

Integrated Design of Low Complexity RSS Based Visible Light Indoor Positioning and Power-Line Communication System for Smart Hospitals

Tian Lang
Dept. of Electrical and Computer
Engineering
University of California,
Riverside
Riverside, CA, USA
tlang003@ucr.edu

Zijin Pan
Dept. of Electrical and Computer
Engineering
University of California,
Riverside
Riverside, CA, USA
zpan015@ucr.edu

Nathaniel Ortiz
Dept. of Electrical and Computer
Engineering
University of California,
Riverside
Riverside, CA, USA
norti013@ucr.edu

Gang Chen
Dept. of Electrical and Computer
Engineering
University of California,
Riverside
Riverside, CA, USA
gachen@ece.ucr.edu

Yehuda Kalay
College of Environmental Design
University of California,
Berkeley
Berkeley, CA, USA
kalay@berkeley.edu

Ramdas Pai
School of Medicine
University of California,
Riverside
Riverside, CA, USA
Ramdas.Pai@medsch.ucr.edu

Albert Wang
Dept. of Electrical and Computer
Engineering
University of California,
Riverside
Riverside, CA, USA
aw@ece.ucr.edu

Abstract—Future healthcare systems require smart hospitals with system-wide wireless communications and positioning functions, which cannot be facilitated by existing radio-frequency (RF) technologies. We present an integrated design of a novel low-complexity received signal strength (RSS) based hybrid visible light communication (VLC) and positioning (VLP) system. This tracking system consists of host optical transceivers embedded in existing light-emitting diode (LED) bulbs and user-end optical tags, which interface with the existing power wiring in a building. This hybrid VLC/PLC tracking system was validated by simulation and experiment. This VLC tracking system will enable smart hospital operations to modernize next-generation intelligent healthcare systems.

Keywords—LED, visible light communication, VLC, visible light positioning, VLP, power-line communication, PLC, received signal strength, RSS.

I. INTRODUCTION

As one of the fastest-growing industries, wireless communication and positioning technologies revolutionized our society. Millions of related applications based on these technologies now serve countless ubiquitous mobile devices. Recently, unlicensed optical wireless communication (OWC) has been considered as an alternative to the existing radio frequency (RF) communications and positioning method, especially indoor localization and navigation where GPS is not available and other RF positioning lacks the precision and accuracy. Visible light communication (VLC) and infrared (IR) can be integrated to achieve visible light positioning (VLP) system, which offers much better indoor positioning in terms of ease of implementation, costs, and most importantly, precision and accuracy needed. Recently, various VLC/VLP based indoor positioning solutions have been reported utilizing methods

including LEDs and cameras as light transmitters and receivers, as summarized in Table 1 [1-9]. VLC/VLP technology offers many potential applications in healthcare environments where wireless is required, but RF wireless is often prohibited because RF is harmful to human being and can interfere with healthcare equipment [10]. Particularly, future healthcare systems require lively tracking of medical instruments and personnel (patients, doctors, nurses, visitors) to enable smart operations. In this paper, we report the design of VLC/VLP-based a low-costs low-complexity indoor tracking system for smart hospitals, which allows real-time and accurate asset and personnel tracking, hence smart hospital management. This VLC/VLP system enables harvesting big data, developing user-hospital-building interaction models and artificial intelligence algorithms for smart hospital operations, such as smartly dispatching medical personnel, deploying medical instruments and retrofitting hospital floor layout [11].

