Visible Light Communication

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Using visible light for data transmission, which is referred to as Visible Light Communication (VLC), opens a broad spectrum of applications, which shall be illuminated in this article. After a short introduction and historical overview the technical details are described. Subsequently, the most important fields of application are presented, such as location estimation in closed rooms, which is particularly well-suited for hospitals. Current standardization efforts, namely JEITA CP-1221 and JEITA CP-1222 are also discussed. This article concludes with a list of recent challenges that are being worked on in the VLC community.

Categories and Subject Descriptors: B.4.1 [**Input/Output and Data Communications**]: Data Communications Devices

General Terms: VLC, VLCC, JEITA, LED, data modulation, SC-kPPM, FSK, location estimation

1. INTRODUCTION

1.1 Visible light

Visible light is the form in which electromagnetic radiation with wave lenghts in a particular range is interpreted by the human brain. Visible light is thus — by definition — comprised of visually-perceivable electromagnetic waves. The visible spectrum covers wave lengths from 380 nm to 750 nm.

Figure 1 shows for each wave length the associated color tone as perceived by human beings.

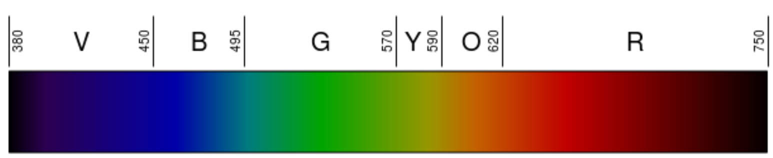


Fig. 1. The visible spectrum (http://commons.wikimedia.org/wiki/File:Spectrum4websiteEval.png, license:public domain)

At the lower end of the spectrum there are violet-bluish tones and light at the other end of the spectrum is interpreted to be distinctly red. Note that some animals exist whose vision merges into the ultraviolet (< 380 nm) or the infrared (> 750 nm).

1.2 Motivation

Using visible light for data transmission entails many advantages and eliminates most drawbacks of transmission via electromagnetic waves outside the visible spectrum. For instance, few known visible light-induced health problems exist today, exposure within moderation is assumed to be safe on the human body [Wurtman

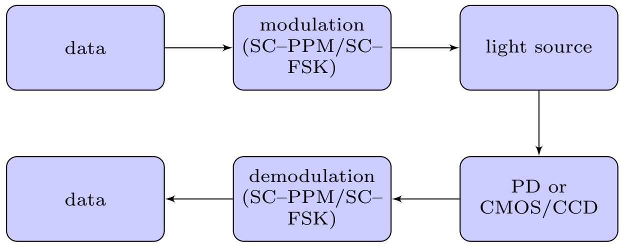


Fig. 2. Overview of the process of sending and receiving data via visible light (adopted from [Lo 2004])

1975]. Moreover, since no interference with electromagnetic radiation occurs, visible light can be used in hospitals and other institutions without hesitation.

Furthermore, visible light is free. No company owns property rights for visible light and thus no royality fees have to be paid nor do expensive patent-licence have to be purchased in order to use visible light for communication purposes [Langer 2010]. Visible light can serve as an entirely free infrastructure to base a complex communication network on.

VLC is mostly used indoors and transmitted light consequently does not leave the room when the doors are closed and the curtains drawn, because light cannot penetrate solid objects such as walls or furniture. Therefore, it is hard to eavesdrop on a visible light based conversation, which makes VLC a safe technology if the sender intends to transmit confidential data.

The most important requirement that a light source has to meet in order to serve communication purposes, is the ability to be switched on and off again in very short intervals, because this is how data is later modulated. This rules out many conventional light sources, such as incandescent lamps.

Over the course of the last years, usage of LEDs[1] has risen sharply [Won et al. 2008]. LEDs are often built into traffic and braking lights, but they also push conventional illumination methods (such as incandescent lamps) aside generally (LEDs are applied in more and more flashlights, headlights, status displays etc.) and might replace these other light sources entirely in the near future ([Wesson 2002] and [Evans 1997]). LEDs fullfill the above requirement in that they can be switched on and off quickly. Thus they are well suited to modulate data into visible light. In order to receive data sent out in this way, photodiode receivers or CCD/CMOS sensors can be used which are typically built into digital cameras.

