Visible Light Communication Cyber-Physical Systems-on-Chip for Smart Cities

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Abstract —This paper reviews recent developments of Light-Emitting Diode (LED) based Visible Light Communication (VLC) technologies and related cyber-physical systems-on-chip (CPSoC) for smart city applications. Critical aspects of LED VLC cyber-physical systems are discussed. Designs of LED-based VLC CPSoC Integrated Circuits (IC) are depicted. LED VLC technology, as a viable internet of things (IoT) solution, has the potential for various applications for smart cities including smart hospitals, smart homes, smart communities and smart traffics in near future.

Index Terms—LED; visible light communication; VLC; CPSoC; smart city; IoT

I. Solid-State Lighting

A major revolution in lighting technology is occurring that will significantly change the world. The traditional incandescent and Compact Florescent Light (CFL) bulbs are being replaced by solid-state light emitting diode (LED) illuminators, which have many advantages. LED is a much greener lighting technology featuring energy efficiency of up to ~200 lumens per watt, much higher than incandescent bulbs (~15 lumens per watt) and CFLs (~73 lumens per watt) [1]. Considering that lighting accounts for up to 30% of electricity consumption, the energy savings of LED lighting is tremendous. The PN junction-based LED illuminating devices also feature longer lifespan, up to >50K hours today, compared to ~8K hours for CFL bulbs and ~1200 hours for "Edison" bulbs typically. LEDs are also very small, "cold" and rich in colors, making LED lighting a perfect solution to lighting up the Globe in a greener way.

LED illumination is based on PN junction, which can be switched ON/OFF via electrical biasing at a high frequency of tens of MHz, without flickering to human eyes. LED switching can be used to modulate the light by information signals to realize Visible Light Communications (VLC), making "communicate as you see" a reality. The LED-based VLC technology is advantageous over radio-frequency (RF) based wireless technologies in many ways [2]-[5]: The visible light frequency spectrum is up to 300THz and is unlicensed, unlike RF spectrum, it hence opens a door for extreme high throughput wireless streaming of well beyond giga bits per second. Visible light is generally harmless to human being and allows more emission power to boost wireless data rates. VLC technology requires line-of-sight (LOS) that is very suitable for secured closed-door wireless communications. VLC technology can co-exist with RF technologies, allowing higher wireless performance while reducing the investment. Particularly, VLC communications can be embedded into the existing LED lighting infrastructure, making the combined LED lighting and wireless communication systems economic-wise. VLC technology can also be used for visible light positioning (VLP), leading to many applications for navigation, ranging and tracking, some are not suitable for RF-based GPS technology, such as, indoor tracking. It is obvious that the revolutionary LED lighting technology is a viable solution for various internet-of-things (IoT) applications, such as smart cities [6]-[12].

II. Visible Light Communications Systems

In recent years, VLC technology has received global attentions, leading to many breakthroughs in VLC research. Consequently, the Visible Light Communication System Standard and Visible Light ID System Standard were proposed by the Visible Light Communication Consortium (VLCC). The IEEE Standard 802.15.7 was also established for VLC communications [13], paved the way for VLC system designs and applications.

The core of VLC system is the VLC transceiver that consists of a transmitter and a receiver. A VLC transmitter comprises an LED light emitter, a driver and a modulation circuit. The electrical information signals are converted to modulated light waves that are sent out via LED light. Typically, white visible light is produced by

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an LED laminator in two ways, using blue LED with yellow phosphor filter or using Red-Green-Blue (RGB) LED combination. It is critical that the VLC modulation will not cause flickering to human eyes since the main role of LEDs is still lighting. A VLC receiver consists of an optical receiver and a demodulation circuit. The optical receiver can be a photodetector (PD) or a CMOS imaging sensor. The current reproduced at the receiver will be demodulated to regenerate the useful electrical information from the optical transmitter. Unlike common RF modulation that is suitable for mostly single electromagnetic mode, Intensity Modulation/Direct Detection (IM/DD) scheme is typically used for VLC modulation since the light signals are not in single EM mode. Fig. 1 depicts the conceptual digital and analog optical IM/DD modulation schemes. In digital IM/DD modulation, LED switching is driven by the electrical signals (current) and the information is embedded into the visible light emitted by the LED. In analog modulation, a DC current is required to keep the LED in the lighting mode and the data are modulated onto the LED light by the AC current signals.