TABLE 1. STATE-OF-THE-ART INDOOR VLP METHODS

Algorithm	Accuracy	Receiver	Transmitter	Ref
ADOA	6cm	Camera	4 color LED	[1]
Fingerprint	5cm	Camera	2 color LED	[2]
Image	4.81cm	Camera	4 white LED	[3]
Differential	4cm	Detector	3 white LED	[4]
RSS	2.4cm	Single PD	3 white LED	[5]
RSS	1.66cm	Single PD	3 white LED	[6]
AOA	1.53cm	Camera	4 white LED	[7]
Image	1cm	Camera	3 white LED	[8]
Bayesian	0.86cm	Camera	4 white LED	[9]

II. LOW COMPLEXITY VLC POSITIONING SYSTEM

In this work, a low-complexity RSS-based VLC/VLP indoor positioning system was designed for accurate personnel and asset tracking and data harvesting real-time in a hospital. The ultimate design goal is to achieve an all-optical indoor positioning accuracy of centimeter without RF and to implement it in a low-cost low-power system-on-chip (SoC). Figure 1 depicts the functional diagram for the new hybrid system consisting of user-end (personnel and asset) transceivers and host-end transceivers built into the LED bulbs of the existing hospital lighting infrastructure (ceiling, wall). The user-end transceiver is an optical tag consisting of a visible light photodetector (PD) and an infrared (IR) emitter. The host-end transceiver comprises an LED emitter and an IR PD receiver. The LED emitter inside the LED bulb supports relatively higher downlink data rates enabling VLC communications. An IR emitter is used in the user end because little data is needed for the uplink and visible light may be uncomfortable for human eyes when wearing a tag. The tracking data will be sent to the central servers through PLC communications using existing 120AVC lighting wires. This all-LED system has the tilting capability, a limiting factor for camera or PD with lens. Long operation time of the user tags will be ensured by ultralow-power design and using a photovoltaic battery. The hybrid VLC/VLP tracking system will be implemented as an integrated circuit (IC) SoC chip to ensure ultralow-power, low costs and small footprint, which hence requires an integrated system design approach.

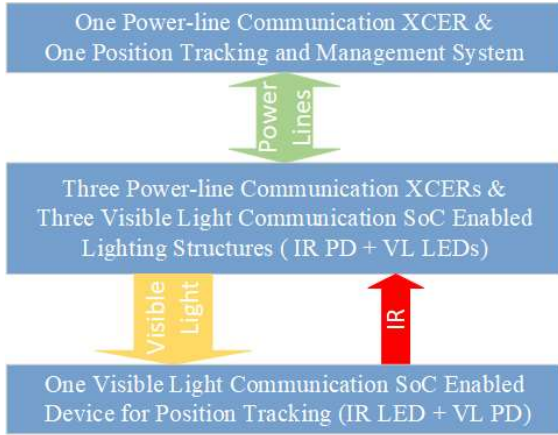


Figure 1. A block diagram for the new hybrid VLP/PLC tracking system.

III. SIMULATION AND EXPERIMENT

For easy implementation and low complexity, the hybrid VLP/PLC system utilizes light intensity-based RSS method for indoor positioning. RSS data are readily obtainable by using a single PD. To evaluate the new position tracking and management system (PTMS), software development is done using Python. Python code is written in the PyCharm IDE to simulate the PLC tracking. Figure 2 shows that the received data is reversely proportional to the distance between the light transmitter and receiver, following Lambert's emission law. To validate the new VLC tracking system, three LEDs were used to form a triangular configuration. As depicted in Figure 3, one can triangulate the approximate location of an object. Each LED has its ID and intensity value marked as circles shown in Figure 3.

The LED IDs combined with their intensity values provide intersections by which an object can be located accurately. Figure 4 and Figure 5 show two tracking examples where the rings of intensities are shown and the object can be pin-pointed by locating the ring intersecting point (i.e., purple dot). Figure 6 and Figure 7 depict two more tracking examples where the light intensity rings are removed for an alternative graphical view on the monitoring screen.

