MULTIMEDIA COMMUNICATIONS TECHNICAL COMMITTEE
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MMTC Communications - Frontiers

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CONTENTS

Message from the MMTC Chair

Dear MMTC colleagues and friends,

Greetings! Welcome to this issue of MMTC Communications – Frontiers, where we present a unique venue for researchers to publish timely updates on recent developments and hot research topics. We are now half-way through the current 2016 – 2018 term for MMTC officers. It has been an honor and pleasure to work and collaborate with all the other MMTC leaders and members.

First, I would like to thank all our members who recently attended ICC 2017 in Paris and especially members who submitted and presented work at the "Communication Software, Services, and Multimedia Applications" (CSSMA) Symposium. The CSSMA symposium at ICC and GLOBECOM is the only symposium sponsored by MMTC and we encourage all members to support the symposium and submit papers as well as to encourage their colleagues to also submit papers. The next CSSMA symposium will take place as part of GLOBECOM 2017 and the next submission deadline for the CSSMA symposium is for ICC 2018 on October 15, 2017.

There was recently a MMTC meeting at ICC 2017 in Paris. The next TC meeting will take place at ICME 2017 on Hong Kong on Thursday, July 13, 2017. All MMTC members are invited to join and participate. Please be on the lookout for more details regarding the exact time and location.

MMTC is always looking for new researchers who are passionate about multimedia communications research to join the TC. Membership is open to everyone and more information regarding how to join is available at http://mmc.committees.comsoc.org/membership/. Active involvement in the TC is beneficial for both the TC as well as the members. Active members who contribute to MMTC can: 1) get the TCs endorsement for special issue proposals and workshop proposals, 2) be nominated for TPC chair/co-chair for TC sponsored conferences/workshops/symposia and associate editor positions, and 3) be nominated for awards and other recognition.

I also encourage all MMTC members to actively participate in interest groups (IGs) which best fit their research interests and for IGs to contribute to future Frontiers issues by submitting proposals for topics. We aim to publish new issues of Frontiers approximately once per month. If you are interested in joining and contributing to an IG, please contact the IG chair.

MMTC is also currently involved in the process for TC recertification. It would be very much appreciated if members can respond in a timely manner to any requests that we may make regarding reporting relevant activities such as conferences, journal editorships, journal special issues, elevation to senior/fellow membership grades, and/or standard related activities.

I hope you will enjoy reading this issue of MMTC Communications – Frontiers!

Sanjeev Mehrotra
Vice-Chair for North America, MMTC

SPECIAL ISSUE ON VISIBLE LIGHT COMMUNICATIONS

Guest Editors: Valeria Loscri and Nathalie Mitton, Inria, France

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"Visible Light communications" (VLC) or sending information through visible light is a very ancient concept, already used in the Roman Empire. But its use in new technologies is rather new and is being attracting more and more attention because of its cheap and ease-of-use features.

This special issue focuses on the recent trend and possible applications and benefits that bring the use of VLC. We are very enthusiast to present you this special issue in which nine leading research groups, report their solutions for meeting these challenges and share their latest results.

The first article is proposed by Z. Ghassemlooy, W. O. Popoola, X. Tang, S. Zvanovec, and S. Rajbhandari introduces the VLC technology, focussing on challenges, solutions and recent research trends.

The second article titled, "*Software Defined Platforms for Visible Light Communication: State of Art and New Possibilities"* presents a brief survey of Software Defined VLC systems, discussing their potential and illustrating it through a concrete example.

Another potential application of VLC is indoor positioning as illustrated in the third and fourth articles from Simon Fraser University, Roma Tre University and Boston University. Authors present their *Experimental testbed for RSS-based indoor Visible Light Positioning* and *a flexible SDR-based testbed for indoor Visible Light Positioning* respectively.

The fifth article by Y. Wang and H. Haas focuses on another key challenge in VLC: resource allocation and shows that resource allocations schemes in OFDMA systems outperform those in TDMA systems.

Finally, the last article exploits these OFDMA features for « a Cognitive Design of VLC Networks »

While this special issue is far from delivering a complete coverage on this exciting research area, we hope that these letters give the audiences a taste of the main activities in this area, and provide them an opportunity to explore and collaborate in the related fields. Finally, we would like to thank all the authors for their great contribution and the MMTC E-Letter Board for making this special issue possible.

Dr. Valeria Loscri is a permanent researcher of the FUN Team at Inria Lille – Nord Europe since October 2013. From December 2006 to September 2013, she was Fellow in the TITAN Lab of the University of Calabria, Italy. She received her MSc and PhD degrees in Computer Science in 2003 and 2007, respectively, from the University of Calabria. Her research interests focus on heterogeneous communication technologies, their coexistence and complementarity, and cooperation of heterogeneous devices. She has been involved in the FP7 European project VITAL, the FP6 European project MASCOT, the national project (PRIN) Stem-NET and the national project (PON) Kom4t-me. She is in the editorial board of Elsevier ComNet, Elsevier JNCA, IEEE Trans. on Nanobioscience. Since September 2016, she is Scientific European Responsible for Inria Lille – Nord Europe.

Nathalie Mitton received the MSc and PhD. degrees in Computer Science from INSA Lyon in 2003 and 2006 respectively. She received her Habilitation à diriger des recherches (HDR) in 2011 from Université Lille 1. She is currently an Inria full researcher since 2006 and from 2012, she is the scientific head of the Inria FUN team which is focused on small computing devices like electronic tags and sensor networks. Her research interests focus on self-organization, energy efficient routing algorithms for wireless sensor networks as well as RFID middlewares. She has published her research in more than 30 international revues and more than 100 international conferences. She is involved in the set up of the FIT IoT-LAB platform (iotlab.info), the FP7 VITAL or H2020 VESSEDIA projects and in several program and organization committees such as Pe-Wasum 2017, VTC 2017&2016, WSCP2017, SWC 2017, WPMC

2017, ICT 2017, Globecom 2017, , infocom workshop 2017, AdHocNow 2016&2015, MobiCom 2015, etc. She also supervises several PhD students and engineers.

Visible Light Communications – A Review

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1. Introduction

The world of mobile communications is growing at a tremendous speed with an exponential growth in the mobile data traffic of a compounded annual growth rate of 63% per year. This is driven by the proliferation of smart devices and the growing demands for device-to-device communications as part of the emerging Internet of things (IoT). It is estimated that by 2020, there will be up to 18 billion connected devices. The current licensed wireless spectrum used for connectivity is saturated thus causing **bottlenecks for the wireless carriers,** and **requiring an upgrade to wireless infrastructure, which can** take years [1]. The evolution of the wireless standards into the fourth generation (4G) and the fifth generation (5G) networks, and development in information and communication technologies (such as ultra-broadband internet access, internet protocol telephony, social networking, gaming services, streamed multimedia applications) will further compound this connectivity bottleneck [2]. The speed of wireless connectivity has continued to increase from a few Mbps in 2G to a few hundred Mbps in 4G and it is expected to continue with 5G offering data rates of up to 10 Gbps with the latency of less 1 ms. However, 5G is still under intensive research and it is not quite clear yet which radio bands and wireless technologies will be adopted. Especially in indoor environments, accommodating of 5G may be challenging.

As part of 5G, future heterogeneous networks will use multiple technologies including distributed and beamforming antennas, small cells, Wi-Fi, massive multiple input multiple output (MIMO) techniques, millimetre wave, and optical communications to deliver the required coverage and capacity - either for in-building wireless, underground, addressing dead spots, densifying the network in high traffic areas or offloading the capacity from the macro networks. Simpler solutions are continuously being developed by converging the best of all possible wireless technologies. This may lead to the converged solutions that can (i) deliver successfully the high capacity of a macro-cell and the flexible coverage of a pico-cell without the traditional interference challenges; and (ii) adopt intelligence-based traffic routing when and where it is needed, thus ensuring optimal quality of service anywhere at any time. To overcome the spectrum bottleneck, there are a number of options including optical wireless communications (OWC), covering the three bands of ultra-violet (UV), and infra-red (IR), visible light, see Fig. 1 [3]. As part of the possible future heterogeneous networks, the emerging visible light communications (VLC) could be a significant game changer in indoor environments as a complementary technology to radio frequency (RF) based wireless technologies [4], [5]. Tables I and II outlines the key features of selected wireless technologies, and a brief comparison of VLC with WiFI, respectively.

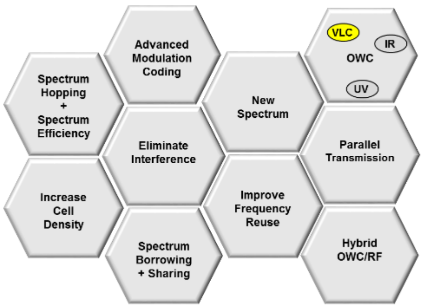


Fig.1. Options to overcome the spectrum bottleneck experienced in RF wireless

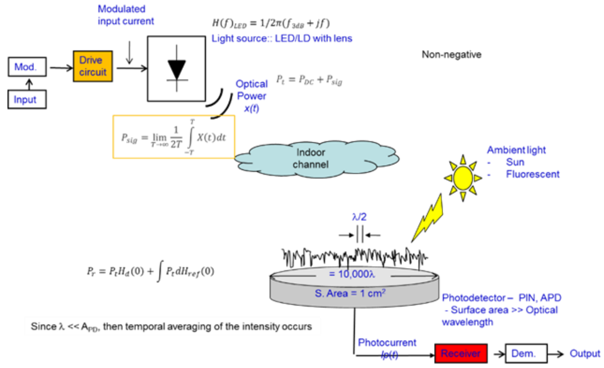


Fig. 2. An illustration of VLC system basic building blocks

Technology	Speed	Data Density
Current wireless technology		
WiFi-(IEEE 802.11n)	150 Mbps	*
Bluetooth	3 Mbps	*
IrDa	4 Mbps	***
Future wireless technology		
Wi-Gig (IEEE 802.11ad)	2 Gbps @ 60 GHz; 10 m	**
White WiFi (IEEE	24 Mbps @54 and 790,	* (a few km)
Giga-IR	1 Gbps	***
VLC	> 10 Gbps; a few meters	****

Table I. Current and future wireless technologies

Figure 2 illustrates the system block diagram of a typical VLC composed of transmitter, channel, and receiver (Rx). In VLC, the data is used for intensity modulation of the light source (typically light emitting diodes (LEDs), but white laser diodes could also be used). The most common and widely used data format in VLC is on-off-keying (OOK), however, other modulation schemes including multi-carriers schemes are also proposed and investigated [5]. At the Rx, the data is extracted by means of direct detection using either photodiode (positive-intrinsic-negative/avalanche photodiode) or cameras [6]. With the latter, the data is extracted from captured video frames using image processing techniques, but at a much lower data rate (order of magnitudes) than the former. Since the light carrier wave in VLC is perceivable by the human eye, then the modulation method must not induce any noticeable flickering, which might affect human health. There are two types of flickering intra-frame and inter-frame. To prevent the latter idle patterns with brightness equal to one of the data frames are used, whereas the former is avoided using the run length limited coding scheme, where the generation of long series of ones or zeros is avoided.

Table II. VLC vs. WiFi

Parameter	VLC	WiFi
Speed	High (>Gbps)	Medium (500 Mbps)
Range	Low	Medium
Data Density	High	Low
Security	High	Medium

Operating Frequency	375 THz	2.4 GHz → 5-5.9 GHz
Reliability	Medium	Medium
Power Consumption	Low	Medium
Standard	IEEE 802.15	IEEE 802.11
Device -2-Device Connectivity	High	High
Shadowing	Medium	Low
Mobility	Low	High

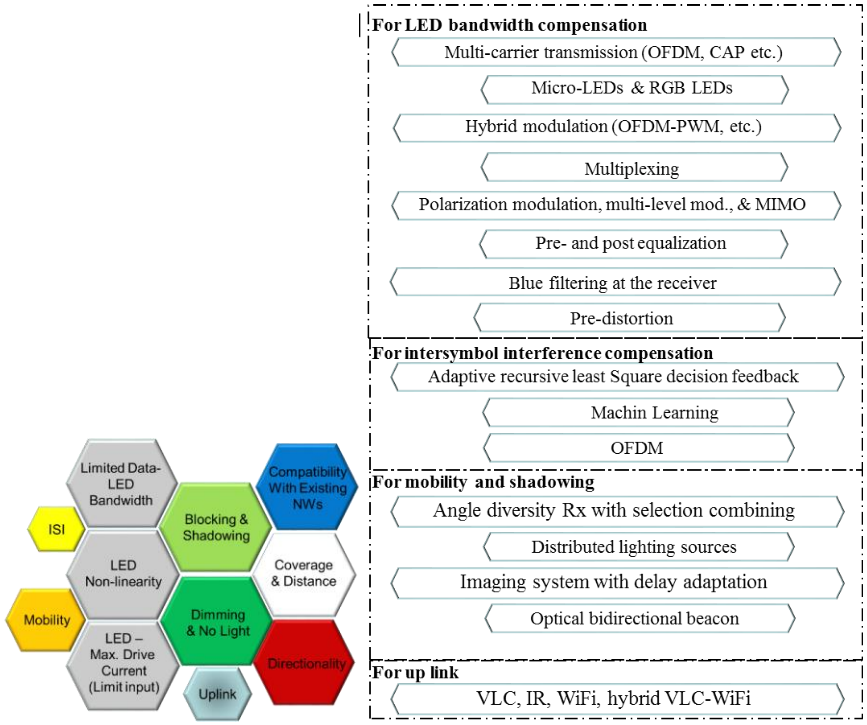
In areas where Wi-Fi offers poor service, VLC could provide super-fast connections given that the spectrum of visible light is 10,000 greater than the spectrum for RF. The VLC wireless technology uses LED-based lighting fixtures, which are more energy efficient light source than the traditional incandescent and fluorescent lights and have a longer lifespan, to provide high-speed communication [7], [8], indoor localization [9], [10], sensing [11] in addition to standard illumination [12]. This is a unique feature not seen in any other technologies. Furthermore, in VLC since communication is achieved as an additional functionality to illumination therefore, no additional power is required for generating the optical carrier thus making it an eco-friendly technology. Since light does not penetrate the opaque wall, VLC has an innate security feature as the data-carrying beam is confined within the room. VLC could also be used in the outdoor environment to provide access to a high-speed base-station for downloading files as well as for navigation. Other key features of VLC include its relatively low transceiver complexity and low energy consumption of the light sources (i.e., mostly VLC requiring a lower energy per bit than RF links) [13]. The VLC system, however, still faces a number of challenges that need to be addressed as summarised in Fig. 3(a) [14-16]. There are several options to address these challenges as shown in Fig. 3(b). [17-23].

