Light Fidelity (Li-Fi): Security and Market Sector

Hikmatyarsyah[1], Sasono Rahardjo[2] and Juliati Junde[2]
[1]*Research and Development Dept, QuadraTel Persada, Mampang Prapatan 12790, Jakarta, Indonesia*
[2]*Electronics Technology Center, Agency for the Assessment and Application of Technology (BPPT), Puspiptek Serpong 15314, Tangerang, Indonesia*

Keywords: Visible Light Communication, Light Fidelity, Radio Frequency, Indoor Building Solutions.

Abstract: The increasing data traffic network is directly proportional to devices connected to the network. Visible Light Communication (VLC) systems such as Light Fidelity (Li-Fi) are not only promising solutions to overcome the limitations of Radio Frequency (RF), but will become a trend of wireless communication technology in the near future, especially indoor building solutions. VLC is inevitable from security challenges which is one of the main problems in communication systems even though the nature of the light itself cannot penetrate walls or enclosed spaces. This paper discusses the security protocol in the VLC system and describes its development especially for the indoor mechanism system. The paper also predicts the business market which will have the highest sector potential to implement the VLC system in the next few years. In conclusion, indoor buildings such as offices, malls and smart homes are the sectors that are most ready to adapt to the VLC system in the near future.

1 INTRODUCTION

Wireless technology has become a necessity for human life, which is widely used as a medium for reliable communication. The development of this technology is one of the crucial factors in the development of the global economy. Wireless mobile communication generations from 2G, 3G, and currently 4G took the role as the biggest portion of this network technology with high subscriber demand every year. According to cisco visual networking index forecast 2016 - 2021 report (Cisco, 2017), overall mobile data traffic is expected to grow to 49 exabytes (1 exabytes equals to 1 billion gigabytes) per month by 2021. Each year several new devices in different form are introduced in the market, in which mobile devices and connections will grow to 11.6 billion by 2021. Another factor contributing to growing adoption of Internet of Things is the emergence of wearable devices. By 2021, there will be 929 million wearable devices globally need to be connected. If this trend continues, the limited available radio frequency (RF) spectrum would no longer fulfil the future wireless data traffic demand. Another challenges is that the deployment of advanced wireless technologies comes at the cost of high energy consumption which increases CO2 emission (Wang et al., 2014). Moreover, it has been reported by cellular operators that the energy consumption of base stations contributes to over 60-80 percent of their electricity bill (Ibrahim et al., 2018). Another RF-based technology concern is to enhance area spectral efficiency (ASE) with the techniques such as advanced transmission schemes utilize the spatial dimension, channel aggregation, improved resource allocation, and cell densification. For an RF Link, the path loss is proportional to the square of the carrier frequency, and propagation becomes line-of-sight (LoS). This means moving current wireless systems from 3 GHz region to the 60 GHz (millimeter-wave) region will cause an additional path loss (Haas et al., 2017). Consequently, high path loss along with the limited signal transmission power constraints require cells to be smaller to direct energy from transmitter to the receiver. Therefore, the small-cell concept such as RF-based femtocell network is one of the solutions to tackle this limitation, although Interference generated from femtocell will still exist due to radio-interference.

One of the solutions to all above challenges is to explore the visible light communication (VLC), with the potential in providing very high-rate data transmission through the use of solid-state lighting

Hikmatyarsyah, ., Rahardjo, S. and Junde, J.
Light Fidelity (Li-Fi): Security and Market Sector.
DOI: 10.5220/0007369901540162
In *Proceedings of the 7th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2019)*, pages 154-162
ISBN: 978-989-758-364-3

device such as LEDs or Laser Diodes. Light Fidelity (Li-Fi) is a Visible Light Communication based technology that uses the visible and infrared light spectrum to provide transmit and receive capability. As in Wi-Fi, Li-Fi can offer mobility for both intra-cell and inter-cell with two principal version of handover mechanism (horizontal and vertical) (Serafimovski et al., 2018). It has been recognized that wireless data traffic mostly originates in indoor environments with 80% in late 2015 (Commscope, 2015). Therefore, by exploiting the already-installed light-emitting-diode (LED) lighting infrastructures for broadband data transmission, VLC could use the same amount of power for illuminate the room while transmitting can be considered as good example of green communication for high-speed local area networks. Li-Fi data is transmitted by the LED bulbs and received by photodetector. In early developmental models, Li-Fi capable transmit of 150 Mbps, with stronger LEDs type, researchers have demonstrated data rates of 10 Gbps (Tsonev et al., 2015). The optical spectrum offers a bandwidth which is many orders of magnitude greater than the RF spectrum can offer. The visible and near infrared (IR) regions together are 2600 times larger than 0-300 GHz RF spectrum (Haas et al., 2017). This spectrum is unlicensed (free) and subject only to eye-safety regulations. This makes optical wireless communication systems, a potentially attractive medium for wireless communication. A femtocell network is one such indoor small-cell system that can significantly increase the ASE of a cellular system (Chandhar and Das, 2014). VLC enables a step-change improvement of the small-cell concept with completely avoiding interference to RF-based technology, while interference from the femtocell comes from the adjacent access point signal. The benefits and challenges of VLC systems compared to RF systems are described (Stevanovic, 2017) (Chowdhury et al., 2018).

