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Communicate to illuminate: State-of-the-art and research challenges for visible light communications

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ABSTRACT

In the near future, the available radio-frequency (RF) bandwidth will not be sufficient to meet the ever increasing demand for wireless access. Visible light communication (VLC) is an alternative method to reduce the burden of RF-based communication, especially in indoor communications. 70% of the communication is indoors, and light emitting diode (LED) arrays are spreading for illumination purposes thanks to their low energy and higher lifetime. VLC can be realized as a secondary application in LED arrays that are placed for lighting. In this way, some of the wireless traffic can be sent using light, with less cost and less carbon footprint. For these reasons, VLC attracts significant research interests. We provide an extensive survey of the current literature by outlining challenges and future research areas in order to facilitate future research in this area.

1. Introduction

The demand for wireless access has become so prevalent that it is possible to consider wireless connectivity as one of the basic commodities like electricity. This rapidly growing demand resulted in ubiquitous deployment of wireless systems. Eventually, the limited wireless spectrum got heavily congested and solutions increasing spectrum efficiency, such as spectrum reuse got to a point that even small cells (pico/femtocells) will not be able to help with covering the huge demand. Recent studies predict that by 2017, more than 11 exabytes of data traffic will have to be transferred through mobile networks every month [1]. To be able to meet this demand, the research community began looking for solutions that target alternative portions of the spectrum. VLC is one of the promising alternative that aims to provide a communication medium by using the existing illuminating devices.

With the improvements in LED technologies, it is possible to modulate light in high frequencies such that human eye cannot detect. Due to their lower cost, higher lifetime and lower power consumption, LEDs are expected to replace conventional incandescent and fluorescent lamps in the near future. This enables the use of LEDs for both illumination and communication, making VLC an economic and ubiquitous data transmission solution.

In Fig. 1, we depict the electromagnetic spectrum. Visible light region corresponds roughly to the portions where the wavelength is between 400 and 700 nanometers. Unlike radio waves, electromagnetic waves in the visible light wavelength are not harmful for the human body. Moreover, the visible light portion of the spectrum is not regulated. This opens up a huge bandwidth for communication, which can be utilized in a wide range of applications.

In this paper, we aim to capture the state-of-the-art for this timely and exciting field by discussing the open research issues. The remainder of the paper is organized as follows. In Section 2, we explain the advantages of VLC and provide comparisons with other wireless communication technologies that use lower parts of the spectrum. In Section 3, we summarize the historical evolution of VLC

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Table 1
Comparison of wireless communication technologies.

Type	Technology	Range	Rate	Mobility
RF	Wi-Fi 2.4 GHz	Indoor 70 m, outdoor 250 m	65 Mbps	Low
	Wi-Fi 5 GHz	Indoor 35 m	780 Mbps	Low
	3G HSPA	Depending on the cell type (pico-macrocell) up to 100 km	42 Mbps	High
	4G	Depending on the cell type (pico-macrocell) up to 100 km	Up to 1 Gbps Up to 100 Mbps	High Low
	MM-wave (60 GHz)	A few hundreds of meters	7 Gbps	Low
Optical	IR	1 m	1 Gbps	None
	VLC	Up to 10 m	Up to 3 Gbps	Low

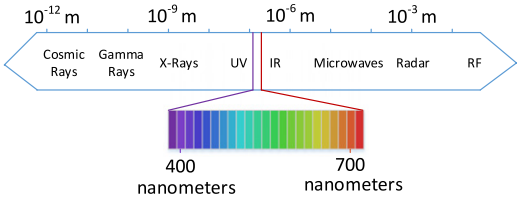

Fig. 1. Electromagnetic spectrum and visible light region.

technology and list the standardization efforts. We review previous work and open research issues on the transmitter LED technologies and modulation schemes in Section 4. Section 5 includes the channel modeling technique for optical paths. The optical receivers and MIMO systems for VLC are summarized in Section 6. We examine the research on medium access control (MAC) and network layers as well as multiple access schemes in Section 7. We list the potential application areas for VLC in Section 8. We present our concluding remarks in Section 9.

2. Why VLC?

In this section, we detail the features provided by VLC and explain why it is an important alternative to RF communication technologies. Below, we list the prominent advantages offered by VLC.

- Cost efficiency
- Energy efficiency
- Unregulated large bandwidth

Today, RF technology is mature. Yet, while a Bluetooth module that provides 1 Mb/s costs around $5 [2], VLC links can transmit at 50 Mb/s with an approximate cost of $1.7 [3]. Furthermore, LEDs used in VLC are also utilized for illumination. Therefore, the exact cost is even less.

LEDs used in VLC are highly efficient devices that use at least 75% less energy and last 25 times longer than incandescent lighting [4]. Since energy used by LEDs is mainly needed for illumination, VLC is extremely energy efficient. Estimations for the United States indicate greatest potential improvement on energy savings will be achieved upon the widespread use of LED lighting. According to these estimations, widespread use of LEDs by 2027 can save about 348 TerraWatt-hour of electricity compared to no LED use. This is an enormous amount of energy saving that is equal to the annual electrical output of 44 large electric power plants. Overall, this corresponds to total savings of more than $30 billion [4].

VLC uses the spectrum between 385 and 800 THz. Considering the huge bandwidth, the potential data carrying capacity of VLC is thousands of times larger than the RF portion of the spectrum [5].

On the other hand, it is difficult to install new cables to the lighting equipment on the ceiling. Fortunately, power line communications (PLC) enable use of electric cables for communication. PLC also enables the use of power outlets to be used as ports. This alleviates the need to install new communication cables to make VLC work. PLC specifications have been consolidated into two standards, i.e. IEEE 1901 [6] and ITU-T G.9960/61 [7] in 2009 and 2010, respectively. Since standardization for both VLC and PLC are complete, there is a strong incentive to investigate the integration of these technologies. In [8], authors point out the potential for this unification and lay out a few promising areas such as MIMO and relaying.

VLC has other advantages but these are more apparent when combined to alternative communication technologies. In the following, we lay out a comparison of VLC with Infrared (IR) and RF communications and point out the advantages provided by VLC. We provide a comparison of VLC with other wireless communication technologies in Table 1.

2.1. Comparison of VLC with IR communication

VLC has two major advantages over IR. One is related to safety issues and the other is about ease of deployment. Most of the Infrared emitting diodes use the 800–960 nm wavelength range. A number of problem may arise if radiation within these wavelengths comes into direct contact with the eye, such as athermal retina hazard and thermal injury risk of the cornea as well as possible delayed effects on the lens of the eye (cataractogenesis). Therefore, transmission power for infrared devices are limited by safety standards such as International Electrotechnical Commissions (IEC) IEC 60825-1 Safety of laser products, and IEC 62471 Photobiological safety of lamps and lamp systems.

VLC uses visible light LEDs which are expected to replace the conventional incandescent and fluorescent lamp since they have lower power consumption, high efficiency and longer lifetime [9,10]. Therefore, the transmitters for VLC will mostly be readily available. Furthermore, technologies such as PLC enable use of existing lighting infrastructure as back-haul in existing installations. For new installations, new technologies such as Power over Ethernet (PoE) may be used.