In VLC compared to RF wireless technologies, there is the requirement for maintaining data communications at low level dimming or even under no light conditions. For dimming, there are two options depending on the modulation schemes adopted: (i) OOK - depending on the required dimming level, dimming is achieved by inserting compensation times, which represent additional time slots where light is completely switched on or off. To overcome the loss of synchronization, additional short resynchronization patterns needs to be inserted. (ii) variable pulse position modulation (PPM) – use of the combination of 2-PPM and pulse width modulation (PWM) for flicker and brightness control, respectively [5].

2. Recent trends in VLC

The recent progress in VLC can be said to be in two folds - application and technology. In addition to the existing wireless technologies for indoor environment, VLC is currently being considered for a number of applications as outlined in [5] and shown in Fig. 4. An overview of research activities to advance the field of VLC is depicted in Fig. 3(b). Due to space constraints, only recent advances in advanced modulation technique and integration of VLC with other technologies within the edge network will be discussed.

Advanced Modulation Techniques - The intensity modulated with direct detection (IM/DD) VLC with the limited bandwidth of the illumination LEDs requires the transmitted signal to be spectrally-efficient, real and unipolar. Traditional optical communication systems fulfiling these conditions are with pulse-based modulation techniques such as OOK, PPM, PWM and pulse amplitude modulation (PAM). An advanced continuous-time modulation technique commonly adopted in VLC is the baseband orthogonal frequency domain multiplexing (OFDM), also called discrete multitone (DMT).

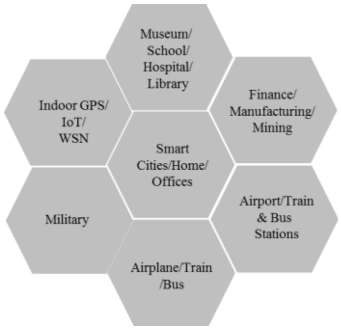


(a) (b)

Fig. 3. VLC: (a) challenges, and (b) possible solutions

In optical OFDM, the complex time domain signal is converted to a real signal by using Hermitian symmetry while unipolar/non-negativity is achieved mainly through either asymmetrical clipping or addition of direct current (DC) offset [24]. Optical OFDM, however, suffers from reduced spectral efficiency and increased computational cost. Other issues with OFDM as a concept include the high peak-to-average power ratio (PAPR) that results in signal clipping and subsequent deterioration of system performance [23]. This problem is addressed by adopting a hybrid OFDM-PWM scheme where the non-linearity of the LED source is no longer an issue and therefore no constraint on the PAPR [25].

An alternative approach to implementing baseband multi-carrier signalling for VLC is carrierless amplitude and phase modulation (CAP), which spectrally efficient and a high order modulation scheme with features that make it specially suited to the VLC channel [19]. CAP has a low complexity transceiver mainly because it replaces computationally intensity fast Fourier transform (FFT) and inverse FFT blocks used in OFDM with digital finite impulse response pulse shaping filter. Furthermore, CAP implementation approach does not require Hermitian symmetry, which results in 50% loss of spectral efficiency in DC-biased optical OFDM. In [26] an experimental CAP-VCL was reported with a data rate of 8 Gb/s using a hybrid equalizer. Multiband CAP, where the single band of CAP is partitioned into multiple subbands such that each subband has an approximately flat frequency response, was proposed and experimentally demonstrated to combat intersymbol interference (ISI) and improve the data rate [19]. However, CAP is not resilient to timing jitter, which can be addressed by maintaining its low complexity feature and using a synchronization algorithm or a fractionally-spaced equalizer achieving synchronization and equalization jointly [27].



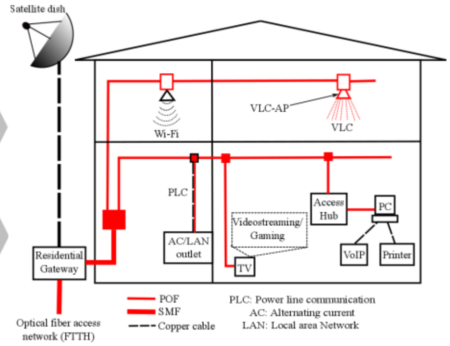


Fig. 5. An illustration of optical-fibre based converged in-home communication network

Fig. 4. VLC applications

In VLC, multiple LEDs are often deployed in groups in order to meet the required illumination level. This property is now being exploited to realise various MIMO techniques in VLC [28]. An attractive MIMO VLC transmission technique is spatial modulation (SM) where only one of the group of LED transmitters is active at any instant and is used as a source of information to boost the spectral efficiency of the regular pulse based or continuous time modulation schemes. Such high-speed, low-complexity technique can greatly improve the spectral efficiency of VLC systems [28].

VLC Integration in Edge Network - VLC provides a perfect fit for in-home networking where the quest for faster data communications is ever increasing and will continue to do so for the near future. The in-home network is inherently heterogeneous with a mix of various wired and wireless technologies. Power line communication has also emerged within the in-home network while wireless LAN continues to grow in applications. Picocells (a direct consequence of network densification) are equally present within the in-home network as a means of increasing wireless network capacity. The interoperability of these technologies as illustrated in Fig. 5 is therefore crucial.

With VLC gaining prominence as a means of providing wireless connectivity within in-home networks, an essential requirement, therefore, is that the backhaul link connecting VLC access points (VLC-AP) to fibre-based wider access networks need to equally have 'light-grade' bandwidth to avoid any bottleneck. This is addressed in [5] by considering an integrated optical fibre and VLC as part of a converged in-home network. In this recent approach, the plastic optical fibre is used to backhaul the VLC-AP to the access network.

3. Conclusion

This short paper discussed the main features of VLC and its comparison with other short-range wireless technologies. An overview of the current research directions in VLC was also provided. The recent modulation techniques of OFDM, CAP and SM were discussed in addition to the integration of VLC with other technologies within the in-home network.

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Wasiu O. Popoola is currently a lecturer and chancellor's fellowship in the School of Engineering, University of Edinburgh. He has published over 75 journal articles/conference papers/patent and over seven of those are invited papers. One of his journal articles ranked No. 2 in terms of the number of full text downloads within IEEE Xplore in 2008, from the hundreds of papers published by IET Optoelectronics since 1980. He co-authored the book 'Optical Wireless Communications: System and Channel Modelling with MATLAB, published by CRC in 2012, and several other book chapters (one with over 10000 downloads as of Sept. 2014 since its publication in 2010). He is a senior member of IEEE, an associate editor of the IEEE Access journal and Guest Editor of Elsevier Journal of Optik for a special issue on optical wireless communications in 2017 and Technical Program Committee member for several conferences. He was an Invited speaker at various events including the 2016 IEEE Photonics Society Summer Topicals.

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Software Defined Platforms for Visible Light Communication: State of Art and New Possibilities

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1. Introduction

The requirement of connected devices exponentially increases day by day as well as the bandwidth needed for novel applications. As a consequence of this, radio frequency spectrum becomes more and more crowded, thus leading to serious limitations in the diffusion of novel technologies when considering challenging environments such as hospitals and airplanes, where EM interferences are particularly unwanted. The integration of Visible Light Communication (VLC) in the existing infrastructures could provide a valid tool to address these issues. In this context, Software Defined concepts could significantly simplify the integration process, leading to the development of low cost and flexible architectures. To this end, Universal Software Radio Peripheral (USRP), designed and commercialized by Ettus Company and National Instruments, is emerging as a comparatively low cost hardware platform for software defined architectures, allowing rapid prototyping and test bed validations. The aim of the present work is to exploit the current literature in the framework of Software Defined Systems based on USRP platform for VLC purposes, while briefly highlighting some useful potentialities for the development of solid and flexible architectures.

2. Visible Light Communication: from Photophone to Software Defined VLC

The adoption of visible light for message transmission is one of the most ancient and intuitive techniques adopted in long distance communications. In the Roman Empire, a system of mirrors and shutters located on apposite towers was employed for communicating messages up to 20 km. The first modern communication in the visible spectrum, however, dates back to 1880, when Charles Sumner Tanter and Alexander Graham Bell invented the photophone. This device allowed speech transmission through the adoption of a light beam modulated by switching concavity and convexity of a reflecting screen [1]. In the first decade of 20th century, the German Siemens & Halske Company improved modulation using carbon arc lamps and provided commercial units for German Navy, while British Almery adopted high infrared sensitive molybdenite cells. Before the second world war, many governments (Italy, Germany, US, Japan) attempted to develop optical wireless communication for military purposes. Then, advances in radio frequency communication and, further, the adoption of low loss optical fibers, caused a progressive decrease of interest in free space VLC. Due to the exponential increase of bandwidth needed by novel applications and the overpopulation of RF spectrum, in the last fifteen years, this topic has gained a new interest in the scientific community. The first significant work, addressing a visible light communication through a white Light Emitting Diode (LED), and discussing the main requirements of the devices, was done in 2003 at University of Keyo, Japan [2], while significant studies have been carried out by Haas et al. [3, 4]. Further, according to the rapid diffusion of efficient and low cost LED's, many authors started to deal with different aspects characterizing visible light communication, especially with respect to modulation and dimming support, until a first standardization of the physical and MAC layer, ratified by IEEE (802.15.7) and included in Wireless Personal Area Networks [5]. However, since novel advances are frequently addressed in last years, new standards should be provided. Nowadays, research in VLC follows two main directions: the first one implies an advance in the design of hardware components used for transmitting and receiving the optical signal (led, photodiodes, driving circuits, amplifiers etc.), with the aim to enlarge the bandwidth of the RF front-end and to allow the possibility of using a larger part of the huge unlicensed electromagnetic spectrum in the visible light frequencies (770THz-400THz). A second way, instead, mainly deals with a practical and low-cost integration of VLC elements into existing infrastructures. With reference to this latter scenario, the development of a solid Software Defined paradigm for VLC seems to be an attractive field in the improvement of this technology. As most of the signal operations are performed by software, low cost hardware could be used and an easier interface with other communication paradigms could be allowed for a practical integration in the existing infrastructures. An interesting low cost platform (OPEN VLC) based on a Beagle Bone Black module, has been recently developed by Wang et al. [6]. The platform, composed of a simple optical front-end, a set of essential medium access primitives and a basic interaction with internet protocols, allows a transmission up to 1 meter with a rate of 12.5 Kbit/s in its basic configuration. Despite the slow rate and the limited communication distance, this architecture could be extended in order to be available for various applications, such as the passive ambient light recognizer described in [7]. An interesting preliminary work, employing the software defined platform USRP is provided in [8], where GNU Radio open source library is employed for signal processing and two simple applications (a chat service and a video download) are developed. The same authors provided a detailed description of the system in [9], where the standard 802.15.7 PHY I is achieved with a data transmission of 100kbit/s. An audio streaming transmission with similar performances is designed in [10]. In both cases, OOK modulation is adopted. Preliminary studies and a proof of concept on OFDM and PPM modulation using USRP platform and MatLab elaboration are provided in [11], while in [12] the same authors developed a driver topology able to drive an array of LEDs using a RPO-OFDM signal coming from USRP. A deeper investigation about Software Defined systems for VLC using USRP platform is provided in the next section.

3. Visible Light Communication through Universal Software Radio Peripheral

The first Universal Software Defined Radio, initially proposed by Ettus in 2006 [13], was obtained from USB2 interface. It owned a 30 MHz instantaneous bandwidth and it was well integrated into GNU Radio, an open source framework developed in the same period [14]. This transceiver, however, does not allow an easy design for a compact device; moreover, a full adaptability of the software code on the fly for different scenarios can be roughly achieved [15]. The second generation USRP (NI2920, NI2921 and NI2922), currently adopted in most of recent implementations, is provided by Gigabit Ethernet interface, owning a 50 MHz instantaneous bandwidth and easily interfaced through commercial software such as MatLab or LabView. It is also equipped with advanced FPGA, with an SD card for stand-alone operations. The main components of this architecture are shown in the block diagram of Fig. 1 [16].

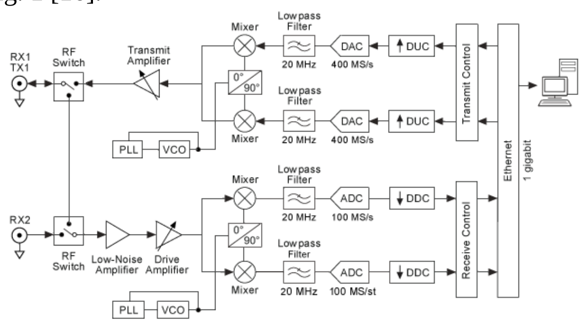

Figure 1. USRP NI2920 Architecture

Clock generation and synchronization, AD and DA conversions, host processor interfacing, and power regulation are provided in the motherboard, while operations such as amplifying, filtering, up and down conversion are implemented in the RF front end, or eventually in modular daughterboards, selected for the specific applications. Since a visible light source is typically incoherent and intensity modulation with direct detection (IM/DD) is mainly used, a low frequency or band-base daughterboard may be employed [10], such as the LFTX NI device [16], whose operative range ranges from DC up to 30 MHz, thus covering the entire bandwidth of most commercial LEDs. In terms of dedicated hardware, only the optical Rx and Tx front-ends are required, instead of antennas used in radio or radar applications [15], while most of the operations are directly performed and controlled on the fly by software. This aspect is particularly important to easily adapting existing signal modulation schemes to VLC transmission. Feeding and amplifying stage, led driving circuitry and the led itself in transmission, the photodiode and the trans-impedance amplifying in the receiver front end, could be chosen in order to find the appropriate trade-off between costs and performances. So, using the USRP and off-the-shelf components, it is possible to achieve reasonable results in terms of data rate, bit error rate and maximum transmission distance, as shown in Fig. 2 for the USRP based Software Defined VLC platforms described in the previous section.