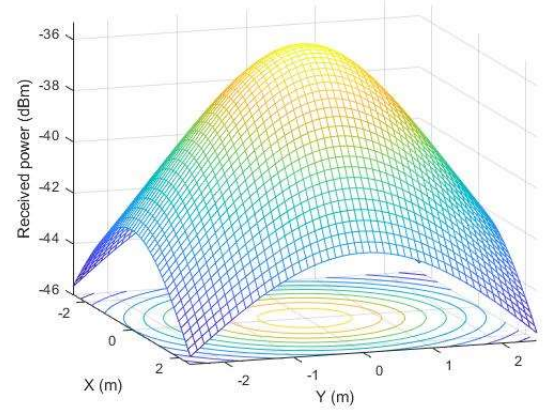


Figure 2. 3D view of LED intensity for the new VLC tracking system in this work evaluated by simulation.

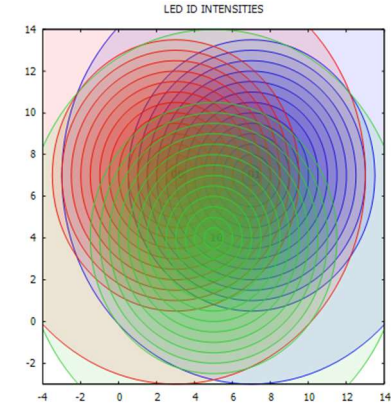


Figure 3. Illustration of a 3-LED beacons intensity map in this design.

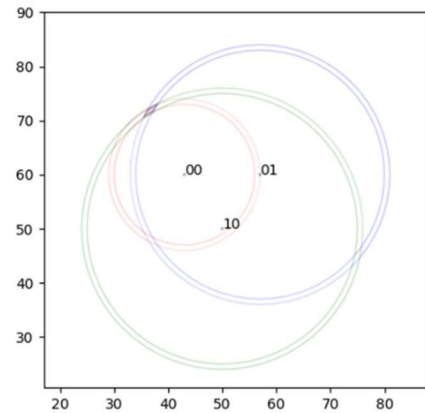


Figure 4. Example 1: locating the object (intersecting point in purple) using the three lighting fixtures (LEDs: 00, 01 & 10) by Python GUI display.

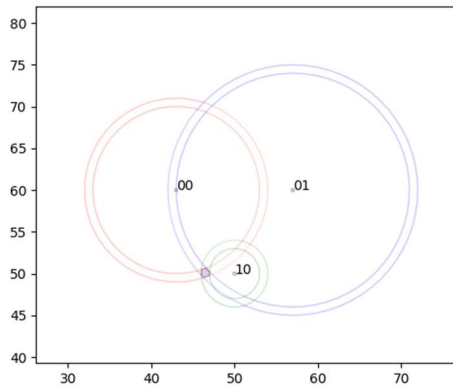


Figure 5 Example 2: locating the object (intersecting point in purple) using the three lighting fixtures (LEDs: 00, 01 & 10) by Python GUI display.

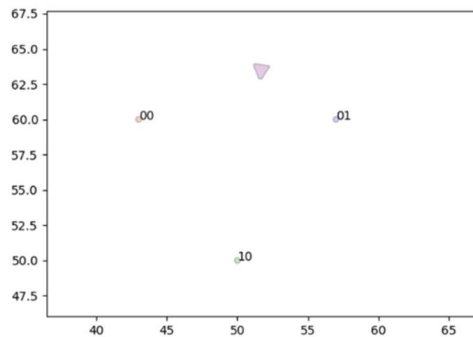


Figure 6. Example 3: locating the object (intersecting point in purple) using the three lighting fixtures (LEDs: 00, 01 & 10) by Python GUI display with the light intensity rings removed.

