Kick-starting the VLC Market via Optical Camera Communications

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***Abstract*— this paper discusses the state of the visible light communication (VLC) market and expresses concern about the lack of VLC market success despite the technology having been introduced over a decade ago; with VLC data rates approaching 1 Gbps; and the completion of several VLC standards. This paper suggests that perhaps VLC should take a different market approach; that is, instead of trying to duplicate the user experience offered by existing RF wireless access such as WiFi, VLC should aim for an extremely low cost unique user experience based upon the merger of imagery and communications utilizing optical camera communications.**

Keywords—VLC; OCC; market; WiFi; Visible Light Communications; Optical Camera Communications; CamCom; LiFi; IEEE802.15.7r1

I. INTRODUCTION

Visible Light Communications (VLC) has a long history dating back to ancient signal fires and the 1880 Alexander Graham Bell photophone which transmitted speech wirelessly using modulated reflected sunlight. But it was the emergence of solid state light sources that sparked the imagination of researchers, such as those at Nakagawa Laboratories at Keio University around the turn of the 21st century, to demonstrate that solid state light sources could be used for secondary purposes such as data transmission and positioning.

Since the early days of VLC there has been much research demonstrating increased unidirectional data rates, with increasingly sophisticated modulation formats exceeding 1 Gbps. And over this same time frame we've seen several VLC standards generated specifying data rates approaching 100 Mbps. But also over this same time frame we've seen several RF wireless standards, such as WiFi, Bluetooth and ZigBee, developed and deployed in numbers that far exceed those for their comparable VLC counterparts. So what are the issues associated with the mass deployment of VLC technology?

II. VLC ECOSYSTEM ISSUES

Comparing the deployment of VLC versus say WiFi, one can observe that the VLC ecosystem is more complex. If we assume that today's platform of choice is the mobile device, than we can see that the user device is in one ecosystem and the transmitting LED lighting device is in another ecosystem; that is, the folks who make mobile devices are waiting for a large percentage of the lights to be modulated before they deploy VLC in the handset, while the LED lighting industry is waiting for the reverse complementary situation. For the lighting industry, modulating LED lights will result in additional complexity and lower efficiency that is hard to justify without being able to realize a return on the investment. Contrast this to the more cohesive WiFi ecosystem where even during the early days of emerging deployment one company could supply devices for both the access point and the client user.

One could argue that trying to disrupt an established RF solution such as WiFi with VLC is a daunting task, especially if there are overlapping data rates and services. There is an argument to be made that VLC offers spectral relief but so far the RF industry seems satisfied to rally around the concept of RF small cells to increase deployment density. Could it be that what is needed to kick-start the market is a usage (e.g. killer app) that provides a unique offering, at a very low cost, that is not readily available from an existing wireless solution? A usage that can bridge across the two ecosystems to stimulate VLC deployments? The inherent advantages of VLC deployments are most strongly realized in applications such as low cost short-range links (i.e. interactive toys) and informational broadcasts (i.e. line-of-sight market). Visible light communications could also have beneficial characteristics in cost effective high accuracy positioning systems.

III. STANDARDS ISSUES

In regards to standardization history, I've participated in the review of IEC TC100/PT 62942 *Visible light beacon system for multimedia applications* and I was the technical editor for IEEE802.15.7 *Short-Range Wireless Optical Communication Using Visible Light* [1]. Not surprisingly, I'm most familiar with IEEE802.15.7. IEEE802.15.7 was initiated in 2008 by a group of companies and academics who recognized the potential of VLC in the market place. The standard was completed in 2011 and offers various bi-directional data rates from approximately 10 kbps to 100 Mbps with various modulation formats and forward error correction schemes. But to my knowledge, not a single significant 15.7 standard compliant deployment has occurred and it has been over 4 years since the standard was published. Such poor uptake of a

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standard is disconcerting and begs the question "was the standard inappropriate or is the market being misjudged". I suspect the issue is the latter; that is, IEEE802.15.7-2011 didn't really address a market need. In particular, deploying 802.15.7 required that additional hardware be added to the user platform - which increases manufactures cost - while not offering any significantly new user experience. Such failed market penetration is bad for VLC technology investment and tends to choke off research and development funding. Could it be that what is needed for VLC to thrive is an extremely low cost and low market entry barrier use case that offers the user a significant experience that is not available with any other technology? For without an emerging VLC market – in any form – it will be difficult to justify addition VLC R&D expenditures.

IV. EMERGENCE OF OPTICAL CAMERA COMMUNICATIONS

These concerns started simultaneously coalescing in the VLC community several years ago with the realization that we already have billions of enabled VLC devices that could use the optical camera as a receiving sensor, in conjunction with downloadable application software, to implement a form of VLC that IEEE802.15.7r1 [2] calls optical camera communications (OCC). Again, referring to the split in the ecosystem between mobile device vendors and lighting vendors, being able to argue to the lighting vendors that there are millions of mobile devices already VLC enabled goes a long ways to stimulating lighting industry investment to "VLC enable" luminaires. In addition, OCC offers users an experience that they cannot get with other communication technologies; which is, is the merger of communications and imaging - a concept that Professor Michael Tsai of National Taiwan University calls "talking pixels".