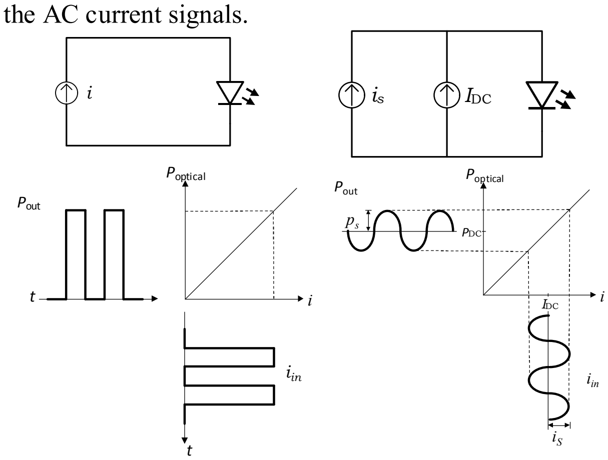

Fig. 1. Illustration of IM/DD-based digital (L) and analog (R) VLC modulation schemes.

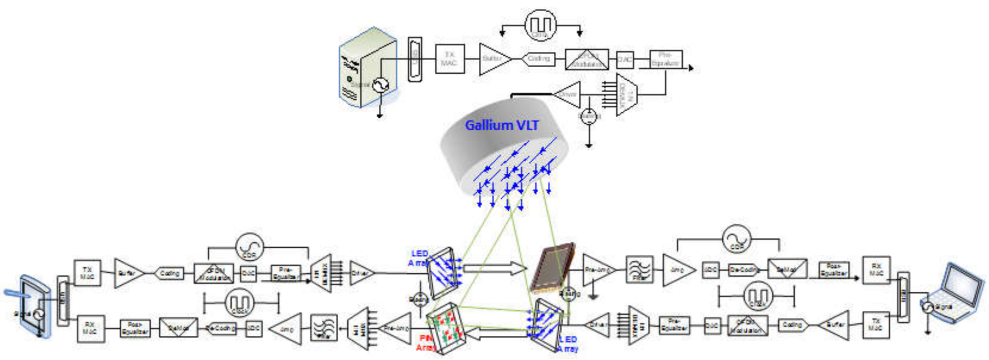

Fig. 2 A LED/PD array-CMOS imager based full duplex VLC wireless system.

Various VLC systems have been demonstrated for wireless streaming, many of them were discrete VLC testbeds using commercial off-the-shelf (COTS) components for easy construction [2]-[8]. Fig. 2 depicts a typical VLC transceiver system allowing both host-slave broadcasting (LED bulbs to users) and peer-to-peer full-duplex communications (e.g., between smartphones and tablets). The transmitter has buffers, coding and OFDM modulation for better signal quality, a pre-equalizer for wider bandwidth, driver and DC biasing for large LED array, DEMUX to handle LED array signals, and DAC and global clock synchronization. The receiver contains pre-amplifier and main amplifier, high/low pass filters, ADC, decoding and demodulation to recover signal information, a post-equalizer to enlarge receiver bandwidth, clock synchronization, and clock and data recovery circuit. Both PD arrays and CMOS imagers can be used to boost signal quality and data rates. A MUX circuit is used for the PD array to fuse the received signals. MAC blocks are used for access control for multi-user systems. ESD protection is needed for real-world VLC systems.

III. VLC/VLP CYBER-PHYSICAL SOCs

While being handy for VLC system demonstration, these COTS-based VLC testbeds have fundamental disadvantages including poor system performance and reliability, large system footprint and high costs. It is apparent that systems-on-chip (SoC) for the VLC cyber-physical systems will be the solution for real-world VLC applications. We recently designed and fabricated the first single-chip custom-designed VLC transceiver SoC IC that demonstrated high-throughput LED-based VLC wireless streaming [11]. This single-chip VLC SoC consists of opto-electrical signal conversion, filtering, bandwidth enhancement, low-noise pre-amplification, power amplification, analog-to-digital conversion, digital signal processing (DSP) and on-chip ESD protection functions. Fig. 3 shows the VLC transceiver SoC IC designed and fabricated in a foundry 180nm BCDMOS technology. The VLC SoC chip consists of a LED transmitter, equalization control unit, Manchester encoding and decoding block, phase lock loop (PLL), voltage and current reference, and optical receiver. It was designed to realize 64bit digital control for multiplexer control using I2C protocol, I2C slave and 8 digital registers. There are 25 IO pads on chip, including two mux testing outputs and two I2C programming interfaces. This VLC transceiver has three main functional domains: IO pad-ring, Analog and Digital. The Analog domain has four blocks including transmitter, PLL, bandgap and receiver. The transmitter block contains Manchester encoder, delay cells, equalizer and LED driver. The receiver has four blocks: front-end, linear amplifiers, comparator and Manchester decoder. The Digital domain comprises I2C slaves, I2C registers, signal start and stop detection, and a counter. The IO Pad-ring domain includes power-on reset (POR) to set the initial value of all of the digital logics and power supply detection. The communication between I2C master and slave is realized by I2C buffer via I2C buses. On-chip ESD protection is designed for each IO pad. The VLC transmitter has pre-equalization and multi-stage amplifier to enhance LED modulation bandwidth. The receiver has VLC-specific TIA and comparator circuits. The IC die size is 2X2mm^2 and uses BGA bonding for packaging. Fig. 4 shows the VLC measurement set-up using the VLC transceiver SoC fabricated in 180nm BCDMOS technology, which can operate over a bandwidth of 50 MHz in measurement.