	Modulation Scheme	Software Platform	Maximum Data Rate	Maximum Distance	BER
[9]	OOK / VPPM	GNU Radio Flexicom	100 kbit/s (1m)	4m	10^{-4}
[10]	OOK / VPPM	LabView	266kbit/s	1m	10^{-3}
[12]	RPO-OFDM	Matlab-Simulink	400Ksps	< 1m	10^{-3}

Figure 2. Performance of Software Defined VLC using USRP NI2920 Architecture

Results achieved in [9, 10, 12] prove the possibility of using a Software Defined System for short and medium range applications which do not require very high rate, thus avoiding the need of expensive dedicated hardware, and providing a flexible simple architecture. Since multiple USRPs could be connected to obtain a MIMO system, some authors recently considered also this scenario. An interesting paper deals with the possibility of using multiple USRP schemes for a full duplex OFDM link [17], while a 2x2 MIMO Software Defined VLC is addressed in [18]. These two-latter works demonstrate how a software defined platform could be expanded to achieve a more sophisticated and performing architecture. Many other several advantages can be provided by USRP, which are not yet addressed in current architectures, such as for example the possibility of adapting on the fly the equalization based on a bit error rate indicator. Another interesting aspect could be the possibility of regulating in real time the minimum transmitting power necessary for closing the VLC link within a dynamic environment. In the context of LI-FI paradigm, in fact, where the same lamp will be used for both lighting and providing signal communication, a software defined control of transmitted power could be useful for implementing a switchable modulation scheme allowing to provide a very low light intensity without turning off the link when high levels of environmental illumination are not required. Considering the nonlinearity of the optical components, different new adaptive techniques could be employed for limiting distortion, and various typologies of software defined filtering could be addressed, especially for future outdoor applications, such as in vehicular network applications. The possibility of designing a RF-VLC hybrid communication systems, using a USRP for a radio frequency communication and another one for the visible light link, could be an interesting issue for many applications, such as indoor geo-localization, Wi-Fi performance improving, or other future scenarios where the coexistence of VLC and RF link, or an adaptive handover between them, could be employed. A possible basic architecture is proposed in Fig. 3.

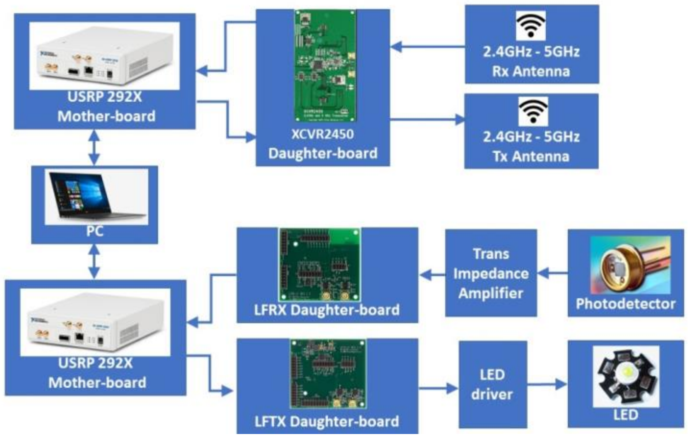

Figure 3. Hybrid Software Defined VLC – Wi-Fi using USRP NI292x Device

In this basic example, a XCVR2450 transceiver daughterboard is used for interfacing the dual band RF front-end covering Wi-Fi ranges and performing up-down conversion, filtering and amplification. Two baseband daughterboards, a LFRX in the receiving VLC path and a LFTX in the transmitting VLC path, are employed for filtering and other signal conditioning. Clock generation and synchronization, ADCs, DACs, and power regulation are performed independently by the two motherboards, through a centralized software coordination. The scheme proposed in Fig. 3 could be considered as a basic architecture for easily implementing a test bed for novel algorithms which employ both directional broadcast VLC channels and omnidirectional Wi-Fi links, recently proposed in literature [19,20] for providing additional capacity and reducing contentions in a crowded environment. Even if a proof of concept of a hybrid RF-VLC link has been addressed in [21], no software defined platform, for the best of our knowledge, has yet been considered with this aim. Providing a flexible and generic platform, however, could significantly speed up the development of novel applications using both VLC and RF links; a hybrid system, for instance, could be used for providing a reliable internet access point in running subway cars. A VLC broadcast channel, in fact, could be provided in each car, while Wi-Fi link could be still used in uplink. Since there is not a significant light interference between different cars, there could be an efficient frequency reuse allowing the system to work even in a crowded environment. Similar systems could be used in rail tunnels and similar environment. Other interesting applications could be developed in the field of indoor positioning, where an adaptive handover between Radio Frequency and VLC channels could be performed to benefit from the accuracy of the optical link where the environmental conditions are conducive, and switching in real time to RF localization where optical link fails. Similar ideas could be also developed in the field of aviation, underwater communications, hospitals and healthcare, where a Software Defined flexible platform like the one briefly discussed in this work could significantly speed up both experimental tests and the development of real systems.

4. Conclusions

A brief survey on Software Defined Visible Light Communication systems, based on USRP platform, has been outlined in this work. Some considerations about possible future applications of the above platform in the framework of Visible Light Communication scenarios have been discussed, and a basic example, showing a Hybrid VLC-LIFI architecture, has been provided. Based on the architecture we have considered in this work, we envisaged different potential future directions that could impose VLC as an effective communication technology in coexistence with other classical communication technologies based on RF signals.

5. Acknowledgements

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Toward an Experimental Testbed for RSS-based Indoor Visible Light Positioning

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1. Introduction

Recent developments in the fabrication of white light emitting diodes (LEDs) have allowed the use of the visible light spectrum for data transmission along with illumination purpose, thus providing the dual paradigm of illumination and communications [1]. The benefits of modulating the intensity of the visible light for data transmissions are mainly associated to the availability of cheap devices and the absence of extra infrastructure thanks to existing lighting architecture in indoor environments [2].

One of the main applications of data transmission through visible light is the Visible Light Positioning (VLP) [3], which has recently emerged as a promising approach for indoor positioning, through the exploitation of ultra dense distribution of the existing lighting infrastructure. In a typical VLP system, the Intensity Modulation with Direct Detection (IM/DD) scheme is used so that the desired waveform is modulated into the instantaneous power of the optical carrier, and the photodetector generates a current proportional to the received instantaneous power.

Different techniques for VLP are based on the metric providing information on positioning, like the received signal strength [4] or the time delay [5], and the appropriate computational algorithm for location estimation, like triangulation, fingerprinting, and proximity. In case of triangulation technique, it is required to measure the angle or distance between the known position of the LED transmitter and the (unknown) position of the photodetector, such as Angle Of Arrival (AOA), Time Of Arrival (TOA), Time Difference Of Arrival (TDOA) and Received Signal Strength Intensity (RSSI) approaches [6].

In this paper, we present our preliminary results of an indoor positioning system comprised of four near infrared (NIR) LEDs deployed on a square geometry, in order to provide a full light coverage to the photodetector. We have implemented a positioning system using the RSSI technique because of its ease of implementation and relatively simple sensing hardware. The preliminary setup of the proposed system will provide information of positioning error via IR. Future work will address on the replacement of NIR LEDs with “white” LED sources.

2. NIR-based Indoor Positioning System

In our implementation, light sources are set to transmit square waves at different frequencies, as shown in Table 1. The single detector receiver determines the received electrical power at each of the specified frequencies, and uses this information to determine the amplitude of the received signal from the corresponding LED.

At the photodetector, the received optical power from the *i*-th LED *i.e.*, $P_{r,i}$, can be obtained as:

$$P_{r,i} = \frac{I_{r,i}}{R_p}, \tag{1}$$

where $I_{p,i}$ is the electrical current from the *i*-th LED and R_p denotes the photodiode responsivity. Under the hypothesis of Line-of-Sight link between the i-th LED and the photodetector, the expression the electrical current from the *i*-th LED can be written as

$$I_{r,i} = R_p P_{t,i} \frac{m+1}{2pd_i^2} A \cos^m\left(f_i\right) T_s\left(y_i\right) g\left(y_i\right) \cos\left(y_i\right), \tag{2}$$

where $P_{t,i}$ is the transmitted power from the *i*-th LED, m is the Lambertian order, T_s is the gain of the optical filter, and g is the gain of the optical concentrator. The angles f_i and y_i are the irradiance and incidence angles, respectively. Fig. 1 depicts the experimental setup with four luminaires and the photodetector.

The estimation of the position $\left(\hat{x},\hat{y}\right)$ is based on the Maximum Likelihood criteria, which under the hypothesis of Gaussian distribution becomes:

$$\left(\hat{x},\hat{y}\right) = \underset{x,y}{\arg\min} \left\| \mathbf{r} - \mathbf{m} \right\|^2, \tag{3}$$

where **r** is the [1x4] power measurements vector w.r.t the LEDs in the position, and **m** is the [1x4] vector of mean values of measurements.

3. Testbed setup

The testbed is constructed with 4 transmitters, each modulated at a different frequency. Each transmitter contains an LMC555 timer for generating the square wave, TCA0372 amplifier for buffering and adding a DC voltage offset, and TSAL6200 NIR LED. A SFH203 receiving photodiode is situated below the transmitters, where the signal is received and amplified. The signal passes through 4 bandpass filters and RMS to DC converters, producing a DC output for each transmitter. Data is recorded using a National Instruments Data Acquisition (DAQ) unit. Data is then saved to computer through a LabVIEW program. The related system block diagram is shown in Figure 1.

The overall system is depicted in Figure 2. The transmitting LEDs are 0.24 m apart in a square formation. With the system height of 0.8 m, each LED illuminates a 0.24 m radius circular area on the testbed based on its half angle, allowing for sufficient overlap in coverage area between each of the transmitters.

Preliminary data recordings in LabVIEW are reported in Figure 3. The data is sampled from the NI-DAQ at 1 kHz frequency, and the resulting data is low-pass filtered at 5 Hz in order to reduce the noise. As can be seen below, moving the photodiode in a cyclic way recreates a recognizable signal pattern, indicating that signal strength varies predictably. Future data recording and algorithm development will allow evaluation of system accuracy for position determination.

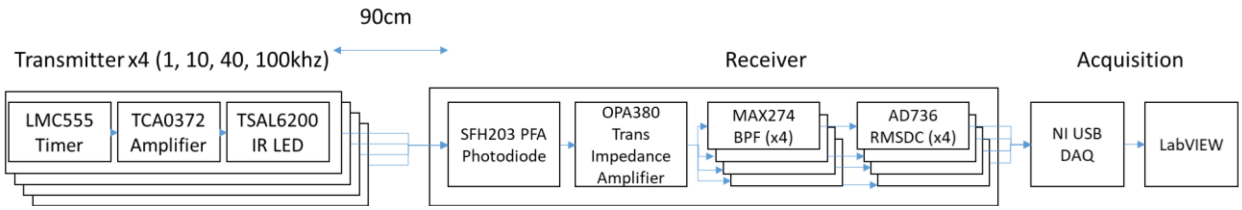

Figure 1. Indoor Optical Wireless Positioning System diagram.

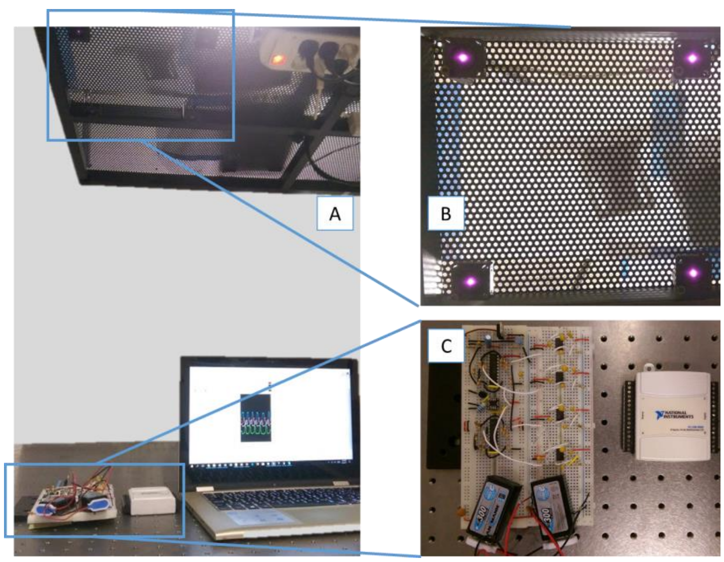

Figure 2 – Test setup. (A) Test bed setup, (B) bottom-up view of transmitters, (C) image of receiver circuit and NI-DAQ.

LED Half angle	17°
Photodiode half angle	75°
System height	0.8 m
LED Power	72 mW/sr
LED interdistance	0.24 m
LED frequencies [kHz]	
LED1	1
LED2	10
LED3	40
LED4	100

Table 1. Parameters used in the experimental testbed.

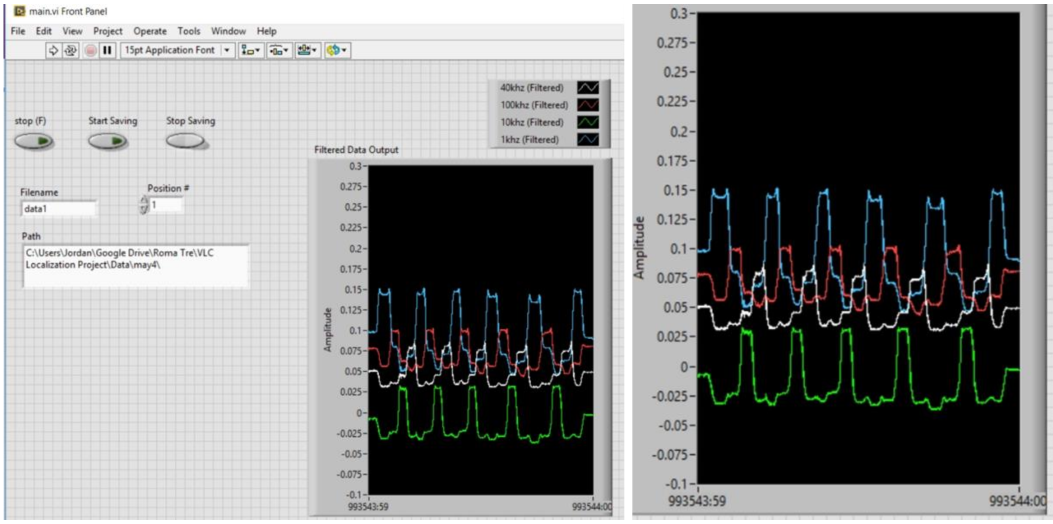

Figure 3. LabVIEW data acquisition.

4. Conclusions

In this paper, we have demonstrated theoretical principles and practical designs for an optical wireless positioning system. The design utilizes commercially available integrated circuits, allowing for future design modification and optimization. Initial data indicates that, as expected, the signal power varies predictably based on position of the photodiode. This first test bed provides information on next steps toward a visible light positioning system, by replacing current NIR sources with "white" LED transmitters. Future work will focus on algorithm development and evaluation of the system's spatial accuracy.