As to the history of IEEE802.15.7r1: early in year 2012, Professor Yeong Ming Jang of Kookmin University, in conjunction with Professor Jaesang Cha of Seoul National University of Science & Technology, initiated the IEEE802.15.LED-ID interest group. By July 2013 the focus had morphed to optical camera communications [3] and an IEEE802.15 study group was formed to write a Project Authorization Request to form an OCC standardization task group. The original intention was to write an amendment to the existing IEEE802.15.7-2011 standard, but for technical reasons - having to do with the word "visible" in the original title - it was required to do a revision (IEEE802.15.7r1) to accommodate wavelengths other than visible light - which opened the door for LiFi to also participate in the revision effort. Task group IEEE802.15.7r1, known as *Standard for Short-Range Wireless Optical Communication*, was kicked-off in January 2015 with authorization to write a revision to the IEEE802.15.7-2011 standard that supported optical camera communications [4], LED-ID [5] and LiFi [6]. The latest timeline for task group 15.7r1 has the presentation of proposals scheduled for early 2016, with the generation of a letter balloting draft in early 2017. It is expected the revision will be published by early 2018.

V. CALL FOR ACTION

In some aspects, at least from my perspective, optical camera communications is a critical chance for VLC to obtain market penetration. As I previously indicated, without some form of market uptake of VLC, it will become increasingly difficult to justify future VLC R&D investments. Which brings us to the importance of activities such as ICEVLC2015 with its emphasis on optical camera communications. We need to do all we can to obtain the much needed critical market penetration while avoiding fracturing the market with multiple incompatible standards. The technical presentations here at ICEVLC2015 are an important step in the process of determining the relevant technical issues that need to be addressed to make OCC, and ultimately VLC, successful.

REFERENCES

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Appendix: UFSOOK OCC Modulation

There have been several modulation formats proposed for Optical Camera Communications, mainly differentiated by the type of image sensor read out (e.g. rolling shutter versus global shutter). I was asked to say a few words about a modulation scheme originating at Intel Labs that is suitable for use with either type of read out, and the only amplitude modulation technique that I know of that allows the demodulation of an LED light flashing at a frequency fast enough to avoid noticeable flicker while using a common frame rate camera (e.g. 30 frames per second) [7] [8] [9]. The technique involves encoding the bits using a form of DC balanced differential encoding called undersampled frequency shift ON-OFF keying (UFSOOK). The modulation concept is similar to frequency shift keying inasmuch as there are defined mark and space ON-OFF keying frequencies for encoding bits, with these frequencies being high enough to avoid flicker. The mark (logic 1) and space (logic 0) frequencies are selected such that when undersampled by a low frame rate camera, the mark/space frequencies alias to low pass frequencies that can then be further processed to decode the bit values. Figure 1 illustrates the concept assuming a 30 frames per second camera.

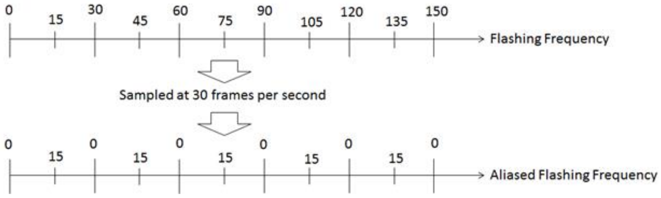

Figure 1 – Aliased flashing frequency sampled at 30 fps

For example, if the camera has a frame rate of 30 fps, and the space frequency is 120 Hz and the mark frequency is 105 Hz, then the aliased frequencies as seen by the camera are respectively 0 Hz and 15 Hz.

In regards to the observability of a “blinking light”, the UFOOK waveform transitions can be seen by a camera with the appropriate exposure setting, but not by the human eye, due to the fact that the camera’s exposure setting can be much faster than the eye as shown in Figure 2.

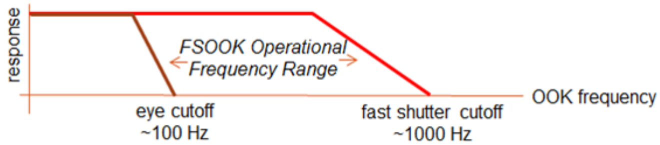

Figure 2 – Camera frequency response compared to the eye

The human eye has a cutoff frequency in the vicinity of 100 Hz, whereas the camera’s cutoff response can significantly exceed 100 Hz depending upon the exposure speed setting (integration time). Under intense light conditions the exposure can be set to well under 1 ms and still result in satisfactory performance. As suspected, the techniques shown in this paper require a relatively intense light source (i.e. high SNR).

An example of how bits are sent via the blinking lights is shown in Figure 3.