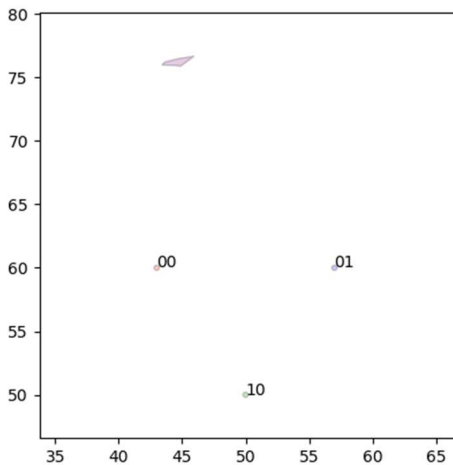


Figure 7 Example 4: locating the object (intersecting point in purple) using the three lighting fixtures (LEDs: 00, 01 & 10) by Python GUI display with the light intensity rings removed.

IV. VLC TRANSCEIVER SoC DESIGN

Before designing the VLC SoC ICs, the new hybrid VLC tracking system was validated at the PCB board level using Arduino. In this new VLC system, optical wireless communications between the host (ceiling/wall LED bulbs) and the users (tags) include visible light downlink and infrared uplink channels. IR uplink is chosen to avoid frustrating light

to human eyes. Figure 8 depicts the circuit schematic designed for the host (ceiling/wall LED bulbs) optical transceiver, including LED visible light transmitter and IR PD receiver, with the PCB photo given in Figure 9. Figure 10 depicts the circuit schematic for the user-end optical tag circuit, including an IR transmitter and a visible light PD receiver, with the PCB image shown in Figure 11. The VLC transceiver consists of analog and digital circuits. The analog circuitry includes LED current driver and preamplifier that was designed and fabricated in PCB. For PCB level validation, the digital functions of the transceivers were implemented by Arduino. The final VLC/VLP tracking system will be implemented in SoC ICs for real-world system applications in hospitals. Figure 13 depicts the architectural diagram for the VLC transceiver SoC chip, which mainly consists of three main parts: bandgap voltage reference circuit, transmitter and receiver [12]. The bandgap voltage reference is used to provide stable and temperature-independent voltage to bias the transceiver ICs. The basic idea of bandgap voltage reference is combining two different kinds of the current signal, i.e., proportional to absolute temperature (PTAT) and complementary to absolute temperature (CTAT), with a proper proportion. When summing them together, a stable output voltage of 1.25V is produced to bias the transceiver circuitry. The transmitter contains a current driver being able to drive the commercial LEDs used (~ 100 s mA). To drive the lighting LED bulbs, we choose to use a multi-stage driver circuit topology (Figure 12) and a current-mode logic (CML) as the output stage. The receiver needs to handle both analog and digital signals. The digital signals are used to detect the LED bulb IDs and LED on-off status with high accuracy. The analog signals are used to determine the receiving light intensity by the user tags. The PDs convert the detected light power into a current signal, which is too low for Arduino to do digital processing. Hence, an analog block is designed to amplify the detected signals. A transimpedance amplifier (TIA) is used to convert the PD current signal to a voltage signal. In the digital signal path, automatic gain control (AGC) circuit is used to automatically

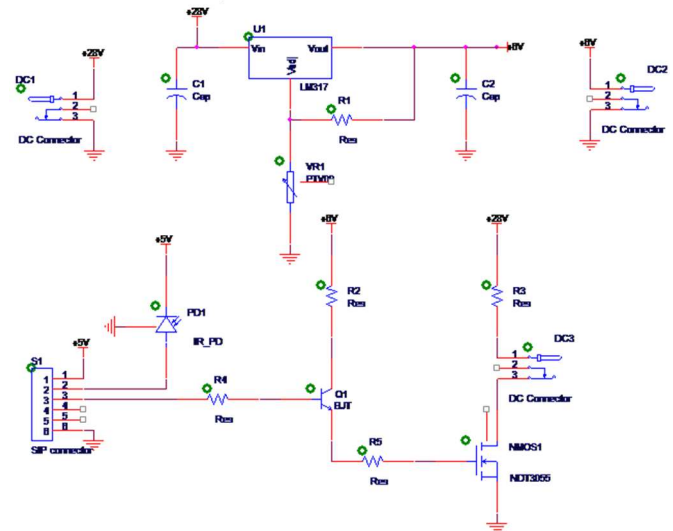


Figure 8. Host LED beacon circuit schematic designed.