Figure 2 shows a general overview of the process of sending and receiving data described above.

1.3 History

The idea of using visible light for data transmission is not entirely new. Using smoke signals to transfer messages goes back several thousand years and was used by many different cultures, e.g. Native Americans and Romans ([**?**; **?**, donaldson1988signalling] [Sterling 2007] and [Crown 1974]).

[1]Light Emitting Diodes

Lighthouses are employed to help ships navigate through dangerous coastal areas by sending out visible beams of light in periodical intervals. The “Pharos of Alexandria” was arguably the first tower which served as lighthouse and was one of the Seven Wonders of the World. Its construction dates back to 300 BC [Rawlins 2008].

The first sophisticated attempt to harness visible light for transmitting data was carried out by the Scottish scientist and inventor Alexander Graham Bell who is credited with inventing — among other devices — the photophone ([Gilleo] and [Eitane et al. 2005]). The photophone was a device that allowed to transmit data on rays of sunlight and was completed in February 1880 by Bell and his assistant Charles Tainter. Figure 3 shows a schematic representation of the photophone which will help to describe its operation. Incoming sunlight is focused through a lense *a* on a very thin mirror *b* which is made to vibrate by a person's voice channeled through a mouth piece. Light beams that are thus reflected from the vibrating mirror contain the modulated speech signal. This light then travels through lense *c* to a parabolic mirror *e* in whose focal point a selenium cell *d* is positioned. Selenium has the convenient property that its conductivity is inversely proportional to the amount of light falling on it. An attached telephone *g* can therefore demodulate the signal back into audible waves.

In April 1880 Bell and Tainter engaged in the first wireless communication in history when they were 213 m apart from each other [Groth 1987]. Tainter spoke to Bell and told him to wave his hat at irregular intervals, thus proving that their apparatus really did work.

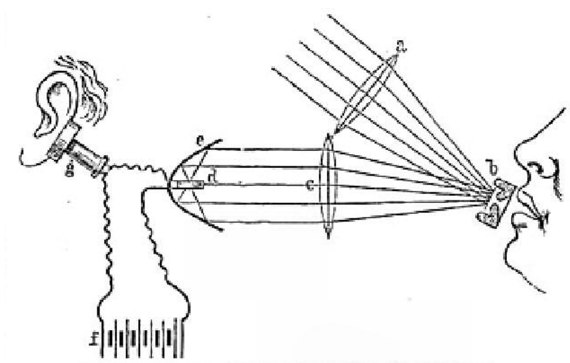


Fig. 3. Schematic view of the photophone (Source: Meyers Konversationslexikon (1888), public domain)

1.4 Visible Light Communications Consortium

The *Visible Light Communications Consortium* (VLCC) which is mainly comprised of Japanese technology companies was founded in November 2003. It promotes usage of visible light for data transmission through public relations and tries to establish consistent standards. A list of member companies can be found in the appendix. The work done by the VLCC is split up among 4 different committees:

(1) Research Advancement and Planning Committee

This committee is concerned with all organizational and administrative tasks such as budget management and supervising different working groups. It also researches questions such as intellectual rights in relation to VLC.

(2) Technical Committee
The Techincal Committee is concerned with technological matters such as data transmission via LEDs and fluorescent lights.

(3) Standardization Committee
The standardization committee is concerned with standardization efforts and proposing new suggestions and additions to existing standards.

(4) Popularization Committee
The Popularization Committee aims to raise public awareness for VLC as a promising technology with widespread applications. It also conducts market research for that purpose.

2. TECHNOLOGY

2.1 Transmitters

Every kind of light source can theoretically be used as transmitting device for VLC. However, some are better suited than others. For instance, incandescent lights quickly break down when switched on and off frequently. These are thus not recommended as VLC transmitters. More promising alternatives are fluourescent lights and LEDs. VLC transmitters are usually also used for providing illumination of the rooms in which they are used. This makes fluorescent lights a particularly popular choice, because they can flicker quickly enough to transmit a meaningful amount of data and are already widely used for illumination purposes.

