were several common advantages of OWC in localization. First, it can be used for positioning where other positioning services, such as GPS, are not practical due to the line of sight requirements. OWC positioning systems extend positioning services to places that are difficult for satellite radio communication to reach, such as indoors or underground. Another common usage of localization is authentication or security services because of the LOS restriction of light. Authentication codes, connected to specific LED tags, limit the propagation of the sensitive information to line of sight, offering better security than radio communications. Digital Signage is another way that OWC localization can be incorporated within smart commerce and cities. It may allow any lighting to communicate with a mobile device, whether handheld or on a vehicle.

B. Hybrid Networks

Several researchers have assessed the benefits of a network that uses both RF and OWC physical links. By utilizing a hybrid network, coverage and data rates can be increased as network traffic in the RF spectrum is offloaded to the shorter range, higher data rate VLC cells [184]–[186]. Underwater networks can also benefit from OWC since RF attenuates faster in water [16].

More research opportunities are available to test which IoT applications could use OWC within the network to reduce cost, power usage, increase security, or become useful with OWC supplementing traditional RF communication. The most common implementations of this have been in healthcare applications where OWC is replacing RF communications in equipment typically used in RF sensitive environments.

C. Device Management

Some device management protocols have been developed that are specific to using OWC links. This is because the low power consumption needed to transmit optical communications between resource-constrained devices. These new device management protocols allow low data rate communications to signal a device to power on or off the RF transceiver or other sensors to save energy.

For example, in [187] Guo et al. suggest a novel way of synchronizing IoT devices called PSync. The idea is to have receiving devices sample at a low frequency during short wake-up intervals to detect when the synchronization data will arrive from the source. Then wait to turn the receiver back on at the correct time and perform high-frequency sampling to obtain needed synchronization data. They found that PSync consumed roughly one-third of the power as the 2.4 GHz synchronization.

Another example is the IoT Device Management Protocol with Visible Light Communication (IDMP-VLC) [188]. Kim et al. propose using VLC for the uplink channel from IoT devices and a low power RF protocol for downlink. IDMP operates over CoAP to ensure that constrained devices can operate effectively, as CoAP reduces packet length while still being able to integrate with IPv6.

D. Hardware

Several hardware-specific considerations could improve OWC coverage for IoT devices. Retro-reflectors as passive transmitters and Solar cells as receivers were two common ways that were researched to increase low-power device OWC capabilities. The modulation of light coming into a retro-reflector is a way for devices to transmit with less power by modulating light from another device with reflectors [180]. Retro-reflectors have a limited transmission distance since they are dependant on external light; the reflection has to be strong enough and directed correctly to overcome the original light source. Creating setups that utilize solar cells to receive both data and power effectively is another factor that could benefit IoT devices [189]. Solar cells cannot modulate as quickly as traditional PD receivers, so the modulation scheme may need to adapt depending on the receiver.

E. Modulation Schemes

Assessing new OWC modulation schemes and comparing them against established schemes is still an active research area. Modulation schemes are still being tested and modified to maximize data rates and distance depending on the environment and device hardware capabilities [190]. For example, the current OCC schemes are listed in 8, but there are more schemes in [24] for PD based modulation and Screen-based modulation.

An example of a non-standard modulation scheme called Dark VLC is proposed by Tian et al. in [191], [192]. It requires modulating visible light in very short bursts such that the human eye cannot register it. This method has been shown to have strict distance and data rate limitations but may prove to be an alternative to IR transmission. Kadam and Dhage explored similar methods in [61].

VI. Conclusions

Optical wireless communication (OWC) is a rapidly developing technology. It gives access to a sizeable unlicensed range of the EM spectrum. Moreover, it has several advantages that make it a suitable wireless technology for future networks and systems such as the Internet of Things (IoT).

In this survey paper, we survey existing research papers in the literature investigating the use of OWC technology in IoT. To this end, we introduce the readers to the concepts and preliminaries of IoT and OWC technologies. We also point the reader to the existing body of existing surveys on each topic. This helps lay the background and explains how and where the OWC technology fits in the IoT architecture.

Using the IoT architecture and the OWC technology elements, we surveyed existing literature combining the two technologies. As a result of our survey, we classified 35 examples of OWC use in IoT systems.

It is found that most of the research done that includes the use of OWC in IoT applications does not consider the IoT's full-stack to observe the effects of OWC on the full system performance. Instead, an OWC link is used in a specific application, and the higher layers of the stack are theorized. Observing how OWC may enable new types of IoT applications necessitates the creation of full-stack systems because the limitations of OWC may affect the IoT solution under consideration. For example, it can control the protocols chosen, and the design of the middleware, how the user's application interface is built, and inform what type of devices can effectively operate using OWC communication.

To enable applications across expanding IoT domains, the creation of hybrid networks that communicate across both RF and OWC physical links is necessary. There are many RF protocols now used to connect these architectures, but OWC supports certain applications better than current RF protocols. Therefore, OWC can compliment RF networks and increase the bandwidth of systems as more devices become connected.

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