Furthermore, the objectives of this paper include: i) describe the characteristics and functions by compare the most reputable low-powered RF-based and VLC-based wireless technologies and ii) from security point of view, we outline the basic wireless mechanism for Li-Fi in OSI layer, especially physical and media access layer. After Li-Fi security detailed, we discuss every aspect for Li-Fi application which has the most potential to be applied in the near future. The rest of the paper is organized as follows. Section II compares low power wireless technologies. Section III describe Li-Fi security protocols. Section IV discuss Li-Fi market based on its application. Lastly, Section V concludes the paper.

2 LOW-POWER WIRELESS TECHNOLOGIES

The Internet of Things (IoT) defined as the network system that connect internet-enable devices such as wearable gadgets, electronics, digital machines, sensors in which have ability to share data securely without requiring human action. IoT enable to be monitored remotely from any network making this smart system dependable for the future. The McKinsey Global Institute (MGI) predicts that the Internet of Things has a total potential economic impact of $3.9 trillion to $11.1 trillion per year in 2025, equivalent to about 11% of the world economy (Manyika, 2015). Wireless communication is steadily grows in recent years and it can be handily implemented in places, that are located in remote areas with difficult environmental conditions and without complete communication infrastructure. With considerable standards available in the market, applying diverse communication protocols in various frequency bands deployment, the choice of the most suitable wireless connectivity technology for an IoT application can be challenging. Higher-frequency bands offer a broader bandwidth, more channels available and higher data throughput. Otherwise, lower-frequency achieve a longer range. Personal Area Network (PAN), Local Area Network (LAN) and Wide Area Network (WAN) categorized as IoT common network range. PAN has coverage of 10 m propagate low power radio while WAN cover up to 20 km typically use high power radio transmission (Pau et al., 2018). This paper focus only on low power technology. The comparison of low power wireless technologies between RF-based and VLC-based is presented in Tabel 1.

2.1 Low-power Radio Frequency

Wireless technology transmitting low-powered radio frequency such as low-power Wi-Fi, Zigbee, NFC, LoRaWAN and Bluetooth Low Energy (BLE) will be suitable channels in the application of IoT. The difference in frequency usage directly proportional to the signal coverage will distinguish these five radio-based technology applications. NFC enables simple and safe two-way interactions between electronic devices and extends the capability of contactless card technology. BLE has advantage in personal device with its well-known integration in smartphones. Zigbee offers short to medium with low data rate which has prominent feature for on body/off body communications (Ghamari et al., 2015). Wi-Fi have

Table 1: The comparison between low power RF-based and VLC-based wireless technologies (Ghamari et al., 2015) (Ali and Hussein, 2016) (Magrin, 2016).

Feature	RF Technologies					LC Technologies	
	Low Power WiFi	Zigbee	NFC	LoRaWAN	BLE	LiFi	IR
Standard	IEEE 802.11	IEEE 802.15.4	ISO/IEC 18000-3	LoRaWAN	Bluetooth 4.0	IEEE 802.15.7	IrDA-1.1
Frequency Band	2.4 GHz	868 MHz / 915 MHz / 2.4 GHz	13.56 MHz (ISM)	470/868/920/2400 MHz	2.4 GHz	400-700 THz	2.4 GHz
Data Rate	54 Mbps	868 MHz: 20 kbps 915 MHz: 40 kbps 2.4 GHz: 250 kbps	400 kbps	868 MHz: 50 kbps 920 MHz: 21 kbps	1 Mbps	1 Gbps	4 Mbps
Modulation	64 QAM	BPSK & QPSK	ASK	SS Chirp	GFSK	OFDMA	PPM
Range	30 m	100 m	10 cm	5 km (Urban)	10 m	10 m (Indoor)	1 m
Power Profile	Hours	Months/Year	Months/Year	Days	Months/Year	Months/Year	Months/Year
Network Topology	Point-To-Multipoint	Peer-To-Peer	Point-To-Point	Star-of-Star	Point-To-Point	Point-To-Point	Point-To-Point
Complexity	Complex	Simple	Simple	Simple	Complex	Simple	Simple
Security	Medium	Medium	High	Medium	Medium	High	High

been widely used for short distance in offices and restaurants, whereas LoRaWAN is applicable for long range communication smart system.