However, with an ever-rising market share of LEDs and further technological improvements such as higher brightness and spectral clarity [Won et al. 2008], LEDs are expected to replace fluorescent lights as illumination sources and VLC transmitters.

The simplest form of LEDs are those which consist of a bluish to ultraviolet LED surrounded by phosphorus which is then stimulated by the actual LED and emits white light. This leads to data rates up to 40 Mbit/s [Won et al. 2008].

RGB LEDs do not rely on phosphorus any more to generate white light. They come with three distinct LEDs (a red, a blue and a green one) which, when lighting up at the same time, emit light that humans perceive as white. Because there is no delay by stimulating phosphorus first, Data rates of up to 100 MBit/s can be achieved using RGB LEDs ([Won et al. 2008]).

In recent years the development of resonant cavity LEDs (RCLEDs) has advanced considerably. These are similar to RGB LEDs in that they are comprised of three distinct LEDs, but in addition they are fitted with Bragg mirrors which enhance the spectral clarity to such a degree that emitted light can be modulated at very high frequencies. In early 2010, Siemens has shown that data transmission at a rate of 500MBit/s is possible with this approach [Siemens 2010].

It should be noted that VLC will probably not be used for massive data transmission. High data rates as the ones referred to above, were reached under meticulous setups which cannot be expected to be reproduced in real-life scenarios. One can expect to see data rates of about 5 kbit/s in average applications, such as location estimation [Haruyama et al. 2008]. The distance in which VLC can be expected to be reasonably used ranges up to about 6 meters [Won et al. 2008].

2.2 Receivers

The most common choice of receivers are photodiodes which turn light into electrical pulses. The signal retrieved in this way can then be demodulated into actual data. In more complex VLC-based scenarios, such as Image Sensor Communication [Iizuka and Wang 2008], even CMOS or CCD sensors are used (which are usually built into digital cameras).

3. MODULATION

In order to actually send out data via LEDs, such as pictures or audio files, it is necessary to modulate these into a carrier signal. In the context of visible light communication, this carrier signal consists of light pulses sent out in short intervals. How these are exactly interpreted depends on the chosen modulation scheme, two of which will be presented in this section. At first, a scheme called subcarrier pulse–position modulation is presented which is already established as VLC-standard by the VLCC. The second modulation scheme to be adressed is called frequency shift keying, commonly referred to as FSK. A detailed account on modulation can be found in Sugiyama et al. [2007]. They also explore how to combine pulse-position modulation with illumination control.

3.1 Pulse-position modulation

To successfully carry out subcarrier pulse–position modulation (SC–PPM) a time window T is chosen in which exactly one pulse of length $\frac{T}{k}$ is expected. Thus, subcarrier pulse–position modulation can also be described as parameterized form, i.e. SC–kPPM. k has to be a power of two, i.e. $k = 2^\ell$ for some ℓ. Then there are $k = 2^\ell$ different points of time for the pulse to occur. Suppose a pulse is registered at some point $k' \leq k$. The data represented by this pulse is then simply the number k' written as k–digit binary number.

Figure 4 exemplifies pulse–phase modulation by showing how the data `1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 0, 1` is modulated into a succession of pulses with SC–4PPM and SC–2PPM. The standard JEITA CP-1222 [Haruyama et al. 2008] which is promoted by the VLCC, recommends using a SC–4PPM modulation scheme. More on standardization will be presented in section 4.

Data is represented by presence and absence of the carrier wave which is a scheme generally referred to as *On–Off Keying* (OOK). An alternative scheme is presented in the upcoming section.

3.2 Frequency–shift keying

In frequency shift keying (FSK) data is represented by varying frequencies of the carrier wave. In order to transmit two distinct values (`0` and `1`), there need to be two distinct frequencies. This is also the simplest form of frequency–shift keying, called binary frequency–shift keying (BFSK). Figure 5 shows an example of frequency-shift keying by modulating of the same data string that was used in the SC–PPM example.