Figure 9. PCB designed for the host LED beacon circuit.

Figure 10. User-end tag circuit schematic designed.

Figure 11. PCB designed for the user-end tag circuit.

Figure 12 A differential LED driver IC topology in this work.

Figure 13. VLC transceiver SoC architecture in this work.

Figure 14. User-end optical tag PCB demo board designed supports a visible light PD receiver and an IR transmitter.

Figure 15. Host-end PBC demo board designed includes an LED visible light transmitter and in IR PD receiver.

V. INTEGRATION WITH POWER-LINE COMMUNICATION

To realize hospital-wide system applications, the designed VLC-based host transceivers will be integrated into the existing LED lighting infrastructure in a hospital, while the user-end optical tags will be worn by the personnel and attached to medical instruments. The host VLC transceivers embedded in the ceiling/wall LED bulbs will communicate between host/user VLC transceivers/tags and with the central IP servers through the 120AVC power wiring within the hospital building. In this demo system design, PLC communication was realized by using Cypress CY8PLC20 chipset featuring a frequency-shift keying (FSK) modem and I2C bus. In our hybrid VLC system, each VLC transceiver is connected to CY8PLC20 using I2C bus, with the VLC transceiver being the master and the PLC acting as a slave, which allows initiating communications with the PLC backbone. Upon receiving a valid data packet from the VLC transceiver, the PLC sends this packet to another PLC controller, acting as a master, connected to the host computer. The host computer, acting as a slave, will parse the data and allow the users (object tags) to examine the position of the user as detected by the transceiver. Figure 16 depicts the functional diagram of CY8PLC20. Once the transmitter PLC module receives a valid packet from the I2C bus, the FSK modem will then serialize the data. This allows the data to be sent to the modulator, which then modulates the data at a frequency of 131.3kHz for a logical '0', or, 131.8kHz for a logical '1'. As our data packets contain a relatively small amount of data (several bytes), these frequencies provide more than enough bandwidth for the tracking applications. In addition to modulating the data, the transmitter will also append a destination and source address packet to allow multiple PLCs operating on the same wiring circuit. To ensure that no data packets may be dropped, the receiving PLC is constantly in a low power 'wait' state when it is not receiving data. Upon the band-in-use (BIU) detector detecting a frequency of $131.1\text{kHz} \leq f \leq 133.5\text{kHz}$, with a power of at least 86dBm for $t \geq 4\text{ms}$, the PLC will exit the wait state and begins receiving and demodulating the data packet.

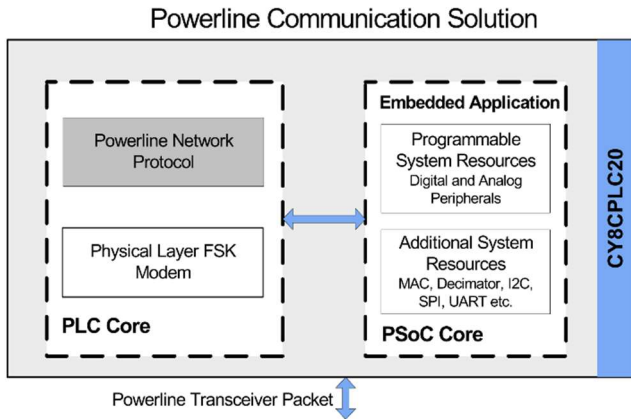


Figure 16. A functional block diagram for CY8CPLC20 used in this work.

This is accomplished by passing the carrier through a bandpass filter with a passband of $125\text{kHz} \leq f \leq 140\text{kHz}$. The resulting signal then passes through an intermediate filter to attenuate any noise that may have modified the carrier. The filtered signal is then fed to a correlator that compares the signal

to the defined logic states. The output is then fed through a low-pass filter to output the packet at a 2400 baud rate, which is then digitized by a comparator. With the re-digitized data packet, we can then send this packet to a given host computer using an I2C bridge, allowing the data to be interpreted by an application on the host server. Our new hybrid VLC/PLC tracking system is scalable depending upon the hospital buildings.