2.2 Low-power Light Communication

Various products use light as a medium to transfer data between various IoT objects. Li-Fi and Infrared (IR) are two of the most popular IoT communication technologies in this category. IR Electromagnetic invisible light is used for data communication over a short distance. IR wireless technology is used in entertainment control units, robot control systems and medium-range line-of-sight laser communications. Similar to Wi-Fi, Li-Fi uses wireless communication technology. It utilizes from visible until infrared spectrum to transfer data with shorter coverage (for indoor system) with higher data rates.

3 LI-FI SECURITY SYSTEM

Light-based network data transmission can accommodate better solution to radio wireless network, since i) they are interface-orthogonal to radio-based communication (low electromagnetic interference) and ii) inherent security due to spatial confinement (light does not penetrate through solid objects) make this system considered to provide a secure way to transmit data within a closed indoor environment, making it difficult to be intercepted from outside. However, the application of the VLC system has limitations and need be addressed. Major challenges are in the form of ambient light interference, co-channel interference and interconnection to existing network technologies. A standardization of VLC is necessary in order to cope the above challenges, from IEEE 802.15.7 (2011) to IEEE 802.15.7m OWC (2014) and IEEE 802.15.13 task group (2017) have been introduced.

3.1 Li-Fi Architecture

A basic user equipment to core network Li-Fi architecture in VLC system for Indoor application as optical channel is shown in Figure 1. LED lamps are used as transmitter and photodiodes are used as Li-Fi receiver while image sensors used as optical camera communication (OCC) that mainly communicate through visual data. VLC access networks are connected to the internet or core network through wired (optical fibres) or wireless (FSO) for backhaul connectivity.

The VLC system sending signals by controlling the ON/OFF repetition of LED or using the color difference of transmitting light without flickering that

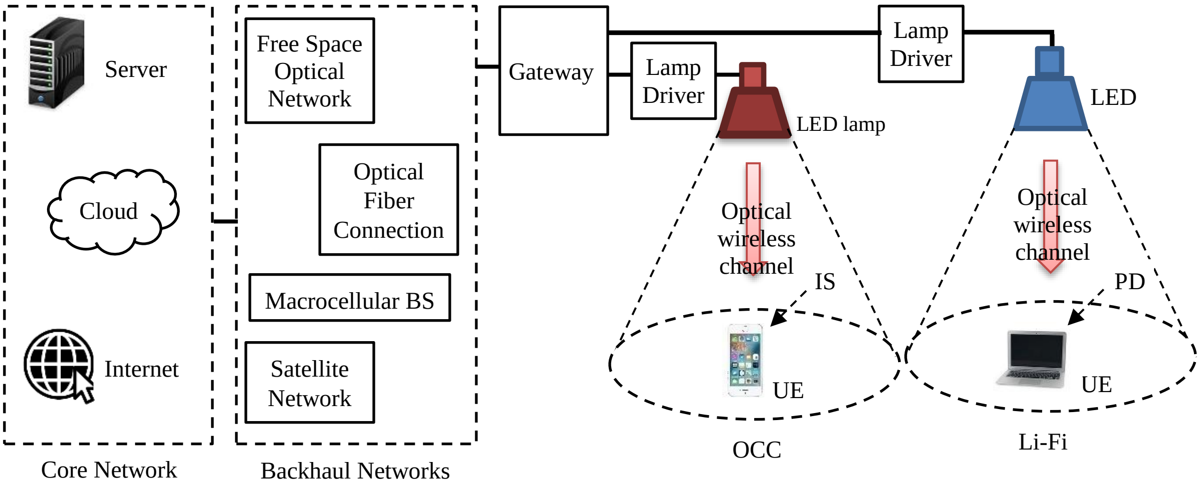

Figure 1: VLC system architecture from user equipment to core network (Chowdhury et al., 2018).