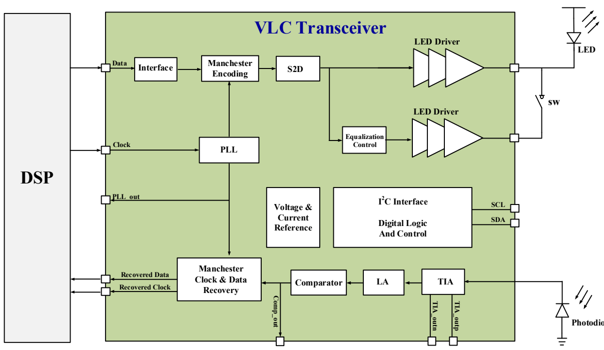

Fig. 3. Architecture for the single-chip VLC transceiver SoC designed in a commercial 180nm BCDMOS technology [11].

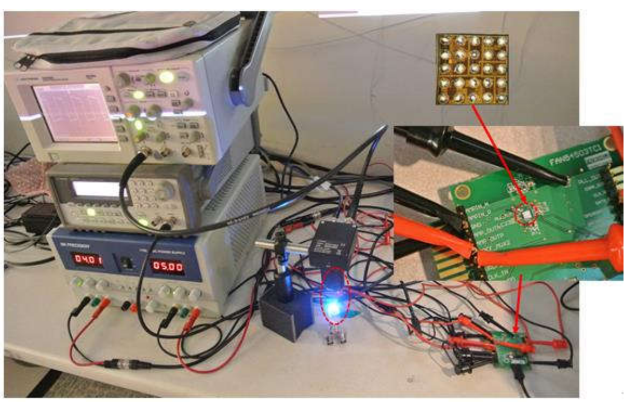

Fig. 4. A VLC demo testbed using the VLC SoC IC (the inset is the IC die photo) shows signal pulse trains through visible light emitted by LED [14].

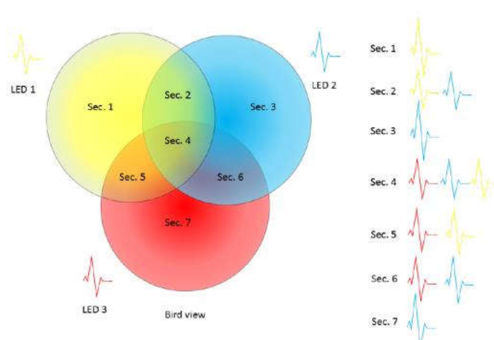

Fig. 5. A simple proximity method for VLP tracking [15].

Uniquely, VLC technologies can be used for various VLP applications, particularly where GPS is incapable or missing, such as indoor and in RF-prohibited facilities, for example, for live personnel and asset tracking in hospitals. Many VLP tracking techniques were developed. Fig. 5 shows a simple Proximity method using three LED lighting devices where the spatial light grids are created according to the difference of the received lights. However, the tracking resolution is limited by the grid density in this method [15]. Another method is a scene analysis technique that functions in two phases [16]: It first collects LED finger prints such as the received signal strength (RSS), time of arrival (TOA) and time difference of arrival (TDOA). It then conducts matching analysis between the stored finger prints and the collected real time light data. A triangulation method using angulation and multilateration can also be used that indirectly estimates the target position by analyzing the received TOA, RSS and TDOA data [17].

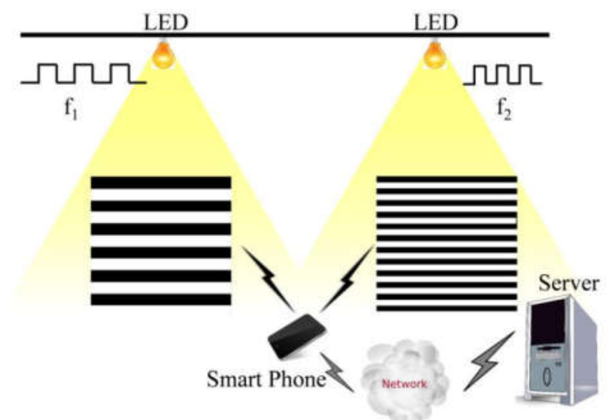

Fig. 6. Illustration of the new LED VLC tracking system [15].