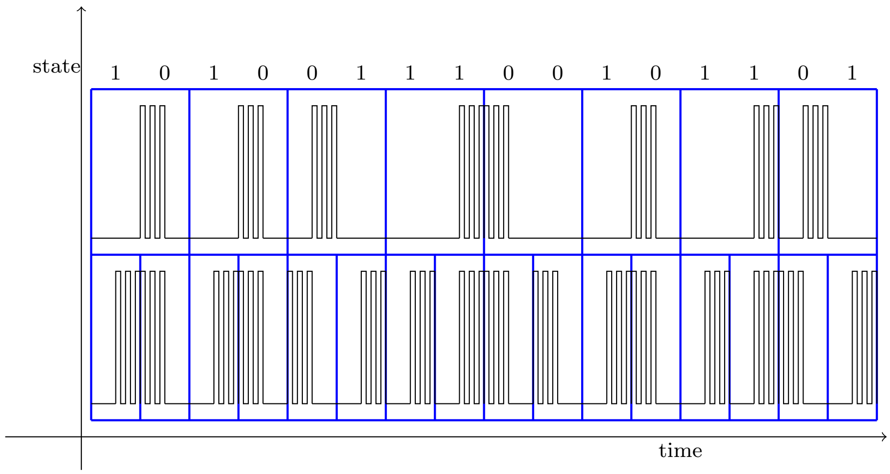


Fig. 4. Examples for sub–carrier pulse position modulation in context of VLC: SC–4PPM and SC–2PPM

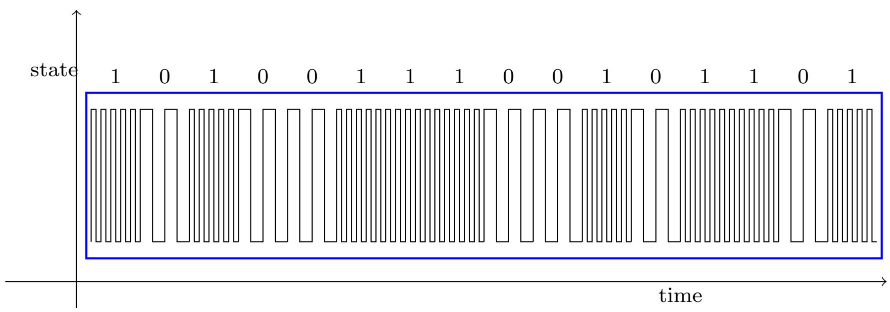


Fig. 5. Example for binary frequency–shift keying in VLC

At this point it is important to clarify a common source of confusion: In none of the modulation schemes it is the actual light frequency that is changed. That would lead to undesired effects as changing the light frequency also means changing the wave length of the light. Since VLC transmitters also serve general illumination purposes, ongoing variation of the color of surrounding light is unacceptable in most circumstances.

In subcarrier pulse position modulation it is the occurrence of light pulses that defines the frequency whereas in frequency shift keying the actual pulse frequency is changed depending on the data that is to be sent. In FSK, there is no “position” of pulses, because light pulses are sent uninterruptedly.

4. STANDARDIZATION EFFORTS

There are currently two JEITA (Japan Electronics and Information Technology Industries Association) standards (JEITA CP-1221 and JEITA CP-1222) which will be presented in this section. There is also an IEEE task group working on the specification of PHY and MAC layers for VLC.

The VLCC played a key role in specifying the two JEITA standards. In 2007, the VLCC proposed two standards which they called Visible Light Communication System Standard and Visible Light ID System Standard. These two standards were accepted by the JEITA and became known as JEITA CP-1221 and JEITA CP-1222, respectively.

Both standards were introduced in an effort to avoid fragmentation of proprietary protocols which experience shows to happen usually when a technology is not standardized.

4.1 JEITA CP-1221

The JEITA CP-1221 [Haruyama et al. 2008] restricts the wave length of all emitted light to be within a range of 380 nm to 750 nm which happens to be the generally agreed-upon definition of visible light (as was also discussed in the introduction of this article). If a manufacturer of VLC applications claims to emit light of a particular frequency, then they have to adhere to that frequency with an accuracy of 1 nm, i.e. if an application claims to send light within 440 nm and 480 nm, wave lengths of actually emitted light have to be between 439 nm and 481 nm. JEITA CP-1221 also suggests to use sub-carrier pulse modulation.