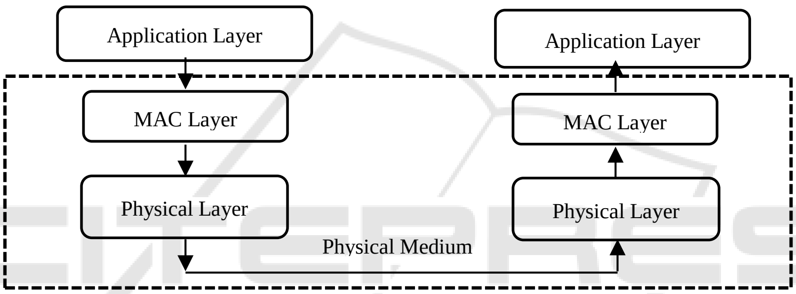

Figure 2: VLC architecture layer.

can cause vision problems. The transmitting part (LED) must have Physical Layer (PHY) and Media Access Control (MAC) functions for illumination and transmission performance. The receiving part photodiode or image sensor uses additional prevention to avoid interference of other light sources. PHY has a modulation and line coding for a wireless communication and MAC has to support different application (Bhalerao et al., 2013). The reference model of the VLC communication system is shown in Figure 2.

3.2 Media Access Control Layer

The role undertaking by medium access control (MAC) layer include mobility support, dimming support, Visibility support, security support, flickering mitigation, colour function, Network beacons, VPAN and entities link provider (IEEE, 2011). The topology that support by MAC layer at least one of three transfer modes: bidirectional (peer to peer) mode, unidirectional (star) mode, or broadcast mode.

3.3 Physical Layer

The physical layer defines the physical specification of the device and the relationship between the device and the medium. One device transmits information to the channel, and another device receives data from channel based on the physical layer. Figure 3 shows the block diagram of the general physical layer implementation of the VLC system. The transmitter typically consists of the channel encoder and the modulator followed by the optical front end. The electrical signal modulates the intensity of the optical carrier to send the information over the optical channel. At the receiver, a photodiode receives the optical signal and converts into an electrical signal followed by the recovery of data.
Three different types of physical implementations of VLC are given in IEEE 802.15.7-2011 in which the operating range are PHY I, PHY II, and PHY III. Due to the growing interest this technology, the new standardization IEEE 802.15.7m Optical Wireless Communication in 2014 formed and adds three more PHY operating range to support LED Identification

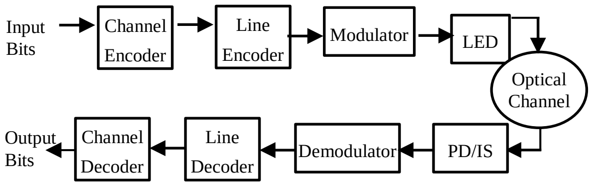

Figure 3: PHY layer for VLC system based 802.15.7 (Khan, 2016).

(LED-ID), Optical Camera Communication (OCC) and Li-Fi (High Rate PD Communications) technology as summarized in Table 2.

3.4 MAC and Physical Layer Security

VLC system often assumed to be eavesdropping-proof due to its properties that light cannot penetrate through wall, this is not entirely true. Although the system mostly propagated via the line-of-sight path, VLC channel has a broadcast nature that distribute to all users illuminated by the LEDs such as in public spaces. This lead to the opportunity for unauthorized users to eavesdrop the information of legitimate users. Power received and bandwidth of the signal by the eavesdropper should become critical parameters that need to observe for either indoor-to-indoor or indoor-to-outdoor mechanism.

The possibility threats such as jamming (range-related), snooping (power-related) and data modification (range and power) for mobile-to-mobile, infrastructure-to-mobile, mobile-to-infrastructure, and infrastructure-to-infrastructure communication schemes based on distance measurement from 10 cm and 3 m have been reviewed (Blinowski, 2015). As the result, the greatest risk of violating VLC security arises when communication with infrastructure is concerned. According to (Rohner et al., 2015), there exist three security mechanisms that can be used to protect VLC in MAC layer: proximity-based protection (LOS communication only), steganographic protection (encryption without authentication or integrity), chaffing and winnowing (authentication without encryption) and cryptographic protection (encryption, integrity, and authentication) with uncomplicated implementation and should not consume too many computational resources as defines in IEEE in 802.15.7. The study for SISO and MISO schemes have been done (Mostafa, 2017), for the simple single-input-single-output (SISO) case, the numerical results revealed that zero-forcing beamforming transmission scheme is an appropriate strategy for secure transmission in VLC scenarios, provided that the transmitter has accurate channel information. In (Marin-Garcia et al., 2017), for indoor-to-outdoor VLC system mechanism, leakages light source that refracted through window not only in front of the window but there are still leakages on the sides and higher power density received at middle range than the closest to the window eventhough the bandwidth of the signal decreased. In another paper (Wang et al., 2018), a secrecy capacity with the dependence of the optical intensity constraints for indoor system has been proposed.

