IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received August 3, 2017, accepted September 9, 2017, date of publication September 14, 2017, date of current version October 12, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2752208

INVITED PAPER

Centralized Light Access Network (C-LiAN): A Novel Paradigm for Next Generation Indoor VLC Networks

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This work was supported by the Turkish Scientific and Research Council under Grant 215E311.

ABSTRACT Visible light communication (VLC) builds upon the idea of using existing lighting infrastructure for wireless data transmission. In a conventional VLC network, each light fixture acts as an access point (AP) which are connected to each other through electrical grid as well as data backbone. These VLC-enabled fixtures consist baseband unit (BBU) followed by the optical front-end (OFE). In this paper, we propose the so-called centralized light access network (C-LiAN) which aggregates all AP computational resources into a central pool that is managed by a centralized controller. Unlike the distributed architecture where each light fixture performs both baseband processing and optical transmission/reception, the centralized architecture employs ''dummy'' fixtures with a VLC OFE. Moving the baseband processing to a central pool reduces the associated cost and complexity of each VLC-enabled LED luminary. It further enables joint processing of signals from different APs making possible an efficient implementation of joint processing, offloading, handover, interference management, scheduling, and resource management algorithms. As an example to demonstrate the virtues of C-LiAN, we further present the performance of coordinated multi-point transmission and enhanced inter-cell interference coordination with almost blank subframe techniques originally proposed for Long Term Evolution-Advanced in the context of indoor VLC networks.

INDEX TERMS Centralized light access networks, visible light communication, interference management.

I. INTRODUCTION

The demand for high-speed and ubiquitous broadband wireless access has spurred an immense growth in mobile data traffic [1]. The increasing number of mobile devices in different form factors and capabilities combined with the worldwide adoption of social media and advanced multimedia applications are the primary contributors to this growth. The design of future wireless communication networks that cope with the ever growing mobile data traffic as well as support varied and sophisticated services and applications in vertical sectors is recognized as a major technical challenge that wireless engineers face today.

To address the needs of future wireless networks, various solutions are currently being discussed and proposed [2]. One particular solution is network densification that allows the same spectrum to be spatially reused. While densification through the use of small cells brings significant capacity, interference eventually imposes a fundamental limit. Through advances in physical layer (PHY) design, such as massive multiple-input multiple-output (MIMO) techniques, some improvements in spectral efficiency are also possible. Regardless of the efficacy of network densification and potential spectral efficiency gains, much more bandwidth is required to cope with the predicted data traffic growth. This can be achieved by moving up to higher carrier frequencies. Current wireless access systems (cellular, WiFi) mostly work in the radio-frequency (RF) band below 6 GHz, often called ''beachfront spectrum''. However, this spectral band is almost fully occupied and heavily regulated. In an effort to yield more bandwidth, ongoing research efforts focus on the upper segments of the RF band with a particular emphasis on millimeter frequencies.

A more radical approach to overcome spectrum congestion is exploring the deployment of the optical band, in particular the visible light frequency band (390 − 700 nm). Visible light communication (VLC), also referred as LiFi [3], [4], systems are based on the principle of modulating light emitting diodes (LEDs) without any adverse effects on the human eye and illumination levels. LEDs are increasingly used both indoors, e.g., home and office lighting, etc., and outdoors, e.g., street lights, traffic lights, vehicle front/rear lights, etc. The idea of using existing lighting infrastructure for data transmission is a revolutionary solution and has the potential to open a new era in wireless communications.

Data transmission speeds on the order of gigabits per second have been already demonstrated in laboratory environments by various VLC research groups [5]–[7]. In addition to high speed, area spectral efficiency is significantly improved in VLC systems due to dense deployment of light fixtures. Therefore, VLC is considered as a powerful alternative and/or complement to existing RF-based wireless access technologies particularly in user-dense environments. In addition, the fact that light is non-penetrative to opaque objects such as walls enables the establishment of secure wireless links via VLC. Furthermore, in RF-sensitive facilities such as hospital and mining, VLC can provide safe data access where RF may not be allowed.

With advantageous features and a wide range of potential application areas, VLC has been enjoying a growing attention. According to a recent report by Global Market Insights, Inc. [8], VLC market size is anticipated to reach 75 billion USD by 2023. In line with such an economic potential, the international standardization works have been initiated both by IEEE and ITU, see IEEE 802.15.13 Task Group [9], IEEE 802.11 Light Communication Topic Interest Group [10] and ITU − TG.vlc [11]. In parallel, first generation of VLC products from a number of start-up companies [12]–[14] are already available.