It defines three major frequency ranges whereas only one is used for communication purposes:

(1) (15 kHz to 40 kHz)
This is the range that is intended to be mainly used for communication purposes. Haruyama et al. [2008] mentions an average transmission rate of 4.8 kbit/s with a subcarrier frequency of 28.8 kHz. Note, however, that the transmission rate is not only depenend on the subcarrier frequency, but also on the modulation scheme.

(2) (40 kHz to 1 MHz)
Frequencies in this range are already too high for some light sources, such as flourescent lights. They cannot be switched on and off again fast enough to uniquely decode the data on the receiving side.

(3) ($>$ 1 MHz)
Frequencies in this range should only be used to exchange massive data using special light sources, such as resonant cavity LEDs.

All frequencies describe the intervals in which pulses occur with respect to the used modulation scheme.

JEITA CP-1221 was originally thought to be mainly used for transmitting information on identification (such as position information of a lamp in a localization estimation scenario), but it is also possible to transmit "non-fixed", i.e. arbitrary, data.

4.2 JEITA CP-1222

JEITA CP-1222 [Haruyama et al. 2008] differs from JEITA CP-1221 in that it is supposed to be only used for communication purposes and is slightly more specific in its suggestions: It restricts the subcarrier frequency to 28.8 kHz and it specifically suggests using SC-4PPM as modulation scheme. Furthermore, it requires cyclic reduncancy checks (CRC) for error detection and correction.

4.3 IEEE 802.15 TG7

Within the IEEE working group for wireless and personal area networks (802.15) the IEEE has formed task group 7 (TG7) which is supposed to write a PHY and MAC standard vor VLC. Unfortunately though, as of writing this document, information on their progress (the most recent of which dates back to January 2009) is scarce.

5. APPLICATIONS

It should be noted that most proposed VLC applications are far from being market-ready. Therefore, most applications mentioned in this section have often been tried out in research settings, but their usage in real world scenarios is still somewhat hypothetical.

5.1 Localization

One of the major applications of VLC, especially in the medical field, consists of estimating one's location.

[Liu et al. 2008] propose a scenario for visually handicapped people. Location estimation is put to use in this scenario to guide people through a series of hallways. All hallways are assumed to be illuminated by fluorescent lights which are capable of transmitting a unique ID via VLC. Estimating the current location consists of two steps: Firstly, the distance to each fluorescent light in reach is computed and secondly, the current position is estimated based on the previously computed distances. The distance to each light source is computed by first measuring the angle of incident light with assistance of a photo sensor that is attached to the person's shoulder. Then, using some trigonometric functions, the distance between

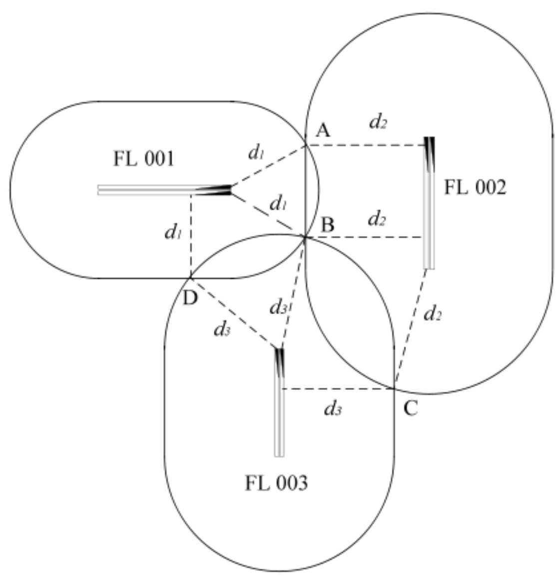


Fig. 6. Intersection of distance range curves to estimate current location [Liu et al. 2008]

the receiver and the light source in horizontal direction is calculated. The distance to each light source describes a unique range curve (a rectangle with two half circles at each end). The intersection of all distance range curves is the estimated location as shown by figure 6.

Nakagawa Laboratories, Inc. propose a different approach in one of their promotional videos (figure 7): They use a projection of surrounding light sources through a lense onto a CCD or CMOS sensor and estimate the location of the receiver based on this projection. Figure 7 clarifies this idea.