4 VLC POTENTIAL MARKET

The VLC global market is expected to grow from USD 1.3 billion in 2017 to USD 75 billion by 2023, at a CAGR of 96.57 % between 2018 and 2023 according to markets and markets (Marketsandmarkets, 2018). The growth of the VLC market is driven by factors such as faster and safer data transfer than other competing technologies, RF spectrum bandwidth crunch, no bandwidth limitation, less energy consumption; and greener, cleaner and safer technology. The major components of the VLC system are LED, photodiode, microcontroller, and software. VLC potential markets are divided according to light-distance application which are indoor, outdoor and underwater.

4.1 LED Lighting Market

The forecast for the global lighting product market between 2016 and 2020, as illustrate in Figure 4. It is estimated that office lighting and residential lighting will dominate a market volume of around 15 billion euros and 32 billion euros respectively in 2020 (statista.com, 2012). The VLC technology is entirely based on light, and LED is used as a main source of transmission for Indoor application, a statistic represents the estimated LED market penetration between 2010 and 2020 in Figure 5. In 2020, light-emitting diodes are expected to reach a penetration into the lighting market of approximately 61 percent (statista.com, 2012).
As per analyst at Zion Market Research, the global LED lighting market added up for USD 26.09 Billion in 2016 and is likely to cross USD 54.28 Billion by end of 2022, developing at a CAGR of almost 13% from 2017 to 2022 (Zion Market Research, 2016).

Table 2: PHY I to VIII Operating Modes Specifications.

PHY	Description	Modulation Schemes	Data rate
I	IEEE 802.15.7-2011 for outdoor usage	OOK & VPPM	100 kbps (OOK), 266 kbps (VPPM) (Khan, 2016)
II	IEEE 802.15.7-2011 for indoor usage	OOK & VPPM	96 Mbps (OOK), 5 Mbps (VPPM) (Khan, 2016)
III	IEEE 802.15.7-2011 multiple light sources & detectors	CSK	96 Mbps (16-CSK) (Khan, 2016)
IV	IEEE 802.15.7m OWC TG7m for Image Sensor Communication modes (discrete light sources)	UFSOOK, Twinkle VPPM, S2-PSK, HS-PSK, Offset VPPM	22 kbps (HS-PSK) (Mariappan, and Cha, 2018)
V	IEEE 802.15.7m OWC TG7m for Image Sensor Communication modes (diffused surface light sources)	MPM, CM-FSK, C-OOK, RS-FSK	12.5 kbps (MPM) (Mariappan, and Cha, 2018)
VI	IEEE 802.15.7m OWC TG7m for Image Sensor Communication modes (video displays)	A-QL, VTASC, HA-QL, SS2DC	512 kbps (VTASC) (Mariappan, and Cha, 2018) (Cha et al., 2018)
VII	IEEE 802.15.7 OWC TG13 for PD Low-rate Communication modes	OFDM-based	Under Research 1Mbps – 10Mbps (Li et al., 2018)
VIII	IEEE 802.15.7 OWC TG13 for PD High-rate Communication modes	OFDM-based	Under Research 10Mbps – 10Gbps (Li et al., 2018)

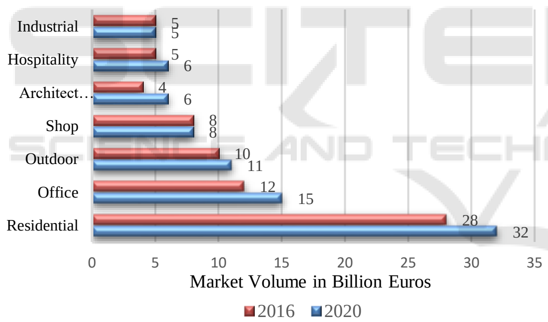

Figure 4: General lighting market volume from 2016 to 2020 (statista.com, 2012).

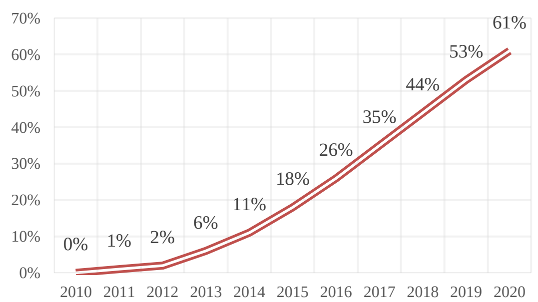

Figure 5: LED penetration estimated market from 2010 to 2020 (statista.com, 2012).