In a conventional VLC network, each light fixture acts as an access point (AP) which are connected to each other through electrical grid as well as data backbone networks. These VLC-enabled fixtures consist baseband unit (BBU) followed by the optical front-end (OFE). In the downlink, the message signal is first modulated at the baseband and then imposed as an AC signal on the DC signal that drives the LED. In the uplink, the received optical signal is first converted into electrical signal through a photodetector and then the baseband processing takes place. In this paper, we propose a centralized architecture that we name as "C-LiAN" which aggregates all AP computational resources (e.g. BBUs) into a central pool that is managed by a centralized controller. Unlike the distributed architecture where each light fixture performs both baseband processing and optical transmission/reception, the centralized architecture employs "dummy" fixtures with a VLC OFE. Inspired by Cloud Radio Access Network (C-RAN) proposed by telecom operators for cellular networks [15], [16], C-LiAN features centralized processing and collaborative signal transmission. In the proposed architecture, moving the baseband processing to a central pool reduces the associated cost and complexity of each VLC-enabled LED luminary. It further enables joint processing of signals from different APs making possible to leverage coordinated transmission techniques as well as enhanced handover management. Load balancing and scalability can be well achieved through the availability of such a central controller, thus yielding more efficient resource management.

The rest of the paper is as follows: In Section II, we present the proposed C-LiAN architecture highlighting the differences from the conventional distributed architecture. In Section III, as an example to demonstrate the virtues of C-LiAN, we discuss multi-cell cooperation processing and provide simulation results on the achievable data rates. In Section IV, we provide our concluding remarks and discuss potential challenges in practical deployment.

II. CENTRALIZED LIGHT ACCESS NETWORK ARCHITECTURE

In this section, we define the proposed C-LiAN architecture highlighting the differences from the conventional distributed architecture. Schematic diagrams for distributed and centralized networks are respectively provided in Fig. 1a and Fig. 1b.

In an indoor VLC network, each light fixture is used as an AP to serve multiple users. This is sometimes referred to as attocells in the literature and handover is also supported among attocells to support mobility of the user [3]. In a conventional distributed network, each light fixture is retrofitted to enable VLC capabilities, see e.g., [17]. Such light fixtures include both BBU and OFE (see Fig. 2). BBU handles PHY and higher layer functionalities such as modulation/demodulation, coding/decoding, medium access control etc. In a typical downlink chain, the output of BBU interfaces to the OFE through a digital-to-analog (DAC) converter. The resulting analog electrical signal is imposed as an AC signal through a bias-tee on the top of the DC signal that drives the LED. In the uplink chain, the OFE includes lens/filter followed by a photodetector. The photodetector converts the optical signal into electrical form. This is followed by signal conditioning and analog-to-digital converter (ADC). The output of ADC then feeds the BBU. For a VLC network, a data backbone is required that can take the form of coaxial or fiber optic based on the available infrastructure. Power-over-Ethernet (PoE) can be also used to feed both power and data. Alternatively, power line communication can be used to take advantage of the existing electrical grid for data transmission. The backbone is connected to a Home Gateway (HG). This unit forwards Internet Protocol (IP) packets from IP backhaul to the VLC backbone. It is also responsible of multiplexing/demultiplexing the packets for each AP.

In the proposed C-LiAN architecture, BBUs are removed from light fixtures and all signal processing takes place at the central unit (CU) which might be, for example, embedded in the HG. Hence, a VLC AP becomes a lighter device which employs only the OFE. The baseband transmission between the CU and APs is carried over the data backbone