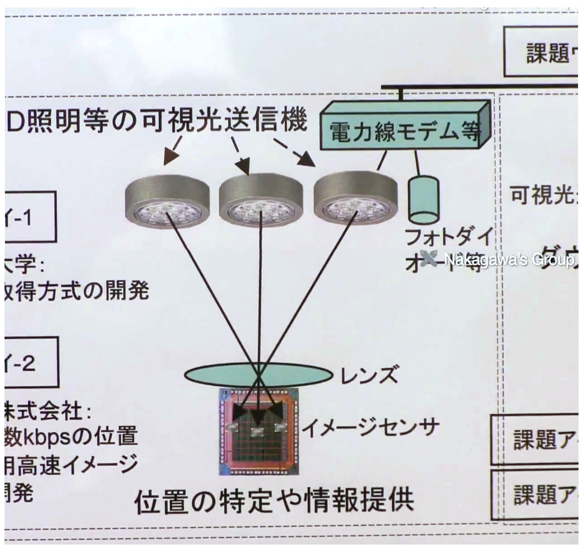


Fig. 7. Schematic view of a projection of available light sources onto a photo sensor (http://www.youtube.com/watch?v=QEh5f49LsB4)

5.2 Further Applications

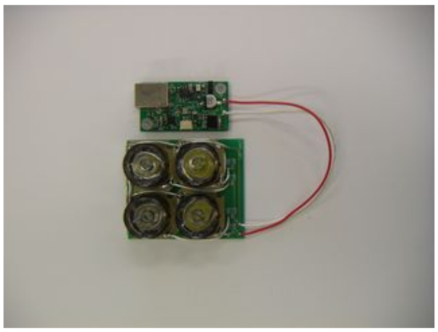
Many prospective applications have been suggested for VLC. These include:

VLC could be used in conjunction with Powerline Communication (PLC). The idea is that voltage changes in an eletrical wire, which serves as PLC carrier, are reflected by the flickering of a light source. In that way, PLC data can be forwarded using VLC. This approach is thoroughly discussed in [Amirshahi and Kavehrad 2006] and [Komine and Nakagawa 2003].

Items at exhibitions or musems could be fitted with a VLC transmitter which sends information about itself to nearby receivers. Pang et al. [1999] describe a scenario where a museum visitor might be provided with auditory information about the item he is currently standing in front of.

Another field of application for VLC lies in vehicle to vehicle communication. Liu [2010] developed a full-duplex vehicular VLC (V^2LC) system which was tested in large-scale experiments resulting in interesting findings such as how multipath effects can be advantageous.

To conclude this section, two real-world applications are briefly introduced. The first one is a device called "VLC ID Kit" (8) made by Nakagawa Laboratories, Inc. and was sold until 2009 to end customers. It contained a transmitter and a receiver unit which satisfied the JEITA CP-1221 and JEITA CP-1222 standards. Figure 8 shows these two parts (which were connected to a computer via USB). As visible, the transmitter had a total of four distinct white LEDs. It was mainly



(a) transmitter unit

(b) receiver unit

Fig. 8. VLC ID Kit by Nakagawa Laboratories, Inc. (http://www.naka-lab.jp/product/kit_feature_e.html)

intended for people with a programming background interested in VLC. The VLC ID Kit sold for $1,000.

Another example where visible light communication is already put to use is a wireless data transmitter named RONJA (Reasonable Object Near Joint Access) which is able to create a 10 Mbit/s link with a range of approximately 1.4 km. It is described in detail by Khumsat et al. [2006a] and Khumsat et al. [2006b]. Its main purpose lies in establishing long-distance point to point links and thus has only limited broadcast capabilities, because the narrow, focused beam of light becomes undetectable by a receiver if it is only a few meters away from the beam axis. It does not adhere to any VLC standards though and uses a simple Manchester encoding to modulate transmission data. The schematics of RONJA are freely available as is all source needed to operate the device. Anyone interested can thus build a RONJA device from scratch: The website http://ronja.twibright.com/ provides detailed information about the project and how to build and operate a transceiver unit.

6. DIFFICULTIES

6.1 General

Even though VLC can lead to many interesting applications, as shown in the previous sections, the technology is not entirely free of certain drawbacks and difficulties, which shall be addressed shortly in this section.