Fig. 6 shows a new rolling shutter enabled positioning method that we developed for a LED VLP tracking system for smart hospitals [15]. The LEDs are individually modulated with unique frequencies as their optical tags (IDs). The optical beacons emitted by the LEDs are captured by a smartphone camera via analysis of the CMOS imager rolling shutter effect. The rolling shutter effect generates the dark and white bands seen by the smartphone camera from the modulated LED lights, which are processed to extract the frequency IDs for different LEDs. The actual object position can be calculated by these acquired frequency information and compared with a pre-installed light grid map, therefore, realizing asset/personnel tracking in real time. This new LED-based VLP smart tracking method utilizes the multi-camera vision triangulation algorithm, rolling shutter effect and the multi-view geometry. It focuses on determining the offset between two camera frames in order to derive the target position. Both accelerometer and gyroscope sensors can be utilized to monitor the pose changes between two frames. The relative position and pose of the device are tracked over the entire positioning process. Based on the relative position and pose of the previous frames, the current camera frames are estimated in the global frame. The tracking inaccuracy due to sensor shot noises, approximation error, and temporary blocking of the LED light can be addressed by using two-stage Kalman filter. Therefore, the new LED VLP smart tracking system can track actual positions even if the optical link is temporarily blocked or the LED moves out of the field of view (FOV) of the camera momentarily [15].

IV. VLC FOR SMART CITIES

The LED-based VLC technologies can complement and sometimes is an attractive alternative solution to RF wireless technologies. LED VLC technology is also a viable solution for various IoT systems for many smart and connected applications.

1) Smart Home/Office: The existing indoor LED lighting infrastructure can be retrofitted to realize full duplex wireless streaming over the light. The LED-based VLC wireless streaming is particularly suitable for high-throughput and secured smart home/office applications. The LOS feature of VLC technology is inherently secure for closed-door wireless because if no light leaks, nobody could intercept the signals. Fig. 7 shows a full duplex multiple-user LED VLC testbed in our Lab that can wireless stream HD videos while allowing wireless communications between two users [14].

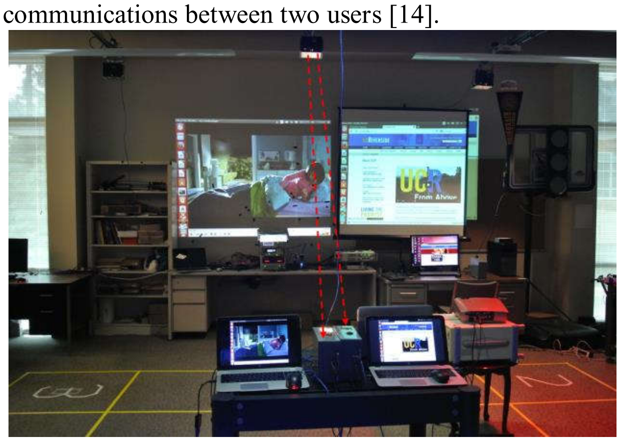

Fig. 7. A two-user LED VLC system for high-definition video streaming over light [14].

2) Smart Traffics: Traffic jam is a global challenge that causes tons of dollars and is also a major contributor to the global warming. Existing traffic monitoring techniques are largely useless in terms of smart traffic control, because the traffic data are collected via fixed and very few sensors (e.g., underground sensors or overhead cameras) installed at limited sites. Using LED VLC positioning technique, we can integrate the VLP function into each LED light source, including, car lights, traffic lights, street lights, display boards and any signage. It essentially creates an Ad Hoc LED-based traffic tracking network that can work dynamically anywhere anytime, and only when it is needed, i.e., if there is no car/street light, no traffic monitoring would be needed. Therefore, big and live traffic data can be collected and sent to the traffic control center for smart and connected real-time traffic control. This will be a wonderful smart traffic control solution that will not only eliminate the traffic jams, but also dramatically reduce the related carbon pollution. Most of all, every citizen in the society will contribute to keeping the traffics smart and the world green. Fig. 8 illustrates a proposed LED VLC based smart traffic application scenario where all lighting devices (car head/tail lights, signal lights, street lights, display boards) are connected on roads. Fig. 9 shows a demo VLP testbed in our Lab that uses LEDs and PD/CMOS imagers to control a vehicle robot for simultaneous optical wireless communications and navigation functions [14].