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A Flexible SDR-Based Testbed for Indoor Visible Light Positioning

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1. Introduction

Indoor positioning is an important emerging technology for supporting many location-aware applications such as human or robotic navigation tools, directed advertisement, in-home assistance, asset tracking, and sensor networking. These opportunities motivate investigation of a variety of sensing modalities including Bluetooth Low Energy (BLE), RFID, WiFi, Ultrasound, Ultra-Wideband, and various combinations thereof. In addition, the growing adoption of LEDs in lighting and the ability to modulate LEDs supports the case for lights, or luminaires, as beacons for indoor positioning. Thus, visible light positioning (VLP) is realized by encoding unique signals on each luminaire; a receiver can decode these signals and by interpreting data from multiple luminaires can identify indoor position.

The use of LED luminaires for indoor positioning has been shown to provide high accuracy with relatively inexpensive hardware. In practice, there are many considerations on how the signals are generated, decoded, and processed. This paper considers an experimental environment for designing and conducting experiments on VLP signal chains. The growing interest in VLP creates a need for a flexible testbed environment to evaluate the practical performance of novel VLP techniques [1]–[3].

VLP systems can be designed with various architectures depending on system constraints, available hardware, and whether cooperation exists amongst the luminaires and/or mobile devices. We present recent developments of a flexible testbed environment for VLP using a software defined radio (SDR), or software defined VLC (SDVLC), platform [4]. We show an implementation of a beacon-based VLP system in which luminaires transmit a fixed and unique frequency as an encoded identifier. Such a design choice can be easily integrated within existing infrastructure, making it an attractive low cost option for indoor positioning. We characterize the performance of this instance of a Received Signal Strength (RSS)-based VLP trilateration algorithm and show that it is capable of determining a receiver's (x, y) coordinates within a range of 1 − 16 cm across the full span of the test space. The remainder of this short paper is organized as follows. Section II describes the testbed environment. Section III introduces the RSS VLP algorithm and Section IV evaluates the algorithm's performance in the testbed. Finally, Section V concludes the paper.

2. Testbed Environment

The objective of the development testbed is to provide an environment that allows experimentation of a wide range of indoor localization scenarios using different light-based sourcing and sensing hardware, modulation techniques, and positioning algorithms. The use of an SDR-based platform enables an environment in which the transmitted and received signals can be processed on a general-purpose processor with multiple SDR toolkits, including GNURadio and Matlab. The flexibility to modify each transmitter's waveform and the receiver's signal processing techniques allows us to evaluate a wide range of approaches within the same set of physical conditions. For the VLP demonstration described here, we have utilized GNURadio with custom signal processing blocks that we have made openly available at http://github.com/mikerahaim/gr-vlp.

Fig. 1 defines our coordinate system to indicate position and orientation in an absolute sense as well as relative to a specified transmitter. To simplify the modeling, we characterize the transmitter and receiver as point sources with receiver location denoted by (x, y, z) and transmitter locations denoted by (x_i, y_i, z_i) where i specifies the transmitter. The receiver's orientation is shown by the vector $\vec{V}_R$ and is defined in terms of azimuth and elevation angle $(\theta_{az}, \theta_{el})$. The transmitters point directed downward. The distance between the receiver and the i-th transmitter is denoted by d_i and the angles φ_i and ψ_i represent the angles of emission and acceptance, respectively.

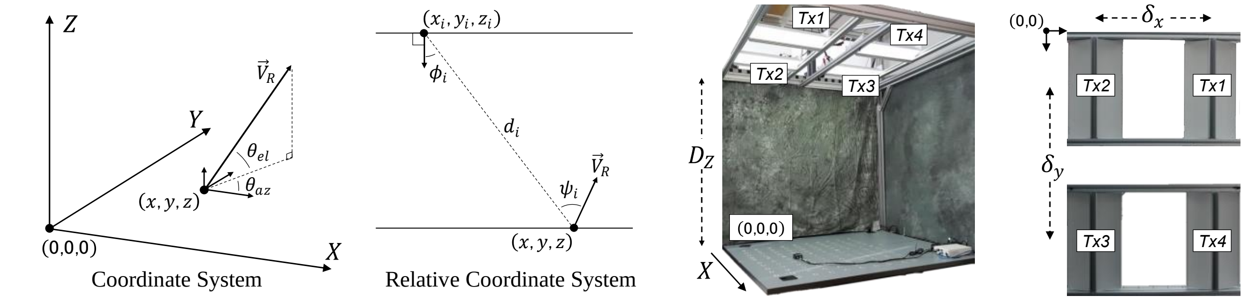

Figure 4. VLP testbed environment, transmitter layout, and coordinate system. Note that the transmitter layout view is looking upwards at the luminaires.

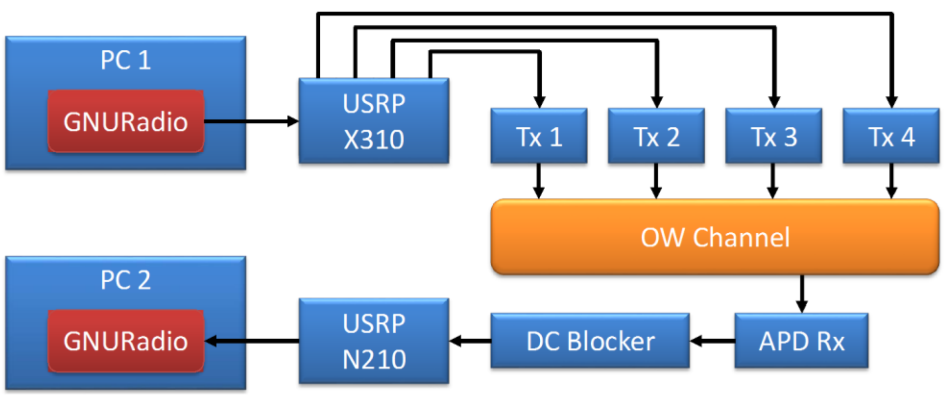

Figure 5. VLP testbed flow graph.

The system layout is also shown in Fig. 1. Four transmitters are placed 1.38 m from the table and aligned in a 2×2 grid. The horizontal coordinates of the transmitters are adjustable with δ_x and δ_y representing the separation in X and Y. The dimensions of the Cree troffers are $0.24\text{m} \times 0.46$ m. The receiver is located at the surface of the table.

Fig. 2 depicts the signal chain for the flow of signals in the testbed. Transmit signals are generated in GNURadio on PC1 and converted to a set of four voltage signals using an X310 universal software radio peripheral (USRP) from Ettus Research with two low frequency transmitter (LFTX) daughter cards. For each transmitter, the USRP drive signal is connected to a voltage- controlled current injector (Picotest J2111A) which connects to a DC-DC bias tee (Pulse Research Labs PRL-BTDC-114L). The biased output is used to drive two of the three LED strings on a $2' \times 2'$ LED troffer from Cree Lighting (CR22-32L-35K-S) and generate the optical signal. At the receiver, the signals are collected at an avalanche photodiode (APD) receiver (Thorlabs APD120A2) and converted into a voltage signal which is passed through a DC blocking capacitor and into the receiving N210 USRP with a low frequency receiver (LFRX) daughter card. The receiving USRP applies the analog to digital conversion and sends the sampled data to PC2 where it is processed in GNURadio to determine estimated positions.

3. Implementation of a RSS-Based VLP Algorithm

There are many approaches to VLP. To demonstrate our testbed we consider an infrastructure-based approach in which RSS ranging is achieved by the mobile receiver. Under this methodology, the VLP system requires a sensing method, a ranging or directional sensing technique to determine relative distances (or directions) to a set of beacons, and a computational algorithm (e.g., trilateration or triangulation) to estimate the receiver's absolute three-dimensional position. Other VLP techniques that have been proposed include Angle of Arrival (AoA), Time Difference of Arrival (TDoA), Time of Arrival (ToA), and Time of Flight (ToF). We have implemented VLP using the RSS technique in order to show the capabilities of the testbed. An intensity-modulated direct-detection (IM/DD) as is appropriate for modulation in this kind of system.

RSS VLP is a method that uses the relationship between a known transmitted signal strength and an estimated RSS to approximate range by solving for distance in the theoretical path loss model. RSS algorithms are widely used in the RF domain; however the optical channel's high dependence on relative orientation makes the VLP problem more challenging. For a point source transmitter and receiver, the line of sight (LOS) optical channel DC gain is defined as [5]

$$H_0(\phi_i, \varphi_i, d_i) = \frac{P_r^{(i)}}{P_t^{(i)}} = \frac{G_T(\phi_i) G_R(\varphi_i)}{d_i^2}, \tag{1}$$

where $P_t^{(i)}$ and $P_r^{(i)}$ represent the transmitted and received optical power from the i-th transmitter, respectively. For the transmitter gain model, $G_T(\cdot)$, and receiver gain model, $G_R(\cdot)$, we consider a Lambertian source with order m and photosensor with no optical lens or filter and with area A, i.e.:

$$G_T(\phi) = \frac{m+1}{2\pi} \cos^m(\phi), \tag{2}$$

$$G_R(\varphi) = A\cos(\varphi). \tag{3}$$

For IM/DD signals, it is also important to account for the conversion between the electrical and optical domain. The transmitted optical signal is represented by optical intensity variations. Assuming the drive signal, $x(t)$, is biased to operate in the linear range of the optical transmitter, we can define a proportionality constant, C_T, that relates the range of $x(t)$ to that of the optical signal. The responsivity of the photosensor, R, relates the received optical power to the received electrical current which passes through the receiver to generate $y(t)$. Assuming the receiver also operates in a linear range, we define C_R as a proportionality constant accounting for area, responsivity and any gain from the receiver circuitry. Accordingly, the relationship between the amplitude of the transmitted and received electrical signals is defined as

$$\frac{A_y^{(i)}}{A_x^{(i)}} = \frac{C_T C_R (m+1)}{2\pi d_i^2} \cos^m(\phi_i) \cos(\varphi_i). \tag{4}$$

Under the assumptions that vertical distance is known and that the receiver is oriented upwards, the above equation can be solved for the distances between the i-th beacon and the receiver:

$$d_i = \left[\frac{A_x^{(i)}}{A_y^{(i)}} C_T C_R \frac{(m+1)}{2\pi} (D_z)^{m+1} \right]^{\frac{1}{m+3}}. \tag{5}$$

In our implementation, luminaires transmit sinusoidal signals of different frequencies to enable distinguishing between beacons. The single pixel receiver determines the received electrical power at each of the specified frequencies and uses this information to estimate the amplitude of the received signal from the corresponding luminaire. This estimation is used in Eq. 5 in order to estimate the distances to each of the beacons. Given $N > 3$ distance estimations and the known locations of the associated luminaires, multilateration is used to approximate the receiver's location.

4. Performance Evaluation

Performance results are based on the error in the location estimates for two transmitter placements (L1 and L2) as defined in Table I. For L1 and L2, δ_x is set to 0.5m and 1m, respectively. In both scenarios, $\delta_y = 0.7$m. Location estimates locations are collected at 10 cm intervals over a 1m $\times$ 1m square below the transmitters. The errors between the true and estimated locations are shown in Fig. 3. In both transmitter placements, the error is largest when receiver moves in the X direction away from the center location of the transmitter grid. The higher inaccuracy from the displacement in X is likely due to the shape of the transmitter as shown in Fig. 1 and the approximation as a Lambertian source. The horizontal bar on the luminaire, due to its construction, occludes part of the surface light emission, and limits the light that reaches the receiver when the receiver is located directly below the luminaire.

Fig. 4 shows a CDF of the measured position error throughout the 1m^2 surface. For both layouts, we see that the receiver is located within 5cm over $20-25\%$ of the surface and within 10cm over $60-70\%$. The maximum error when the transmitters are close (L1) is 16.5cm and the maximum when transmitters are spread out in X (L2) is 13.4cm.

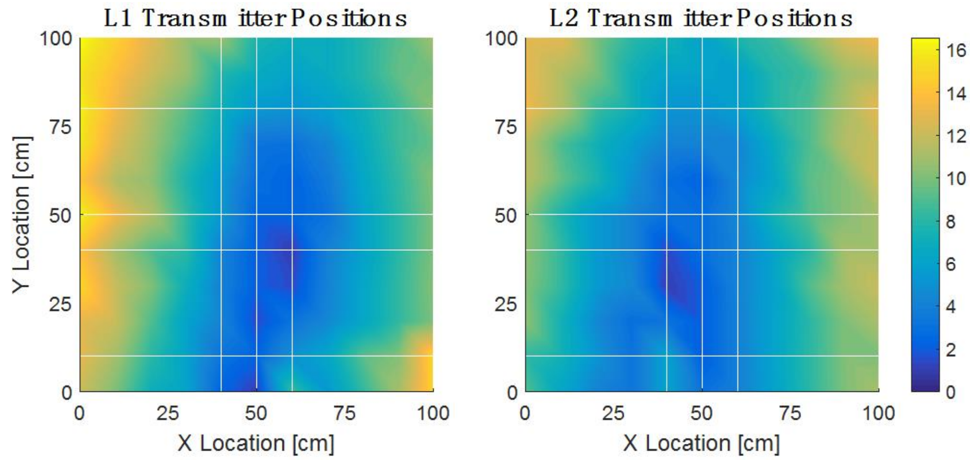

Figure 6. Indoor Optical Wireless Positioning System diagram.

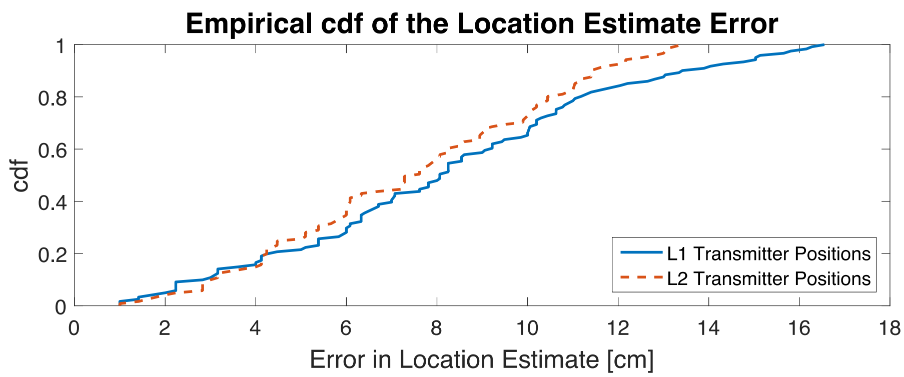

Figure 7. Cumulative distribution of the error distances when transmitters are located at locations L1 and L2 as defined in Table I.