4.2 VLC Indoor Applications

VLC has many indoor networking applications and where the intercommunication of personal electronic devices is priority, Li-Fi has potential to apply in the near future due to its low ambient interference, higher data rate for short distance communication and already-existed infrastructure. Smart lighting market is estimated to grow from USD 7.93 Billion in 2018 to USD 20.98 Billion by 2023, at a CAGR of 21.50% between 2018 and 2023 (Marketsandmarkets, 2018). The major factors driving the growth of the smart lighting market include modernization and development of infrastructure to transform cities into smart cities. VLC indoor smart lighting applications are such as offices, universities, shopping markets, airports and restaurants (facilitates illumination, communication and control simultaneously that save cost and energy consumption), hospitals (where surroundings electromagnetic wave sensitive areas and VLC will not interfere with radio waves), aviation (LEDs can also be used instead of wires to provide media services to passengers that reduces the cost of aircraft construction and its weight), residential houses (VLC system will integrate with smartmeter to send and store data daily). Smart retails such as shopping market is the early adopters of visible light communication technology. The retail indoor positioning segment such as sending coupons, notifying customers of discounts and helping customers reach the exact position of the product by communicate through smartphones has become exceptionally easy through VLC modules. Indoor positioning segment is expected to represent an opportunity worth USD 33.54 billion by 2022 as it expands at a CAGR 93.82% between 2015 and 2022.

4.3 VLC Outdoor Applications

VLC can be used for vehicular communication (V2X) due to the presence of the LED vehicle lights and the existing traffic lights infrastructure that are adopting LED technology. Factors such as rising demand for real-time traffic and incident alerts for increasing public safety are driving the growth of the V2X market. The V2X market is valued at USD 22.60 Billion in 2016 and is projected to grow at a CAGR of 17.61% during the forecast period, to reach USD 99.55 Billion by 2025 (Marketsandmarkets, 2018). For long-distance communication purposes, Free-Space Optics (FSO) technology uses laser-diode lights for high transmission of data and is ideal for outdoor networking. FSO can be installed along with any line of sight up to more than 10,000 km (Chowdhury et al., 2018). The invention of lasers in 1960s boosted the FSO market that market is expected to grow from USD 0.15 billion in 2017 to USD 1.45 billion by 2023, at CAGR of 39.58 % between 2018 and 2023 (Marketsandmarkets, 2018). Because of the scalability and flexibility of this technology, optical wireless products based on FSO can be deployed in many applications such as mobile backhaul enterprise connectivity, disaster recovery, defence, satellite and metropolitan area network.

4.4 Underwater Communications

There are three underwater communications preference for implementing underwater wireless sensor networks: acoustics, RF and optics. Compared with the acoustic waves that have scattering, high attenuation, low bandwidth and RF waves still have high attenuation even use ultra-low frequencies which lead to higher cost for hardware, underwater optical wireless communication (UOWC) has the highest transmission data rate, the lowest link delay and the lowest implementation costs. UOWC also has higher communication security over the acoustic and RF methods. Most UOWC systems are implemented in line-of-sight (LOS) configuration, rather than the diffused broadcasting scenario such as acoustic and RF wave which it becomes more difficult to be eavesdropped (Zeng et al., 2017) (Saeed et al., 2018). According to (Wu et al., 2017), a 7.2 Gbps UOWC system has been proposed in for 450 nm blue laser with the transmission distance of 6 m. The market promotion of UOWC has not been achieved so far, mostly this system owned by military. Only a few limited UOWC products were commercialized in the early 2010s (The Sonardyne Site, 2016) (The Ambalux Site, 2016). The proposal of underwater wireless sensor networks (UWSN) has facilitated the development of UOWC due to increasing demands for ocean exploration with efficient high bandwidth data transmission, make it the UOWC market showing future promise.

5 CONCLUSIONS

Further research is needed to reduce interference, environmental effects, and transmitter power levels in VLC system for outdoor. Visible light system using LED for indoor application is more suitable to be applied in the near future due to low ambient light source, higher sector for data consumption, low cost infrastructure, and high level of needs other than RF-based system. Furthermore, LEDs advantages to have high switching capability along with other important features such as energy efficiency and longer lifetime make them the most favourable light source that can be incorporated into VLC. LED can be used in different types of lighting applications. The potential market growth of LED lighting technology is foreseen to be very strong in the coming years, which create a strong case for this lighting technology to be integrated into VLC system. Although at security level in IEEE 802.15.7 standard does not provide adequate MAC-level protection against physical level risk and still under research to develop, physical layer security must be the priority to be enhanced due to the first layer of security for unintended user interface. The unification of 5G radio technology especially femtocell for indoor application will make both systems work better to cope each other challenges.