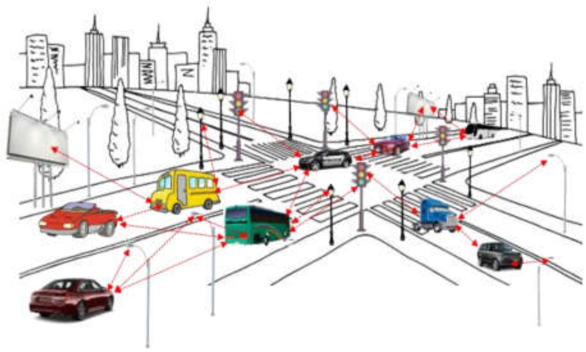

Fig. 8. A VLC-based Ad Hoc smart traffics system scenario.

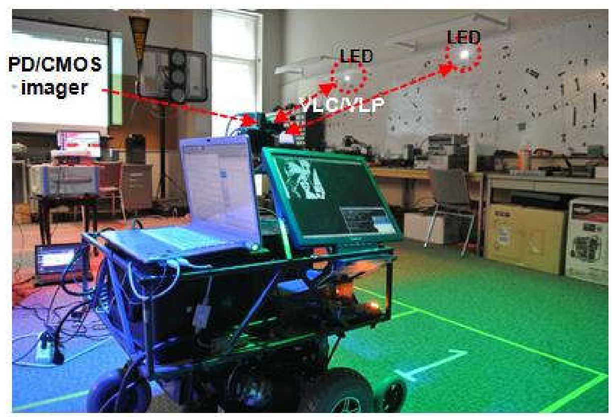

Fig. 9. A demo vehicle with VLP/VLC functions in our Lab [14].

3) Smart Hospitals: Modern hospitals require high-volume wireless networking (e.g., for telemedicine), and real-time asset and personnel management. RF wireless is unsuitable because RF may interfere with medical equipment and is harmful to human being. Building the VLC functions into the existing LED lighting infrastructure in hospitals can simultaneously provide high-throughput wireless streaming and accurately track asset/personnel in real time, without any harm to users. This solution will eventually make smart hospitals a reality, leading to efficient, affordable, smart and connected next-generation healthcare in near future. Fig. 10 depicts a proposed LED VLC based smart hospital scenario. Fig. 11 shows a simple LED VLC tracking prototype demonstrated at the Loma Linda Medical Center [14].

4) Smart City: Further, by integrating VLC/VLP functions into all lighting devices in a city, all communities and cities will be connected in a live mode. Since the VLC functions are embedded into the existing lighting infrastructure, it minimizes investment, while realizes countless smart city and smart community applications, hence making our Globe greener, safer and more human-friendlier.

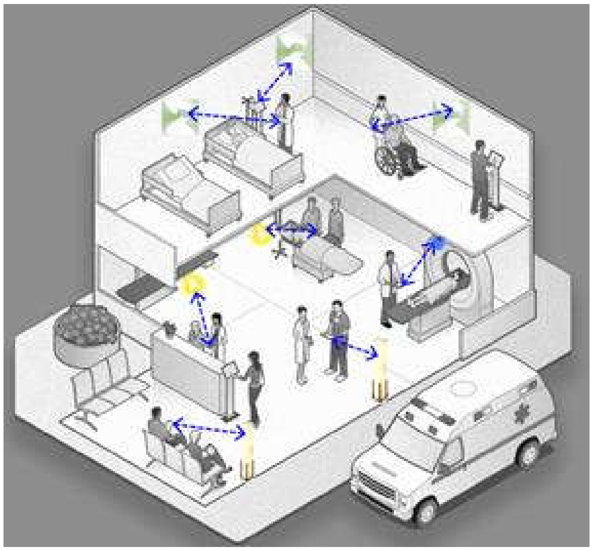

Fig. 10. Illustration of an LED-based VLC system scenario for smart hospitals using a given hospital layout.

Fig. 11. Demo of a LED VLC prototype in a local hospital [14].

V. SUMMARY

This paper reviews recent advances and application perspectives of LED-based VLC technologies and related cyber-physical SoC designs. Critical aspects of LED VLC system technologies and CPSoC ICs are discussed. LED VLC and IoT technologies will facilitate smart cities, smart traffics and smart hospitals in near future.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Wang was the Principal Investigator for this project. Pan, Lang, Li, Di and Chen contributed equally to this work. All authors had approved the final version.

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