Transmitter	Frequency [kHz]	$C_T C_R$	A_x [V]	m	L1 [cm]	L2 [cm]
Tx1	100	1.38	0.7	0.88	75.23	100.23
Tx2	300	1.45	0.7	0.88	25.23	0.23
Tx3	200	1.51	0.7	0.88	25.93	0.93
Tx4	400	1.39	0.7	0.88	75.93	100.93

Table 2. Testbed parameters.

5. Conclusions

We describe and characterize a software-defined visible light positioning testbed suitable for design, development, and evaluation of VLP hardware, software and systems. The system is exercised with a set of commercial luminaires modulated using unique frequency codes and received by a single mobile receiver that applies RSS multilateration. This demonstration of the system and testbed shows location estimates with an accuracy of $1 - 16$ cm under the defined constraints. Like any software-defined system, our environment allows rapid evaluation and benchmarking of novel VLP algorithms and hardware.

Our approach, and testbed is scalable to a larger network with additional luminaires and/or multiple receivers. In future work, we expect to show the impact of signal blockage effects in the presence of multiple moving user-receivers and to investigate techniques to mitigate these effects.

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material are those of the author(s) and do not necessarily reflect the views of the NSF.

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OFDMA-Based Resource Allocation in LiFi Networks

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1. Introduction

Light Fidelity (LiFi) is a recently proposed technology that combines illumination and high speed wireless communication using light emitting diodes (LEDs). Using a potential visible light spectrum greater than 300 THz, LiFi is able to achieve data rates of 14 Gb/s [1], far beyond 108 Mbps, the throughput of a WiFi access point (AP) in IEEE 802.11ac Standard [2]. In multi-user LiFi systems, an efficient multiple access scheme can avoid intra-cell interference and achieve multi-user diversity gains. Orthogonal frequency division multiplexing access (OFDMA) has been widely used in conventional radio frequency (RF) networks, e.g. LTE, due to its flexibility in resource allocation (RA). By using OFDMA technology, resources are partitioned in both time and frequency domains, as shown in Fig. 1. Such time-frequency blocks are known as resource blocks (RBs), and each RB contains a number of resource units (RUs), which are the minimum and indivisible time-frequency slots. It is evident that allocating those RUs to different users is more efficient and flexible than allocating subcarriers or time slots only. Moreover, due to frequency-selective channels, an adaptive user-to-RU assignment is able to substantially enhance the overall system spectral efficiency compared to time division multiplexing access (TDMA) schemes.

Unlike in RF systems, the LiFi channel response in the frequency domain consists of two components: LED characteristics and multipath effects. It has been shown that in an open space office scenario, LiFi channels are mainly affected by the LED characteristics, functioning as a low-pass filter. This results in a decrease in channel response, with an increase of frequency. The diffusing component, however, plays a less important role in LiFi links with a maximum variance less than 2.5 dB [3]. Therefore, for all users served by a specific LiFi AP, the LiFi channel response over the subcarriers are almost the same, and the channel quality at low frequencies is always better than that at high frequencies.

Despite the inconspicuous multi-user diversity, we find that OFDMA can still achieve a higher SE than TDMA in LiFi systems by carefully allocating high-frequency subcarriers to users. It is shown in

[3] that the LiFi channel response in the frequency domain is approximately inversely proportional to the frequency. This means that users with high direct-current signal-to-noise-ratio (DC SNR) are able to use a large modulation bandwidth, while the users with low DC SNR may not be able to transmit signals on high-frequency subcarriers. As shown in Fig. 1 (a), in the TDMA scheme, some of the high- frequency RUs, which are in white colour, are not usable due to the low DC SNR of the corresponding users. However, those RUs can be assigned to users with high DC SNR to enhance overall data rates, depicted in Fig. 1 (b). In this study, two OFDMA-based RA schemes are proposed in order to exploit the multi-user diversity gain in LiFi systems. One formulates the RA issue as an optimisation problem while the other exploits the unique characteristics of LiFi channels to reduce the computational complexity.

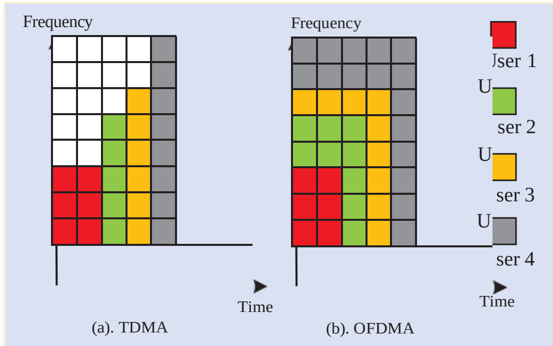

Figure 1. Resource allocation in TDMA and OFDMA schemes.

2. Resource Allocation in LiFi Networks

We consider an indoor LiFi network, and the deployment of the LiFi APs follows a square lattice topology which models a regular lighting placement commonly used in large offices and public places. The LiFi system uses baseband communication, relying on intensity modulation (IM) at the transmitter and the direct detection (DD) at the receiver. Direct current biased optical orthogonal frequency division multiplexing (DCO-OFDM) is used in this system [3]. In the overlapping areas of LiFi attocells, the co- channel interference exists, which is considered and treated as noise. The link data rate achieved between user μ and its host LiFi AP on subcarrier m is denoted by $r_{\mu,m}$. In this study, two OFDMA-based resource allocation schemes are proposed to improve the overall system throughput.

2.1. Optimisation RA Scheme

It is assumed that a RB contains MK RUs, where M is the number of effective OFDM subcarriers, and K is the number of subframes in the time domain. Since LiFi channels do not exhibit fading characteristics, the LiFi channel state information (CSI) on each subcarrier can be assumed to be constant in a RB period. In this scheme, the RA is formulated as an optimisation problem, and an iterative algorithm is proposed to find the optimum. Specifically, a utility function involving the data rates and fairness of users is considered for RA. This is referred to as β-proportional fairness function, which was defined in [4]:

$$\psi_\beta(x) = \begin{cases} \ln(x), & \beta = 1 \\ \dfrac{x^{1-\beta}}{1-\beta}, & \beta > 0, \beta \neq 1 \end{cases}, \tag{1}$$

where x is the user data rate; and β is the fairness coefficient. This utility function includes several well known fairness concepts. For instance, when $\beta \to +\infty$, a max-min fairness scheduler is realised and when $\beta = 1$, a proportional fairness is achieved. In a LiFi attocell, the resource allocation with the

β-proportional fairness function can be formulated as an optimisation problem:

$$\max_{k_{\mu,m}} \quad \sum_{\mu \in \mathcal{U}} \psi_\beta\left(\sum_{m=1}^{M} k_{\mu,m} r_{\mu,m}\right) \tag{2}$$

$$s.t. \quad \sum_{\mu \in \mathcal{U}} k_{\mu,m} = K, \; 1 \le m \le M, m \in \mathbb{N}; \tag{3}$$

$$k_{\mu,m} \in [0, K], k_{\mu,m} \in \mathbb{N} \tag{4}$$

where $\mathcal{U}$ is the set of all users; and $k_{\mu,m}$ is the number of RUs allocated to user μ on subcarrier m. The Lagrangian multiplier method is used to solve this problem via an iterative algorithm [5].

2.2. Low-complexity RA Scheme

In this scheme, RUs are allocated to users from high-frequency to low-frequency subcarriers in order to make full use of high-frequency subcarriers. This method can significantly reduce computational complexity as it does not require iterative operations.

As shown in [3], the LiFi channel gain in the frequency domain decreases with an increase in frequency. Therefore, in a LiFi attocell, there are fewer users that can use high-frequency resources than those that can use low-frequency resources. Based on this fact, a low-complexity RA scheme is proposed in which RA is carried out from high-frequency to low-frequency subcarriers. On each subcarrier, the RUs are assigned based on the CSI and the resources obtained by users on the higher-frequency subcarriers. The aggregate data rate achieved by user μ over subcarriers from m to $M_e + 1$ is denoted by:

$$Z_{\mu,m} = \begin{cases} Z_{\mu,m+1} + k_{\mu,m} r_{\mu,m}, & m < M \\ 0, & m = M \end{cases}. \tag{5}$$

On the m-th subcarrier, the resource allocation using β-proportional fairness function can be formulated as an optimisation problem:

$$\max_{k_{\mu,m}} \sum_{\mu\in\mathcal{U}_m} \psi_\beta\left(k_{\mu,m} r_{\mu,m} + Z_{\mu,m+1}\right) \tag{6}$$

$$s.t. \quad \sum_{\mu\in\mathcal{U}_m} k_{\mu,m} = K; \tag{7}$$

$$k_{\mu,m} \in [0, K], k_{\mu,m} \in \mathbb{N} \tag{8}$$

where $\mathcal{U}_m$ is the set of users whose link data rates on subcarrier m, $r_{\mu,m}$, are greater than zero. Similarly, the Lagrangian multiplier method is used to solve this problem, and a close form solution can be obtained as:

$$k_{\mu,m} = \frac{r_{\mu,m}^{\frac{1}{\beta}-1}}{\sum_{\mu\in\mathcal{U}_m} r_{\mu,m}^{\frac{1}{\beta}-1}} \left(K + \sum_{\mu\in\mathcal{U}_m} \frac{Z_{\mu,m+1}}{r_{\mu,m}}\right) - \frac{Z_{\mu,m+1}}{r_{\mu,m}}. \tag{9}$$

3. Performance Evaluation

An indoor office space scenario is considered where 9 LiFi APs are deployed in a square lattice topology. Each AP covers a 4 m $\times$ 4 m attocell, and 6 users are uniformly distributed in the central attocell, which are served by the central LiFi AP and receive interference from neighbouring APs. The other simulation parameters follows those in [5]. A TDMA-based RA scheme using β-proportional fairness function is considered as a benchmark, where resources are partitioned only in the time domain [5].

In Fig. 2, the average data rate corresponding to β is presented. It appears that the RA schemes in OFDMA systems outperform that in TDMA systems on user data rate because the OFDMA scheme can more efficiently utilise the high-frequency RUs than the TDMA scheme. In addition, it is shown that the LC RA scheme achieves throughput performance close to the optimal scheme. The largest gap of data rate between the optimisation scheme and the LC scheme takes place at around $\beta = 1$. The LC scheme performs RA based on how much resource users have gained. Users that have obtained more resources on the high-frequency subcarriers will obtain less resources on the low-frequency subcarriers, and this principle may decrease the user data rate but can improve user fairness.

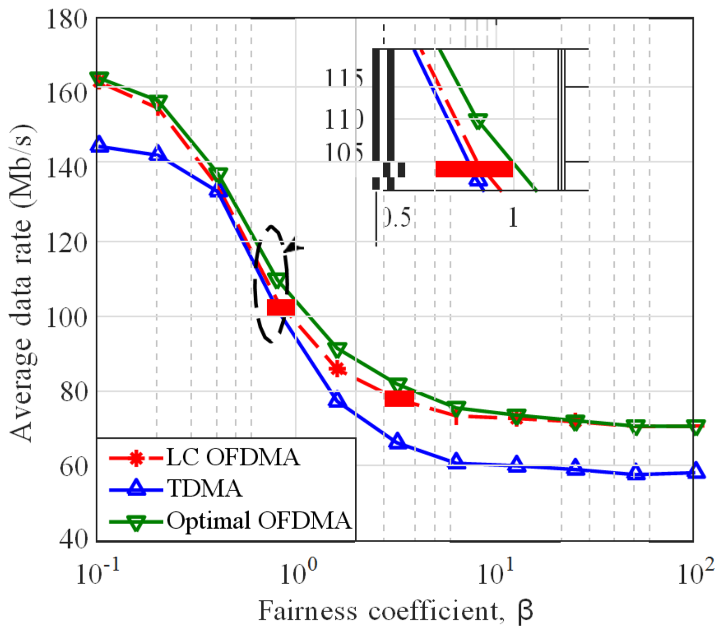

Figure 2. User data rate corresponding to β (Baseband bandwidth used in LiFi systems is 280 MHz.)

4. Conclusion

The RA issue in LiFi OFDMA systems is studied in this paper, and the optimisation RA scheme and the LC RA scheme are proposed. Two conclusions can be drawn based on the simulation results: i) the RA schemes in OFDMA systems outperform those in TDMA systems on data rate because of an efficient use of high-frequency resources; ii) the LC RA scheme is able to achieve near-optimal performance at a reduced computational complexity.

Acknowledgement

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The statements made herein are solely the responsibility of the author[s].

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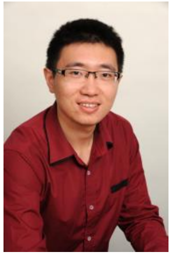

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A Cognitive Design of VLC Networks [1]

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1. Introduction

Visible light communication (VLC) [2] has been gaining an increased attention as a promising solution for the overcrowded radio frequency (RF) spectrum problem, thanks to the potential advances in white light emitting diodes (LEDs) technology. In addition to supporting high data rates, using white LEDs for data transmission has many advantages over the RF technology [3, 4]. For example, they are cheap, energy efficient and no extra infrastructure is needed since white LEDs would be already installed for lighting. Furthermore, data security would be inherently ensured since light does not propagate through walls.

However, the VLC technology comes with other restrictions and challenges that should be carefully handled. For instance, the main lighting functionality of the LED-based access points (expressed in terms of illumination requirements) should be considered when designing the VLC networks. In addition, since each VLC cell can cover a small area of square meters, typical indoor scenarios are equipped with multiple lighting sources to cover the entire area. This further makes the network planning more challenging when dealing with mobile users, since the connectivity switching process from one access point (AP) to another (known as *handover*) is expected to occur more often. While each handover process requires extra signaling overhead, the user connectivity also becomes an issue during the switching process. The existing literature studies deal with these problems separately, *i.e.*, they either target the influence of the illumination requirements on the VLC network design [5, 6], or deal with the handover requirements and approaches [7–9].

Different than that, in this paper we propose a cognitive design for VLC networks that takes both the illumination and handover requirements into account. In particular, we consider an indoor VLC network, in which multiple LED-based APs serve end users by employing the orthogonal frequency division multiple access (OFDMA) scheme. We assume that each lighting cell can be divided into two regions, such that each region is allocated different amounts of transmission resources. Under the assumption of equal power allocation among all subcarriers, we investigate the effects of fulfilling illumination, mobility, and handover requirements on defining each region in terms of physical area and the number of allocated subcarriers. Consequently, we formulate a design criteria that ensures fulfilling the mentioned constraints.