VI. CONCLUSION

We report the integrated design of a novel low-complexity, ultralow-power, low-costs and small footprint RSS-based hybrid VLC/PLC indoor positioning system for smart hospital applications. The new all-optical indoor tracking system includes host LED bulbs, user-end optical tags, LED triangular positioning algorithm and PLC interface to realize centimeter tracking accuracy. The new VLC/VLP system was validated experimentally. This VLC tracking system can potentially revolutionize future hospital operations.

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REFERENCES

- [1] B. Zhu, J. Cheng, J. Yan, J. Wang, and Y. Wang, "VLC positioning using cameras with unknown tilting angles", *Proc. IEEE GLOBECOM*, pp. 1-6, 2017.
- [2] T. Tanaka and S. Haruyama, "New position detection method using image sensor and visible light LEDs", *Proc. IEEE Intl Conf. Machine Vision*, pp. 150-153, 2009.
- [3] Y. Li, Z. Ghassemlooy, X. Tang, B. Lin, and Y. Zhang, "A VLC smartphone camera based indoor positioning system", *IEEE Photonics Technology Letters*, Vol. 30, No. 13, pp. 1171-1174, 2018.
- [4] H. Lv, L. Feng, A. Yang, P. Guo, H. Huang, and S. Chen, "High accuracy VLC indoor positioning system with differential detection", *IEEE Photonics Journal*, Vol. 9, No. 3, pp. 1-13, 2017.
- [5] H.-S. Kim, D.-R. Kim, S.-H. Yang, Y.-H. Son, and S.-K. Han, "An indoor visible light communication positioning system using a RF carrier allocation technique", *Journal of lightwave technology*, Vol. 31, No. 1, pp. 134-144, 2012.
- [6] E.-M. Jeong, S.-H. Yang, H.-S. Kim, and S.-K. Han, "Tilted receiver angle error compensated indoor positioning system based on visible light communication", *Electronics Letters*, Vol. 49, No. 14, pp. 890-892, 2013.
- [7] W. Pan, Y. Hou, and S. Xiao, "Visible light indoor positioning based on camera with specular reflection cancellation", *Proc. IEEE CLEO-PR*, pp. 1-4, 2017.
- [8] J. Xu, C. Gong, and Z. Xu, "Experimental indoor visible light positioning systems with centimeter accuracy based on a commercial smartphone camera", *IEEE Photonics Journal*, Vol. 10, No. 6, pp. 1-17, 2018.
- [9] W. Guan, X. Chen, M. Huang, Z. Liu, Y. Wu, and Y. Chen, "High-speed robust dynamic positioning and tracking method based on visual visible light communication using optical flow detection and Bayesian forecast", *IEEE Photonics Journal*, Vol. 10, No. 3, pp. 1-22, 2018.
- [10] Z. Pan, T. Lang, C. Li, M. Di, G. Chen, Y. Kalay, R. Pai, and A. Wang, "Visible light communication cyber-physical systems-on-chip for smart cities", *J. of Communications*, Vol. 14, No. 12, pp. 1141-1146, December 2019.
- [11] Y. Kalay, H. Sathyanarayanan, D. Schaumann, A. Wang, G. Chen and R. G. Pai, "VLC-enabled human-aware building management system", *Proc. HCII*, pp. 207-222, 2020.
- [12] Z. Dong, F. Lu, R. Ma, L. Wang, C. Zhang, G. Chen, A. Wang and B. Zhao, "An integrated transmitter for LED-based visible light communication and positioning system in a 180nm BCD technology", *Proc. BCTM*, pp. 84-87, 2014.