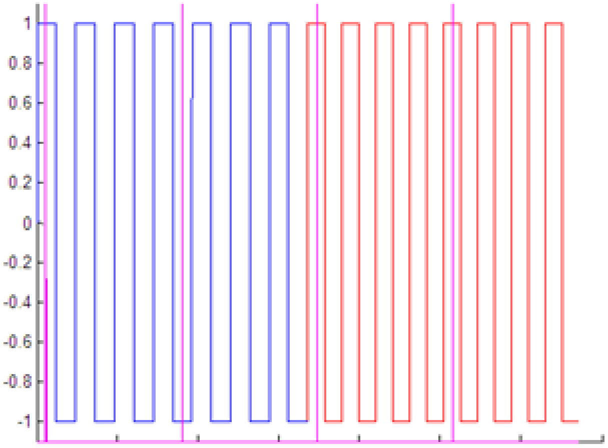

Figure 3 – UFSOOK encoding of a logic “1 0” bit pattern

In Figure 3 the Y-axis is read as a +1 turns the light ON and a -1 turns the light OFF. A logic one is transmitted as 7 cycles of 105 Hz OOK (shown in blue) and a logic zero is transmitted as 8 cycles of 120 Hz OOK (shown in red); therefore, the composite waveform represents the bit pattern “1 0”. This OOK waveform is sampled 30 times per sec by a camera as represented by the magenta sampling strobes. There are two samples per bit making the bit rate half the sample rate (i.e. camera video frame rate). For logic 1 (blue) the two samples differ in value (light ON-OFF). For logic 0 (red) the two samples have the same value (light ON-ON).

By selecting the space frequency to be a multiple of the camera frame rate and the mark frequency to have a 15 Hz offset from the space frequency, we can invoke the following simple decoding rule.

$$x(t,\omega_\Delta) = \begin{cases} \mathit{unchanging} & \text{"0"} \\ \mathit{toggling} & \text{"1"} \end{cases}$$

Adhering to the stated rules will always result in there being an even number of cycles of OOK per bit for a space frequency and an odd number of cycles for a mark frequency; hence, the “code” is always balanced.

Next it is required to form frames of data and this can be done by defining a start frame delimiter (SFD) that is appended to the beginning of each frame of data. The end of the frame is indicated by the second appearance of the SFD which implies the beginning of the next frame. The SFD is shown in Figure 4.

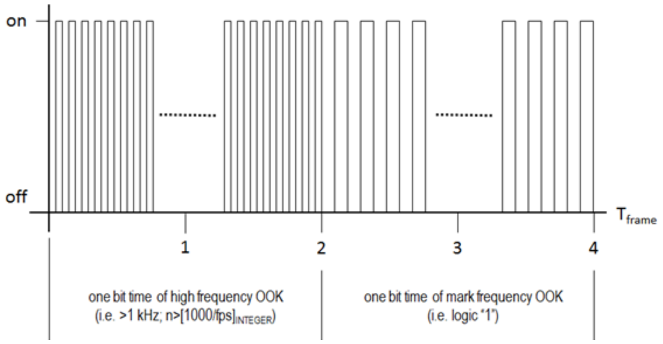

Figure 4 –Start frame delimiter definition

This SFD, which is two bit times long (i.e. four video frames), is sent prior to a data frame. The first bit of the SFD is sent at an OOK frequency that cannot be followed by a normal smartphone grade image sensor (in our lab we use 25 KHz). The pixel integrator in the image sensor extracts the average light intensity such that in the image frames, associated with the first bit of the SFD, the light appears half ON (assuming 50% duty cycle). This half ON condition persists for one bit time and signals the beginning of the frame. The next bit of the SFD is just the transmission of the logic “1” mark OOK frequency.

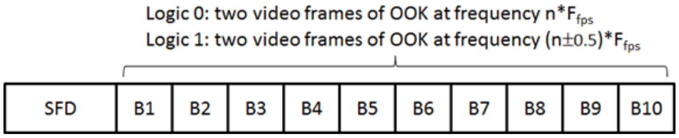

Figure 5 – Data frame definition

Following the SFD is the rest of the frame of data which consists of logic ones and zeros as represented by transmission of the appropriate mark or space OOK frequency. Each bit has a duration of two video frames as required by the differential code.

The processing of the frame of data can be done real-time or non-real-time. In our laboratory we normally send repetitive frames of data, and then record a video of the lights for the prescribed number of video frames commensurate with the data frame length, and then post process the video in regards to the salient light features. We first look for the SFD initial two video frames (lights half ON) and then we unwrap the frame by linearly reordering the recorded frames with respect to the initial SFD frames. It should be mentioned that we typically set the image sensor exposure time (integration time) to be on the order of 100 uS while observing relatively bright lights.

This brief introduction ignores some nuances necessary to support a viable implementation such as forward error correction which is necessary to compensate for sampling error. References [8] and [9] provides more implementation detail.