2. System Model

We consider an indoor communication scenario consisting of K LED-based APs and M mobile users. We regard a downlink transmission scenario and assume that each AP employs OFDMA scheme to serve multiple users within its coverage area. To simplify, we assume that each AP produces an ideal cone of light, *i.e.*, its entire light output is projected as a circular lighting field with a hard boundary, centered at the AP location. The coverage area of each AP is divided into two regions, namely Zone 0 and Zone 1. Without loss of generality, we assume that users located in each zone are uniformly distributed in that zone. Herein, we define Zone 0 and Zone 1 in terms of both the geographical area and the amount of resources allocated for each region. To that end, the radius of Zone 0 related to the k-th AP is denoted as $r_{0,k}$ [m], whereas the radius of the entire coverage area is denoted as r_k [m] for $k = 1, \dots, K$. It follows that Zone 1 is defined as a two-dimensional ring whose width is $r_{1,k} = r_k - r_{0,k}$ [m]. Figure 1 depicts the system model in the case of two APs.

We assume that all APs have the same resources of power, bandwidth, and number of subcarriers, *i.e.*, P_{cell}, B_{cell}, and N_{cell}, respectively. Subsequently, we assume that $P_{z,k}$, $B_{z,k}$, and $N_{z,k}$ are the corresponding resources allocated for Zone z for $z = \{0, 1\}$. We further assume that all subcarriers in each AP are allocated the same bandwidth and power. Consequently, we observe that Zone z (with $z = \{0, 1\}$) of the k-th AP can be completely characterized by finding its radius $r_{z,k}$ and the allocated number of subcarriers $N_{z,k}$. Finally, note that if the subcarriers allocated in Zone 1 have different frequency bands in the adjacent cells, and that the overlapping area of any two adjacent cells occurs only over Zone 1 in both cells, then the co-channel interference in the overlapping areas can be mitigated.

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[1] This work is a shorter version of the paper in [1].

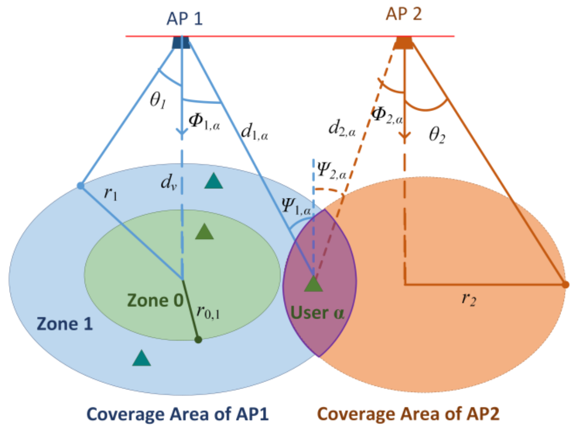

Figure 1. General system model for $\boldsymbol{K = 2}$.

3. Network Design

In this section, we explore the effects of the illumination and handover requirements on defining Zone 0 and Zone 1. Regarding the illumination requirements, illuminance is the most commonly used measure that characterizes the brightness level at a given location. In this paper, we target a brightness span of $[E_{\min}, E_{\max}]$ lx within Zone 0, such that the brightness level at the zone edge fulfills the minimum level of $E_{\min}$, while it is equal to $E_{\max}$ at the cell center for the eye safety concerns. Recalling that each AP is assumed to have an interference-free coverage area, then we have the following design limitation:

$$r_{0,k}^2 \leq d_v^2 \left[\left(\frac{E_{\max}}{E_{\min}} \right)^{\frac{2}{m_k+3}} - 1 \right] \coloneqq \Lambda_{0,k}^2, \tag{1}$$

where d_v is the vertical distance between the transmitting and receiving planes, and m_k is the Lambertian index of the transmitting LED.

On the other side, the handover process normally requires an extra overhead as control signaling. In addition, a seamless handover mechanism is preferred in order to maintain service connectivity without interruption while a user moves from one cell to another. According to cell design, handovers are expected to happen more frequently in smaller cells, and hence the design of Zone 0 and Zone 1 is a critical factor for handover initialization. Now, let $U_{z,k}$ be the number of users located in Zone z related to the k-th AP for $z = \{0,1\}$, and ε be the user density [user/m^2] within the entire indoor environment. Then, we have $U_{0,k} = \pi\varepsilon r_{0,k}^2$, and $U_{1,k} = \pi\varepsilon\left(r_k^2 - r_{0,k}^2\right)$. Furthermore, the bandwidth required to handle one handover process is denoted as B_{HO} [bits], and the percentage of users leaving Zone 0 is denoted as β. Herein, we consider a special case and assume that each user of Zone 0, either when being located in Zone 0 or when moving to Zone 1, is allocated a single subcarrier. Based on these assumptions, we can formulate the following design limit:

$$r_{0,k}^2 \leq \frac{N_{\text{cell}} - \pi\varepsilon r_k^2 \frac{B_{\text{HO}} N_{\text{cell}}}{B_{\text{cell}}}}{\pi\varepsilon\left[1 + \beta - \frac{B_{\text{HO}} N_{\text{cell}}}{B_{\text{cell}}}\right]} \coloneqq \lambda_{0,k}^2. \tag{2}$$

Note that $\pi\varepsilon\lambda_{0,k}^2$ represents the maximum number of subcarriers that can be allocated, and hence the maximum number of supported users, in Zone 0, for a given ε. Now, combining (1) and (2), we can observe that for the k-th AP, in order to fulfill both illumination and mobility (handover) requirements, while serving at least U users in Zone 0 for a given user density ε, the radius of Zone 0 should obey the following condition:

$$\frac{U}{\pi\varepsilon} \leq r_{0,k}^2 \leq \min\left\{\Lambda_{0,k}^2, \lambda_{0,k}^2\right\}. \tag{3}$$

4. Simulation Results

In this section, we show the numerical results obtained with MATLAB, in order to validate our proposed design scheme. Herein, we assume that each AP has dominant line-of-sight links to all users. We further set the LED viewing angle to $\varphi_{1/2} = 60°$, the vertical distance to $d_v = 2.5$ m, the cell bandwidth to $B_{\text{cell}} = 20$ MHz, and the number of subcarriers to $N_{\text{cell}} = 64$.

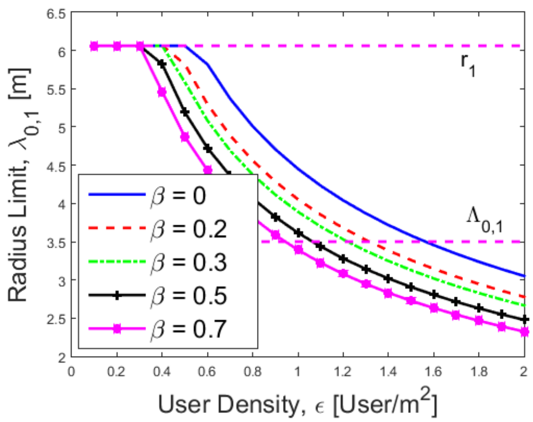

Figure 2. Limit on Zone 0 radius based on the handover requirements as a function of the user density (*i.e.*, ε), for different values of β when $B_{\mathrm{HO}} = 10$ kbits.

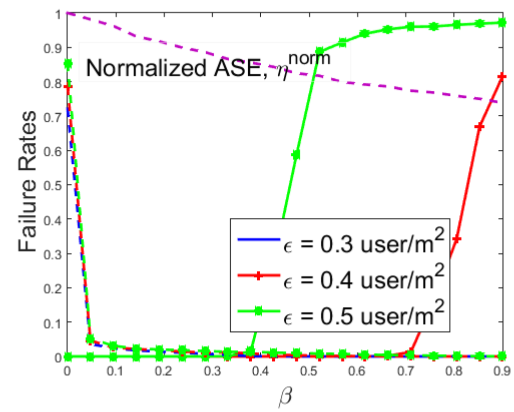

Figure 3. Average failure rates $\boldsymbol{\delta_0}$ (*solid lines*) and $\boldsymbol{\delta_1}$ (*dashed lines*) for the simulation example as a function of the ratio $\boldsymbol{\beta}$ for different values of $\boldsymbol{\varepsilon}$.

In Figure 2, we set the AP index to $k = 1$ we show the radius limit based on the handover requirements, *i.e.*, $\lambda_{0,1}$, as a function of the user density ε and for different values of β and for $B_{\mathrm{HO}} = 10$ kbits. We also show the cell radius (*i.e.*, r_1) and the radius limit based on the illumination requirements, (*i.e.*, $\Lambda_{0,1}$). Here, we set $\lambda_{0,1} = r_1$ if we have $\lambda_{0,1} > r_1$. Note that the value of $\beta = 0$ means that none of the users is leaving Zone 0, *i.e.*, all users are stationary or they (or some of them) are moving within Zone 0. We initially observe that, at low user density values of $\varepsilon \leq 0.3$, the handover process has no effects on the cell coverage (flat behavior) for the considered settings and values of β. This means that the available number of subcarriers can support both the transmission and the handover requirements of all users within the entire area of the cell with radius r_1. As either the user density or the number of users in Zone 0 that move to Zone 1 increases, Figure 2 reveals that the area of Zone 0 shrinks, and hence the number of users in Zone 0 that can be served by the cell is reduced. We finally notice that the handover process has stricter limits on the radius than the illumination requirements at higher user density and/or higher values of β.

Next, we investigate the performance of the proposed resource allocation scheme in a practical indoor scenario. In particular, we consider a $10 \times 30 \times 3.5$ m^3 indoor hall, covered by K VLC APs with overlapping lighting cells. By assuming that all APs have the same characteristics, a number of $K = 3$ APs is sufficient to cover the entire space. We further assume that the overlapping area between any two adjacent cells has a maximum distance of 1.2 m. The number of users is M, and hence the user density can be calculated as $\varepsilon = M/300$ [user/m^2]. All users are uniformly distributed and move with random speeds and directions. Particularly, each user moves with a speed uniformly distributed between 0 and $v_{\max}$ [m/s]. Speed limits are affected by user positions, assuming lower (higher) speeds for users in Zone 0 (1). This is justified since users are expected to be looking for spots with better illumination and communication conditions, which can be found in Zone 0 of each cell. On the other hand, the user located in Zone 0 changes its direction uniformly between 0 and 2π in each simulation step, whereas it moves in the direction of the closest AP otherwise. In this section, we calculate the radius and the number of allocated subcarriers of Zone 0 related to the k-th AP as $\min\{\Lambda_{0,k}, \lambda_{0,k}\}$ and $\varepsilon\pi\lambda_{0,k}^2$, respectively. Let $U_z^{(t)}$ be the total number of users located in Zone z of all APs in the scenario at a time instant t for $z = \{0, 1\}$. Then, we define the total failure rates in Zone 0 and Zone 1 over the entire space at the time step t, respectively, as the probability that no user is within Zone 0 and Zone 1, respectively:

$$\delta_0^{(t)} = \mathrm{Prob}\left\{U_0^{(t)} > \varepsilon\pi \textstyle\sum_{k=1}^{K} \lambda_{0,k}^2\right\}, \quad \text{and} \quad \delta_1^{(t)} = \mathrm{Prob}\left\{U_1^{(t)} > N_{\mathrm{cell}} - \varepsilon\pi \textstyle\sum_{k=1}^{K} \lambda_{0,k}^2\right\}. \qquad (4)$$

In Figure 3, we show the average failure rates, $\delta_0 = \mathbb{E}_t\left\{\delta_0^{(t)}\right\}$ and $\delta_1 = \mathbb{E}_t\left\{\delta_1^{(t)}\right\}$, over a simulation time of 2 minutes, $B_{\mathrm{HO}} = 10$ kbit/s, and the number of users is $M = \{90, 120, 150\}$. We can clearly see that β has a potential impact on the average failure rates for any values of ε. As expected, increasing β degrades the performance in Zone 0 in terms of the user connectivity, since less subcarriers are allocated in Zone 0. On the other hand, increasing β

results in more subcarriers in Zone 1, and hence better user connectivity, as also shown in Figure 3. We also plot the normalized area spectral efficiency factor *i.e.*, $\eta^{\text{norm}} = \eta/\max(\eta)$, where $\eta = \frac{\text{Total average throughput}}{\text{Total area}}$. Note that the total area illumination constraints have the main limits on the radius of Zone 0 for the considered values of ε, and hence the area spectral efficiency (ASE) curve is the same here. While increasing β shrinks the area of Zone 0, it also means that Zone 1 has a larger area with more allocated subcarriers. Therefore, the ASE performance degrades with β. As a conclusion, optimizing the value of β is a critical task in the proposed scheme, in order to reduce the failure rates in both zones, while achieving the best possible ASE for a certain scenario.

5. Conclusions

Considering OFDMA-based networks, in this paper we proposed a cognitive design for VLC networks that take both illumination and handover needs into account. We assumed that each cell is divided into two non-overlapping regions, such that each region is allocated different amount of resources. Simulation results showed that a proper value for the mobility parameter can fulfill the mentioned requirements, while achieving a high throughput within the cell.

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SPECIAL ISSUE ON IoT TECHNIQUES TOWARDS 5G

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Internet of Thing (IoT) has become an inherent part of areas such as electricity, transportation, industrial control, retail, utilities management, healthcare, water resources management and mining. It can greatly improve productivity and daily lives and will be well supported by the fifth generation (5G) mobile networks. This special issue of E-Letter focuses on the promising current progresses on IoT when it is going to 5G era.

In the first article titled, "An IoT Based Health Monitoring System to Predict and Prevent Bradycardia in Preterm Infants", *Md Shaad Mahmud, Honggang Wang, Hua Fang* from University of Massachusetts and Dartmouth University of Massachusetts Medical School, studies specific events in cardiac and cardiorespiratory signal processing in real-time for preterm infants. The authors also analyze and extracted the feature for the machine learning module. Their works can be used for risk analysis, personal health monitoring, and implementation of preventive systems for minimizing the mortality of the preemies for home and medical usage.

In the second article, "Privacy-preserving Data Access Control in Smart Grid", by *Kan Yang, Xiaohua Jia, and Xuemin (Sherman) Shen* from University of Waterloo, investigates the data access control problem in smart grid. This paper takes the energy consumption data as an example and proposes a cryptographic implementation for attribute-based access control in smart grid. The authors also provide security analysis about this scheme, which has demonstrated its broad application prospects in the area of data security and privacy preserving.

Finally, the third article, titled "Blockchain-based Distributed Data Management Systems towards Secure Transmission in Vehicular Networks", by *Zhe Yang, Long Zhao* and *Kan Zheng* from Beijing University of Posts and Telecommunications, proposes a distributed data management system in vehicular networks based on Blockchain techniques. The article provides a novel framework on how to adapt Blockchain to the field of vehicular security. The authors also present two case studies in order to validate the proposed framework. Their works can be used in a wide range of IoT security applications.