ACKNOWLEDGEMENTS

The first author wish to thank for Indonesian Agency for the Assessment and Application of Technology (BPPT) to facilitate and cooperate to finish this paper, the author also thank author’s future wife for her support and encouragement thus author can complete this paper on time.

REFERENCES

Cisco, 2017. *Cisco Visual Networking Index (VNI) Update Global Mobile Data Traffic Forecast, 2016-2021*. [online] Available at: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html [Accessed 9 Sep. 2018].

Wang, C., Haider, F., Gao, X., You, X., Yang, Y., Yuan, D., Aggoune, H., Haas, H., Fletcher, S., Hepsaydir, E., 2014. *Cellular Architecture and Key Technologies for 5G Wireless Communication Networks*. In: IEEE Comm.

Ibrahim, A., A., Kpochi, K., P. Smith, E., J., 2018. *Energy Consumption Assessment of Mobile Cellular Networks*. American Journal of Engineering Research (AJER), vol.7, Issue-3.

Haas, H., Chen, C., O'Brien, D., 2017. *A Guide to Wireless Networking by Light*. Elsevier Journal of Progress in Quantum Electronics, no.55, pp.88-111.

Serafimovski, N., Lacroix, R., Perrufel, M., Leroux, S., Clement, S., Kundu, N., Chiaroni, D., Patwardhan, G., Myles, A., Jurczak, C., Fleschen, M., Ragusky, M., Jungnickel, V., Ktenas, D., Haas, H., 2018. *Light Communications for Wireless Local Area Networking*. IEEE 5G Tech focus*:* vol. 2, no.2.

Commscope, 2015. *Indoor Wireless in Mobile Society: Research Reveals Gap Between Expectations of Wireless Consumers and Those Who Design and Manage Buildings*. [online] Available at: https://www.commscope.com/NewsCenter/PressReleases/Indoor-Wireless-in-Mobile-Society-Research-Reveals-Gap-Between-Expectations-Of-Wireless-Consumers-and-Those-Who-Design-and-Manage-Buildings/ [Accessed 10 Sep. 2018].

Tsonev, D., Videv, S., Haas, H., 2015. *Towards a 100 Gb/s visible light wireless access network*. Opt. Exp., vol. 23, no. 2, pp. 1627-1637.

Chandhar, P., Das, S., 2014. *Area spectral efficiency of Co-Channel deployed OFDMA femtocell networks*. IEEE Trans, Wireless Commun., vol. 13, no.7, pp. 3524-3538.

Stevanovic, I., 2017. *Light Fidelity (LiFi)*. OFCOM-Report.

Chowdhury, M., Z., Hossan, M., T., Islam, A., Jang, Y., M., 2018. *A Comparative Survey of Optical Wireless Technologies: Architectures and Applications*. IEEE Access: vol. 6.

Manyika, J., 2015. *Unlocking the potential of the Internet of Things*. [online] McKinsey Global Institute. Available at: http://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world [Accessed 2 Sep. 2018].

Pau, G., Chaudet, C., Zhao, D., Colotta, M., 2018. *Next Generation Wireless Technologies for Internet of Things*. Sensors 2018, 18, 221.

Ghamari, M., Arora, H., Sherratt, R., S., Harwin, W., 2015. *Comparison of Low-Power Wireless Communication Technologies for Wearable Health-Monitoring Applications*. International Conference on Computer, Communications, and Control Technology (I4CT).

Ali, H., A., E., A., Hussein, M., A., 2016. *Wireless Telecommunication Technologies: Li-Fi Vs. Wi-Max Vs. Wi-Fi Vs. Zigbee Vs. Bluetooth*. International Journal of Recent Trends in Engineering & Research, ISSN (Online): 2455-1457.

Magrin, D., 2016. *Network level performances of a LoRa system*. Universita degli Studi di Padova.

Bhalerao, M., V., Sonavane, S., S., Kumar, V., 2013. *A Survey of Wireless Communication Using Visible Light*. International Journal of Advances in Engineering & Technology, vol. 15, Issue 2, pp. 188-197.

IEEE, 2011. P802.15.7 – Standard for Short-Range Wireless Optical Communication.

Khan, L., 2016. *Visible light communication: Applications, architecture, standardization and research challenges*. Elsevier: Digital Communications and Networks.

Mariappan, V., Cha, J., 2018. *IEEE802.15.7m OWC PHY Specification Overview*. IEEE COMSOC MMTC Communications: vol. 13, no.3, pp. 25-28.