First of all, to successfully transmit data, there has to exist a line of sight between sender and receiver, because visible light cannot penetrate solid items or objects.

Apparently, this is not always a problem, but might even be a desired property when it comes to location estimation in closed rooms.

Another problem that may arise consists in interference which is, admittedly, not a VLC–specific problem. There can be no interference with other electromagnetic waves in the non–visible spectrum, such as WLAN or mobile phone radiation, but additional light sources may vastly impair data transfer. Very high light intensity of another light source which is not involved in VLC may lead to a scenario where the signals of a sending LED can not be registered by a sensor any more, because they are scarcely distinguishable from the overwhelming amount of light sent out by the other light source.

A severe disadvantage of VLC in the medical field is that it is sometimes imperative during surgery to switch off background illumination (in order to view some monitors for instance). This scenario is obviously incompatible with VLC and it might perhaps never be used in operating rooms.

Conditions such as fog and hazy air also vastly hamper data transmission via visible light as described by Jamieson [2010].

Moreover, reflections might occur on mirroring surfaces which can lead to receiving wrong data. However, this seems to cause fewer problems than e.g. multipath effects in GPS.

6.2 Providing an uplink

Although VLC is a natural broadcast medium, it is sometimes desired to send information back to the transmitter. There are three different approaches as discussed by O'Brien et al. [2008] and Le Minha et al. [2008] that shall be briefly mentioned here. Currently, these approaches are somewhat hypothetical as none of them is ready for the market yet.

(1) The light source can be co-located with a VLC receiver (e.g. a photodiode). This means, however, that receivers, i.e. small, handheld devices running on battery power, would have to be equipped with a VLC transmitter which may be costly (energy-wise) and make the device look ugly to some customers.

(2) A retroreflector can be used to return incident light back to the source with a minimum amount of scattering. The light is modulated upon reflection with the data that is to be sent back to the source. This is a very promising approach, because it would solve the problems raised by the energy-intensive approach mentioned previously. O'Brien et al. [2008] claim that first experiences with retroreflectors have resulted in rather low data rates.

(3) The light source can be fitted with an infrared or radio transmitter. This obviously solves the problem, but even though comparatively high data rates can be achieved, this approach has one major drawback: No VLC is used for the uplink which might be unacceptable in some scenarios, because it eliminates some of the primary advantages of VLC, such as the absence of EM-interference.

7. CONCLUSIONS AND OUTLOOK

It has been shown that even though most existing efforts are still in a very early stage, VLC is a promising technology with a wide field of prospective applications. An ever-growing interest in VLC throughout the world can be expected to lead to real-world applications in the future. In some fields of application it poses a favorable alternative to conventional solutions (infrared, WLAN etc.). The main goals for the future are increasing the transmission rate and improving standardization.

It is possible to improve the transmission rate through parallelizing communication by using multiple emitters and receivers, i.e. implementing the well-known MIMO principle (multi input, multi output) [O'Brien et al. 2008]. Afgani et al. [2006] and Elgala et al. [2007] propose using OFDM, a more advanced modulation technique.

Completing standardization is challenging in that technical requirements and other regulations, such as eye-safety and illumination constraints, have to be combined.

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A. LIST OF VLCC MEMBERS

NEC Corporation

Panasonic Electric Works Co., Ltd

THE NIPPON SIGNAL CO.,LTD

TOSHIBA CORPORATION

JAPAN RURAL INFORMATION SYSYTEM ASSOCIATION Information System Research Institute

SAMSUNG ELECTRONICS CO.,LTD.

NTT DoCoMo, Inc.

CASIO COMPUTER CO.,LTD.

Nakagawa Laboratories, Inc.

Outstanding Technology Co., Ltd.

Sumitomo Mitsui Construction Co., Ltd.

TAMURA Corporation

Sharp Corporation

Japan Coast Guard - Coast Guard Research Center

COMTECH 2000 Corporation
RISE Co., Ltd.
JAPAN TRAFFIC MANAGEMENT TECHNOLOGY ASSOCIATION
NHK (Japan Broadcasting Corporation)