These articles provide different viewpoints for IoT techniques. It is believed that IoT will play the important role in our life. I am very grateful to all the authors for making great contribution and the E-Letter Board for giving this opportunity to this special issue.

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An IoT Based Health Monitoring System to Predict and Prevent Bradycardia in Preterm Infants

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[2]University of Massachusetts Medical School

1. Introduction

According to the statistics, millions of infants around the world die because of bradycardia. Critical health conditions (CHDs) like bradycardia can be predicted and prevented using medical sensors, actuators, and artificial intelligence. Infants born before they reach 37 weeks of development are considered premature (preemies). Globally, premature infants are born at a rate of 10%. Only in the USA, more than 1 in 10 pregnancies end in preterm birth (and this number is rising) with CHDs. About 25% of the preterm babies are affected by critical CHDs, that is about 40,000 births per year [1]. Cardiovascular diseases are one of the major causes of death around the world. These diseases are especially dangerous for infants as they are at a serious risk of developing disabilities or even dying due to a lack of growth of vital organs. Apnea is most common in premature babies because their nervous system has not finished developing [2]. The general definition of Apnea is a pause in the regular breathing of a baby lasting longer than 15-20 seconds. Normal breathing will vary, but does not stop for any length of time. During sleep apnea however, an infant's heart rate will decrease and this is called bradycardia. A significant part of this thesis is devoted to the extraction of information relating to these two events (Apnea and Bradycardia) from electrocardiogram (ECG) and Photoplethysmogram (PPG) signals. We observe the problem of acquiring low frequency components from vital signals filtering all other noises. We also showed how to identify and predict future event of Bradycardia and produced a tailored treatment for sleep apnea.

Heart rate variability (HRV) has been one of the most popular and major tools to analyze different cardiovascular diseases for the last couple of decades [3]. HRV is a physiological phenomenon that consists of variations in the time duration between heartbeats. It helps to non-invasively study and quantify variability in one's heart rate. Features like time, frequency, time-frequency and nonlinear components have been extracted from the HRV data of an ECG signal [4]. Current solutions have two major drawbacks, 1) they do not take any action based on the detected bradycardia/sleep apnea, and 2) most of the solutions are non-real-time. The purpose of this work is to solve and identify these problems and build a full-phase prototype for a wireless portable incubator. The results show that HRV has special features that occur before the critical event itself, which may help classify preemies prone to bradycardia verses preemies in healthy condition. We found that if one reads all of these features, it may lead to a higher accuracy in predicting bradycardia. Also, we developed an acoustic actuator that can be placed inside of the mattress where a preemie may be resting. After the system predicts the bradycardia, it sends a signal to the acoustic actuator within the mattress and it helps prevent the preemies from experiencing sleep apnea. Our work is applicable for risk analysis, personal health monitoring, and implementation of preventive systems for minimizing the mortality of the preemies for home and medical usage.

2. Problem Statement and Solutions

HRV is an important indicator of the cardiovascular health of a subject. The autonomic nervous system activity regulates it, thus accurate quantification of HRV provides vital information on a subject's autonomic modulation, and cardiovascular health. Further, respiratory sinus arrhythmia is characterized as the heart rate oscillations, which occur simultaneously with the respiratory cycle [5]. Though named as an arrhythmia, respiratory sinus arrhythmia is a normal physiological process, which characterizes the variations in the heart rate during inspiratory and expiratory phases of the respiratory cycle [6]. It serves an important role in providing synchrony between the respiratory and cardiovascular systems. Accurate quantification of respiratory sinus arrhythmia provides critical insights into the mechanisms involved in short-term and long-term cardiorespiratory coupling [7]. Several algorithms have been presented in the literature for characterizing heart rate variability and respiratory sinus arrhythmia in time and frequency domains [8, 9].

The problem with heart rate abnormality and respiratory sinus arrhythmia instantaneously is how you want to quantify it, how to identify the fast changes in the heart rate, handling the inputs of the model, modeling the data, and integrating with peripheral devices. The novel algorithms presented in this thesis can extract all the features from heart rate and respiration to predict bradycardia of preterm infants. It is important to test and evaluate the novel algorithm on experimental data. Hence, we developed a respiratory simulator, mimicking the exact respiration and heart rate to conduct the experiment. It helps to test and evaluate the accuracy and the robustness of the algorithms, also to analyze and predict bradycardia in real-time. However, we plan to finish the prototype as a fully functional portable incubator for preemies and validate the system with an actual baby. This is one of the future phases of this work.

3. Technical Approach and Results

We have used data's taken from the MIT/BIH RR interval database of physiological signals hosted at Physionet [10]. Data on 60 preterm infants have been studied thoroughly, among them 30 preemies with bradycardia and 30 without bradycardias have been classified. The data were sampled at 128hz with beat annotation, which helps to review and correct the analysis.

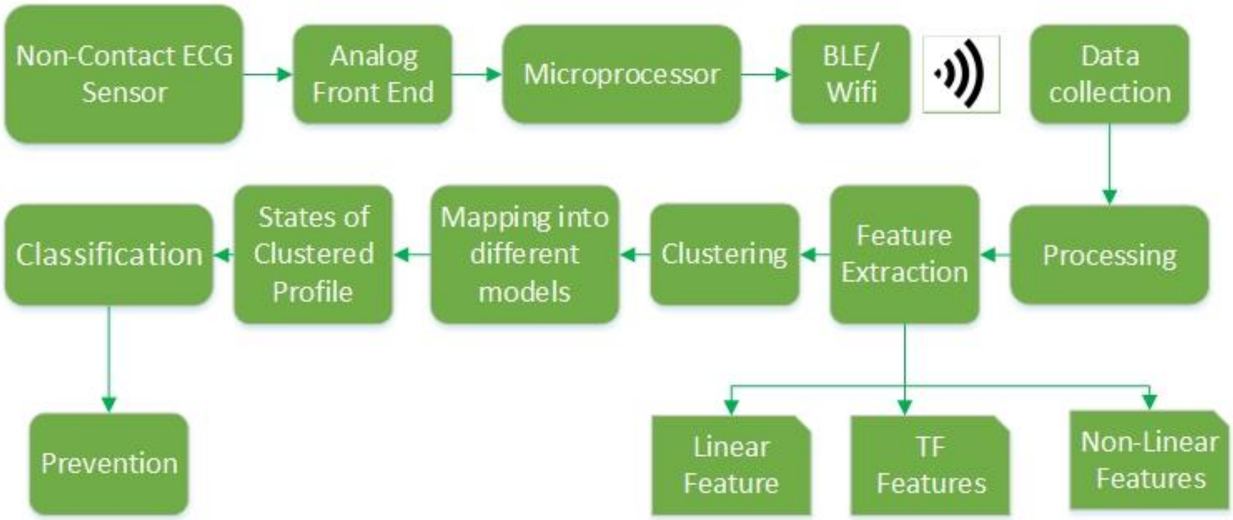

Figure 1: A complete process of IoT Architecture to Predict and Prevent Bradycardia.

A non-contact monitoring system is sensing information without physical contact with the subject. We have used a capacitive sensor, which has a high input impedance to the human skin and acts as a variable capacitor. The input is shielded by a dielectric material for isolation between the skin and the electrodes. In [11], we have developed a low power and high input impedance capacitive ECG sensor with custom made analog front end (AFE). Also, a miniature printed circuit board has been designed, consisting of an AFE, Microprocessor, Bluetooth low energy (BLE) and lithium battery with USB charging capability. The BLE component of the circuit has the added advantage of being very secure, localized, and easy to use. It is so secure, that is has even been used as a payment method in the past. BLE can also sync as well as communicate with the other BLE hosts. The proposed system uses a high performance, professional grade Bluetooth 4.0 transceiver with a built in 32-bit ARM Cortex M0 processor. The module can be categorized as IoT4EE (IoT for Everyone and Everything). Unlike other IoT devices, it can directly upload GUI description code to one's cell phone. Hence, no need to make an additional mobile phone app to work with the developed sensor node. The operating voltage is 1.8 to 3.6 volts and can communicate with other devices within a few centimeters of the device or up to 50 meters away.

To connect the module to a computer, it uses a Gazell or GZLL protocol, which was developed by Nordic Semiconductor. The data can be stored directly in the cloud server through this module [12]. Preprocessing is required to analyze HRV to reduce noise and errors due to motion artifacts. The four primary types of IBI preprocessing are interval correction, detrending, interpolation and IBI resampling [13]. In this work, we extracted Linear and Time-Frequency features. These features were later used to predict and prevent sleep apnea. However, until now different linear analysis has been used to analyze HRV, but recent research shows that Nonlinear features give more information/insight compared to linear methods. Therefore, we also added Nonlinear parametric analysis. The next step in this research is to cluster data from healthy infants to infants prone to sleep apnea. We used K-Nearest Neighbor to perform this task, as it presents the highest accuracy among other models. The model choice for this classifier and predictor is a Hidden Markov model (HMM). HMM can capture the dynamics before an actual event. This is achieved by representing each time slice as a state. For an actual bradycardia event, there is a sequence/pattern of state transitions before and during bradycardia. This state sequence is captured from the extracted features representing an actual bradycardia, a score or profile value is then generated for each sequence associated with an actual critical event and normal state. With this score value defined by a range of values, new patient's ECG can be classified and for the first few hours of ECG readings, a patient's propensity of having bradycardia can be predicted even a few minutes ahead of the event. After prediction, the next step is preventing the bradycardia. The developed system consists of a mattress installed with acoustic actuators which will be only triggered if the alert signal of bradycardia events has been predicted.

4. Conclusion

In this work, we focus on some specific events in cardiac and cardiorespiratory signal processing in real-time for preterm infants. Experimental results show that there is important information on HRV which can be extracted in real-time by the proposed algorithm and used for predicting bradycardia. With the help of time-frequency and nonlinear analysis the feature for the machine learning module have been extracted. The accuracy of the analytical method is derived using combined features of HRV. The system also contains an actuator to stimulate the preemies to breathe, preventing sleep apnea or bradycardia. It can reduce the visiting frequency of a patient, and minor injuries/illness can be operated from a remote location. In addition to the hospitals, it can also be used in one's home.

5. Acknowledgment

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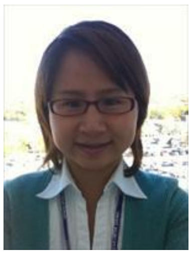

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Privacy-preserving Data Access Control in Smart Grid

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1. Introduction

Smart grid is regarded as the revolutionary and evolutionary generation of power grid, which integrates power system engineering with information and communication technologies. Due to bidirectional flows of energy and two-way communication of information, smart grid enables utilities to actively sense and monitor each interconnected elements in the power grid ranging from power generation, distribution and consumption, and respond to changes in power demand, supply, and costs in a close-loop way [1], [2]. On the other hand, smart grid also enables consumers to manage the energy use efficiently and conveniently [3].

Electrical consumption data collected from Remote Terminal Units (RTU) can be used to monitor the status of the power system, distribute electricity, predict future conditions and calculate costs. However, these data may not only contain sensitive information (e.g., home address, name, account information, etc.) but also reveal user's personal behaviors. For example, the real-time energy/appliance usage data may reveal personal activities at home like showering, cooking, sleeping, surfing the Internet, or even determine if anyone is home. Energy usage patterns over time can also determine the number of people in the household, work schedule, vocation, and other lifestyle habits. Sometimes, customers may employ third parties to assist them in better managing energy consumption by analyzing their energy usage data, which also provides the opportunity for those dishonest third parties to abuse or misuse smart grid data, e.g., theft of physical property, surveillance of residences or business. On the other hand, customers' home area networks (HANs) and/or building energy management (BEM) systems may also want to interact with the electric utilities as well as third-party energy services providers to access their own energy profiles, usage, pricing, etc. Thus, data access control becomes one of the most critical and challenging issues in smart grid.

In this letter, we investigate the data access control problem in smart grid. Specifically, we take the energy consumption data as an example and propose a cryptographic implementation for attribute-based access control in smart grid.

2. A cryptographic implementation of ABAC for energy consumption data

We propose a cryptographic implementation of Attribute-based Access Control (ABAC) for the access control of energy consumption data based on a multi-authority ciphertext-policy attribute-based encryption method [4].

A. Cloud-based energy consumption data control model

We consider the cloud-based energy consumption data control model, as shown in Figure 1, which usually consists of the following types of entities: customers (data owners), utility company, cloud servers, data users, and attribute authorities (AAs).

- **Customers.** Customers are the owners of the energy consumption data. As customers may not trust the utility company (or the cloud server) to control the access of their data, before sending the data to the cloud server, customer (data owner) defines an access policy over some attributes and encrypt the data under this access policy.
- **Utility company.** The utility company provides utility services for customers. Due to the large volume of energy consumption data, it may employ cloud servers to store and process the data.
- **Cloud server.** The cloud server stores the energy consumption data of customers and provide data access service to data users. However, the cloud server may curious about the data content and disclose the data to unauthorized users.
- **Data users.** Data users may be marketing operators, third-party analysts, researchers, etc. Each user may hold attributes from multiple attribute authorities. For each attribute, the user may receive a secret key associated with this attribute from the corresponding attribute authority. Users are dishonest in the sense that they may

collude to try to access unauthorized data, but they cannot collude with the cloud server or other adversaries.

- **Attribute authorities (AAs).** Each AA is responsible for managing attributes in its domain in the system. It assigns attributes to users according to its role or identity in its domain, and release public parameters that are used for data encryption. Each AA is fully trusted in the system and the channels between each AA and users are secure.