Cha, J., Lee, M., Mariappan, V., 2018. *VTASC-Light based flexible Multi-Dimensional Modulation Technique for OWC*. IEEE COMSOC MMTC Communications: vol. 13, no.3, pp. 39-43.

Li, Q., Baykas, T., Jungnickel, V., 2018. *IEEE 802.15.13 Multi Giga bit/sec Optical Wireless Communication Project*. IEEE COMSOC MMTC Communications: vol. 13, no.3, pp. 34-38.

Blinowski, G., 2015. *Security Issues in Visible Light Communication Systems*. International Federation of Automatic Control (IFAC-PapersOnLine) 48-4, pp. 234-239.

Rohner, C., Raza, S., Puccinelli, D., Voigt, T., 2015. *Security in Visible Light Communication: Novel Challenges and Opportunities*. Sensor & Transducers, Vol. 192, Issue 9, pp. 9-15.

Mostafa, A., 2017. *Physical-Layer Security for Visible-Light Communication Systems*. University of British Columbia.

Marin-Garcia, I., Guerra, V., Perez-Jimenez, R., 2017. *Study and Validation of Eavesdropping Scenarios over a Visible Light Communication Channel*, Sensors 2017, 17, 2678.

Wang, J., Liu, C., Wang, J., Wu, Y., Lin, M., Cheng, J., 2018. *Physical-layer Security for Indoor Visible Light Communications: Secrecy Capacity Analysis*.

Marketsandmarkets, 2018. *Free Space Optics (FSO) and Visible Light Communication (VLC) Market – Global Forecast to 2023*. [online] Available at: https://www.marketsandmarkets.com/Market-Report/visible-light-communication-market-946.html [Accessed 3 Sep. 2018].

General lighting market volume outlook from 2011 to 2020, a. 2018. General lighting market trend by application 2020 | Forecast. [online] Statista. Available at: https://www.statista.com/statistics/216387/general-lighting-market-trend-by-application/ [Accessed 4 Sep. 2018].

Global lighting market: estimated LED penetration 2020 |

Forecast. [online] Statista. Available at: https://www.statista.com/statistics/246030/estimated-led-penetration-of-the-global-lighting-market/ [Accessed 29 Sep. 2018].

Zion Market Research, 2016. *LED Lighting Market for Residential, Architectural and Outdoor Applications: Global Industry Perspective, Comprehensive Analysis, and Forecast, 2016 – 2022*. [online] Available at: https://www.zionmarketresearch.com/report/led-lighting-market [Accessed 5 Sep. 2018].

Marketsandmarkets, 2018. *Smart Lighting Market by Offering (Hardware (Lights & Luminaires, Lighting Controls), Software, and Services), Communication Technology (Wired and Wireless), Installation Type, Application Type, and Geography - Global Forecast to 2023*. [online] Available at: https://www.marketsandmarkets.com/Market-Reports/smart-lighting-market-985.html [Accessed 6 Sep. 2018].

Marketsandmarkets, 2018. *V2X Market for Automotive by Communication Type (V2C, V2D, V2G, V2P, V2V and V2I), Offering Type (Hardware and Software), Connectivity Type (DSRC and Cellular), Propulsion Type (ICE and EV), Technology Type, and Region - Global Forecast to 2025*. [online] Available at: https://www.marketsandmarkets.com/Market-Reports/automotive-vehicle-to-everything-v2x-market-90013236.html [Accessed 5 Sep. 2018].

Zeng, Z., Fu, S., Zhang, H., Dong, Y., Cheng, J., 2017. *A survey of underwater optical wireless communications*. IEEE Commun. Surveys Tuts., vol. 19, no. 1, pp. 204-238, 1st Quart..

Saeed, N., Celik, A., Al-naffouri, T., Y., Alouini, M., 2018. *Underwater Optical Wireless Communications, Networking, and Localization: A Survey*. IEEE Communication Surveys and Tutorials.

Wu, T., C., Chi, Y., C., Wang, H., Y., Tsai, C., T., Lin, G., R., 2017. *Blue Laser diode enables underwater communication at 12.4Gbps*. Scientific Reports, vol. 7, no. 8, p. 40480.

The Sonardyne Site, 2016. [online] Sonardyne International Ltd. Available at: http://www.sonardyne.com/products/all-products/instrumets/1148-bluecomm-underwateroptical-modem.html [Accessed 7 Sep. 2018].

The Ambalux Site, 2016. [online] Ambalux. Available at: http://www.ambalux.com/underwater-transceivers.html [Accessed 7 Sep. 2018].