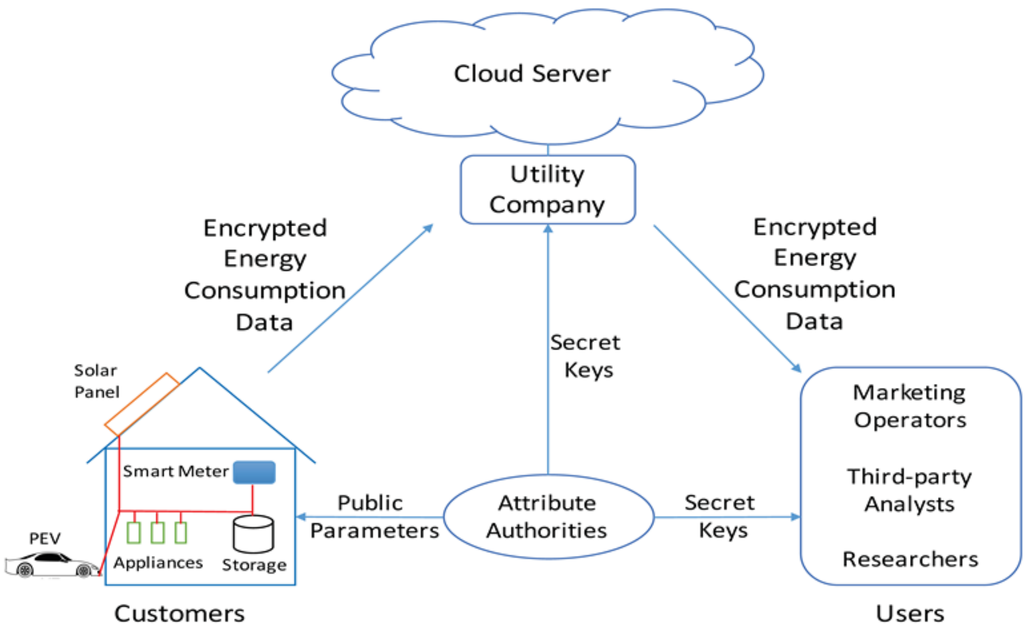

Fig. 1 System model of attribute-based access control for energy consumption data.

B. Definition of framework

We define the framework of energy consumption data access control (ECD-AC) scheme as

Definition 1 (ECD-AC). The energy consumption data access control (ECD-AC) scheme consists of the following algorithms:

- $\mathrm{GlobalSetup}(\lambda) \to \mathrm{PP}$. The global setup algorithm takes no input other than the implicit security parameter λ. It outputs the public parameters PP for the system.
- $\mathrm{AASetup}(\mathrm{PP}, aid) \to (\mathrm{SAK}_{aid}, \mathrm{PAK}_{aid})$. The AA setup algorithm is run by each AA with its identity aid. It takes the public parameters PP and the authority identity aid as inputs and outputs a pair of secret/public authority key $(\mathrm{SAK}_{aid}, \mathrm{PAK}_{aid})$ for this AA.
- $\mathrm{SkeyGen}(\mathrm{SAK}_{aid}, \mathrm{PP}, \mathrm{S}_{aid,uid}) \to \mathrm{SK}_{aid,uid}$. The secret key generation algorithm takes as inputs the secret authority key SAK_{aid}, the public parameters PP, and a set of attributes $\mathrm{S}_{aid,uid}$. It outputs a secret key $\mathrm{SK}_{aid,uid}$ for the user uid.
- $\mathrm{Encrypt}(m, \mathrm{PP}, \{\mathrm{PAK}_{aid}\}, \mathbb{A}) \to \mathrm{CT}$. The encryption algorithm takes as inputs the message m, the public parameters PP, a set of relevant public authority keys $\{\mathrm{PAK}_{aid}\}$, and an access policy $\mathbb{A}$. It outputs a ciphertext CT.
- $\mathrm{Decrypt}(\mathrm{CT}, \mathrm{A}, \{\mathrm{SK}_{aid,uid}\}) \to m$. The decryption algorithm takes as inputs the ciphertext CT, the access policy $\mathbb{A}$ and a set of secret keys SMK_{uid} corresponding to the access policy. It outputs the data m if the user's attributes satisfy the access policy. Otherwise, the decryption fails and outputs $\perp$.

C. Security analysis

Theorem 1. The ECD-CA scheme is indistinguishable secure against static corruption of authorities and chosen plaintext attacks under the generic bilinear group model [4] and random oracle model.

3. Summary and outlook

To summarize this chapter, we have investigated the system architecture of smart grid and abstracted some critical data security and privacy issues in smart grid. We have also reviewed some access control schemes in the literature and discussed the suitability to be adopted into smart grid. Taking the energy consumption data as an example, we have further proposed an energy consumption data access control (ECD-AC) scheme for smart grid, and provided the security analysis and performance evaluation.

There are still many research problems in the design of attribute-based access control schemes. For example, how to efficiently revoke the attribute when user's attributes have been changed? How to update the access control policies for those published data? Although many studies have been done in the data access control for cloud storage systems [5]–[7], how to apply these technologies for smart grid is still an opening problem. For example, in cloud storage system, people care more about the efficiency of data decryption; while in smart grid, the encryption efficiency is more interesting and significant, as smart meters or gateway in Home Area Networks (HANs) are not so powerful.

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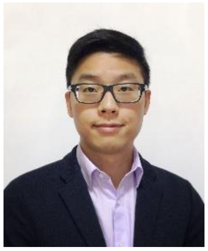

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Blockchain-based Distributed Data Management Systems towards Secure Transmission in Vehicular Networks

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1. Introduction

Recently, vehicles have been given increasing autonomy with the help of various sensing, communications, and data analysis techniques. Gathered by onboard sensors, both internal and external information about a vehicle can be sent to base stations or nearby vehicles through wireless channels [1] [2]. All these infrastructures and smart vehicles constitute the vehicular network, which has become an important scenario of the fifth generation (5G) mobile networks. Security is usually regarded as a vital issue in communication systems, especially for vehicular networks with an open and complex communication environment. Without effective security measures, attackers may eavesdrop and manipulate some sensitive data, which can eventually harm the security and efficiency of the network.

Several techniques have been utilized to improve the security of data transmission in vehicular network, such as identity authentication, data encryption, and trust management. All these techniques are based on the reliable management of some critical information, such as vehicle identities, public keys, and reputations. Traditionally, these data are managed in a centralized manner, which cannot always suit the decentralized vehicular network with high mobility and variability. Therefore, how to deliver and store the information in a distributed manner is still a problem needed to be solved urgently.

It is believed that Blockchain has the potential to cope with the above problems in vehicular network and eventually revolutionize the Internet of Things (IoT) as well [3] [4]. Known as one of the disruptive technologies in financial industry, Blockchain enables distributed nodes to trade with each other and maintain a tamper-proof ledger without a centralized bank.

In this paper, we firstly propose a generic framework of Blockchain-based distributed data management systems. Based on this framework, data can be spread and stored in vehicular networks safely and efficiently. Then two case studies are presented to validate the proposed framework, which illustrate that Blockchain can play a vital role in distributed reputation systems and public key infrastructures (PKI).

2. Framework of Blockchain-based distributed data management systems

Since the behaviors of a specific vehicle can hardly affect vehicles far away from it, the Blockchain only needs to store the data of nearby vehicles. All the neighboring vehicles travelling together consist the local vehicular network (LVN), which mainly contains the following types of entities, i.e., the ordinary node and the miner.

- **Ordinary node**
  Ordinary nodes make up the bulk of the LVN. Every vehicle joining into the LVN can be regarded as an ordinary node until it is elected as the miner. Ordinary nodes are able to broadcast messages to others and receive validated data packages (i.e., the blocks) from the miner.
- **Miner**
  Miner is elected from ordinary nodes through specific rules. It can be regarded as a temporary center node which is responsible for collecting messages from ordinary nodes, validating these messages, packing the messages into a block, and finally broadcasting the block to ordinary nodes.

Main procedures of the proposed Blockchain-based distributed data management framework include: 1) data collection; 2) data validation; 3) miner election; 4) block distribution.

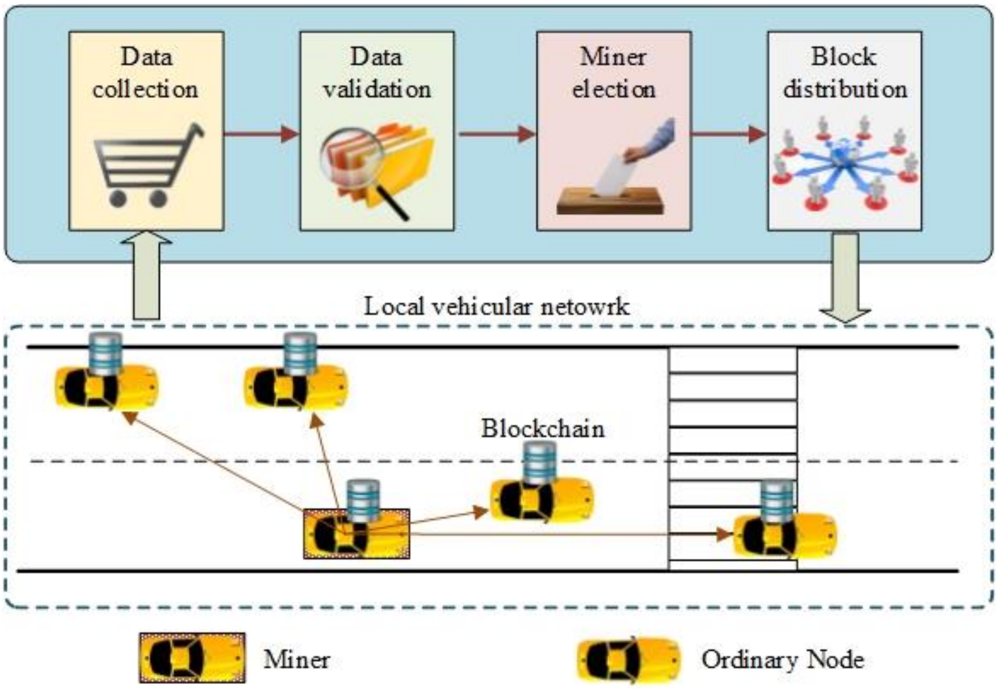

Fig. 1 Framework of Blockchain-based distributed data management systems.

- **Data collection**
  Since there are no stable center nodes for moving vehicles, every node needs to broadcast its own data and collect others' data simultaneously.
- **Data validation**
  The collected data are not always authentic and reliable with the existence of potential malicious attacks or transmission failures [5]. Therefore, each node needs to validate the gathered data in order to remove the invalid or fake messages. Obviously, the performance of data validation depends on the capacities of the node, e.g., the computing capacity, storage capacity, etc. As a result, nodes with different capacities may have different versions of the validated data.
- **Miner election**
  As is mentioned above, nodes with lower capacities cannot always validate the data well. For instance, a poor node may mistake fake messages for real ones due to the insufficient computing power and prior information. Therefore, a powerful node needs to be elected as the miner in order to help the poor with data validation. Several miner election schemes have already been proposed in recent Blockchain-based systems, e.g., the proof-of-work, proof-of-stake, and proof-of-capacity [6] [7], which take computing power, capital, and storage capacity as the election criteria, respectively. In general, miner election schemes need to follow the principles below:
  - **Uniqueness:** Only one miner is permitted in an LVN after each election.
  - **Randomness:** Every node in the LVN has the opportunity to become a miner. The phenomenon that a specific node being the miner for a long time needs to be avoided.
  - **Unfairness:** Nodes with high capacities tend to have more chances to become the miner compared with the poor ones, which ensures the good performance of the data validation.
- **Block distribution**
  The miner packs the validated data into a block and distributes it to all the other nodes. After receiving a block, nodes need to validate it and determine whether to accept it or not.

3. Case studies for Blockchain-based distributed data management systems

Based on the proposed framework, Blockchain can be utilized to store some important data, e.g., node reputations and public keys, for the sake of secure transmission. In order to provide a deep and detailed description about the Blockchain-based distributed data management systems, two case studies are presented as follows, i.e., the Blockchain-based reputation system and the Blockchain-based PKI.

3.1 Blockchain-based reputation system

Due to the openness of wireless channels, there may be some malicious nodes trying to disturb the interactions between honest vehicles and then benefit from it. For example, an attacker in vehicular ad-hoc networks (VANETs) may deliberately drop data packets from others instead of relaying them, which is usually called the Black hole attack [8]. Therefore, a reputation system is needed to measure the behaviors of nodes in vehicular networks. With the help of reputation systems, normal nodes can publish negative ratings of malicious nodes if being attacked and therefore, vehicles tend to behave more honestly in the network. However, traditional reputation systems usually work in a centralized manner, which cannot be directly applied in vehicular networks. So far, the effective sharing and storing of unmodified reputation information remains unsolved.

Thus, the use of Blockchain can provide a new way to tackle this problem. Every time when a node finishes an interaction with another node, it can broadcast a rating of this node to the network. In the meanwhile, each node is able to collect ratings from others and then calculate reputations of them. It should be noted that malicious nodes may publish fake ratings in order to attack honest nodes or promote the reputations of their partners. Thus, nodes need to validate the authenticity of the ratings after receiving them. As is mentioned in Section 2, nodes with poor capacities may not always filter fake ratings well. Therefore, a miner with good reputation and high capacity is elected to help ordinary nodes validate the data and remove malicious ratings from them. Finally, the miner adds the reputations of all nodes into the Blockchain which is open and tamper-resistant. Based on the reputation system, vehicles are able to choose more reliable partners for vehicle-to-vehicle communications or data relaying, which eventually improve the security of data transmission.

3.2 Blockchain-based PKI

In order to prevent malicious nodes from eavesdropping or manipulating the messages, asymmetric encryption techniques are usually utilized in vehicular communications. Each node has a pair of keys, i.e., the private key and public key, which are used to encrypt and decrypt messages. These techniques has to face the problem that how to verify the correspondence between the public key and the node identity. Usually, A PKI is used to cope with the above problem, which enables users to look up others' public keys based on identities. However, the centralized PKI cannot totally satisfy the demands of vehicular network and is also likely to suffer from single points of failure [9].

This problem can be alleviated significantly if the PKI is established on the Blockchain. When a vehicle joins into an LVN, it firstly publishes a registration message which contains an identity and a corresponding public key. Then the miner could add this message to the Blockchain. Hence, each node is able to verify or look up the public key of a given identity. For the sake of privacy protection, key pairs of a specific identity need to change at intervals, which is also easily achieved on the Blockchain. The vehicle just needs to publish an updating message containing the identity and a new public key, which is signed by the old private key. Records in the Blockchain are tamper-resistant to a great extent unless the malicious nodes have obtained most of capacities in this LVN. Therefore, the Blockchain-based PKI only requires that the majority of nodes are honest, instead of having to trust a third party.

4. Conclusion

In this paper, a framework of Blockchain-based distributed data management systems was proposed, in which data can be efficiently delivered and stored for decentralized vehicular networks. Based on the proposed framework, this article then presented two case studies in order to elaborate on potential benefits of Blockchain, which covered two important research fields of secure transmission, i.e., reputation systems and PKI. However, this paper only gives some preliminary hints for the applications of Blockchain in vehicular networks, which still needs a significant amount of solid work in following studies.

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