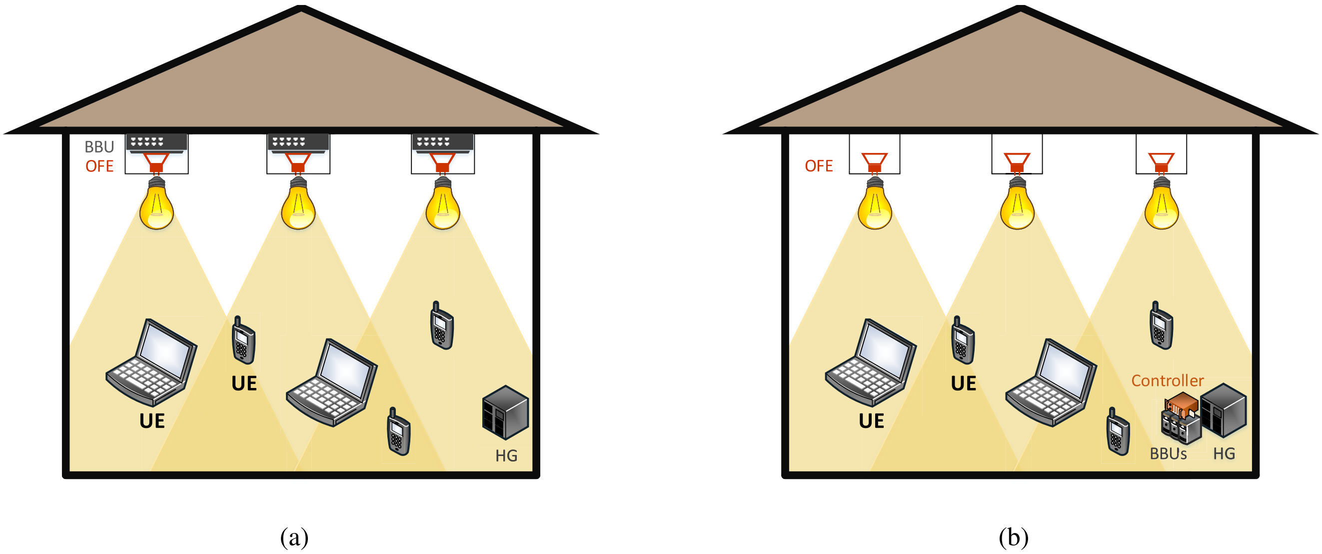

FIGURE 1. (a) Conventional distributed network architecture, (b) Proposed C-LiAN architecture.

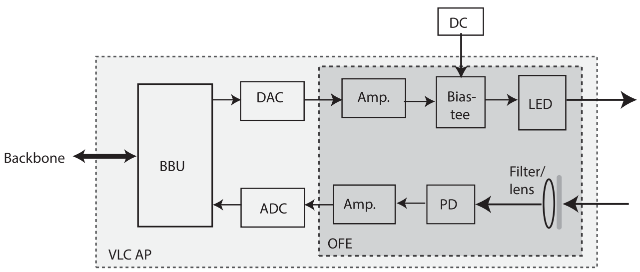

FIGURE 2. A VLC-enabled light fixture.

that is already required for any VLC network. To handle the streams generated from different APs properly, user data, control data and synchronization information should be multiplexed.

Such a centralized architecture is appealing particularly for the upcoming IEEE standard on VLC [18] where advanced PHY techniques such as various variants of optical orthogonal frequency division multiplexing (O-OFDM), MIMO communications and adaptive transmission are considered. These PHY techniques obviously bring additional processing complexity over simple pulse modulation techniques that were initially considered for VLC systems. In the C-LiAN architecture, the individual BBUs for each AP are aggregated and virtualized in BBU pools. In BBU pools, a common BBU platform managed by a centralized controller can be shared among APs which will decrease signal processing and associated power consumption for the APs with low or no traffic load. The CU can use multi-threading techniques on a general purpose processor platform in order to implement virtual BBU pools. Furthermore, to improve energy efficiency and improve the computation speed, the CU can be assisted with hardware accelerators optimized for specific operations such as fast Fourier transform (FFT), MIMO, etc.

The fact that a data backbone is already required to feed data to the light fixtures makes the proposed centralized approach a natural solution for VLC networks and brings important advantages. First of all, separating BBUs from APs and moving them to a CU will make the VLC-enabled LEDs cheaper and smaller in size than those in the distributed approach. This is particularly important for the market penetration of a new wireless access technology. Second, in the C-LiAN, since the BBUs are placed close to each other (either physically or virtually), they can easily share the channel state information (CSI), reference signal received power (RSRP), and reference signal received quality (RSRQ) for user equipment (UE) in the network, traffic load and other signalling information. This would lead to easier and more efficient implementation of joint processing, offloading, handover, interference management, scheduling and resource management algorithms to enhance the capacity of VLC networks. As an example to demonstrate the virtues of C-LiAN, we discuss coordinated transmission techniques in the next section.

III. MULTI-CELL COOPERATION PROCESSING IN C-LiAN

An indoor room environment typically includes more than one ceiling light and several other secondary light sources (desk light, task light etc.). Each of these fixtures can act as a VLC AP. The dense distribution of VLC APs improves the signal quality at the receivers due to the reduced distance between the receivers and APs. However, since all the ceiling and secondary light sources operate in the same frequency, the frequency reuse becomes one and users may suffer from interference from neighbouring APs.

In RF cellular networks, several solutions have already been proposed in order to mitigate the impact of interference. For instance, *Coordinated Multipoint (CoMP) transmission* *and reception* [19] was introduced by the Third Generation Partnership Project (3GPP) in order to increase signal-to-interference-plus-noise ratio (SINR) levels of the users located at the cell edges. Based on RSRP and RSRQ levels of UEs, cells serve the UEs in a coordinated manner, hence, the interference caused by intra-frequency adjacent neighbour cells is reduced.

Enhanced Inter-cell interference coordination (eICIC) with almost blank subframe (ABSF) [20] is another solution that increases the total number of users connected to small cells with nearly zero interference. eICIC is part of Heterogeneous Network (HetNet) architecture in Long Term Evolution Advanced (LTE-A) systems where there are small cells served by low power base stations inside the wide coverage of macro base station. eICIC improves the system spectral efficiency by optimally orchestrating the activities of macrocell base stations and performing time-slot basis scheduling. A signal offset denoted as *cell range extension (CRE)* is added to the received signal level measured from small cells. Hence, more UEs can be connected to these cells. Then, interference caused by macrocells is compensated with the use of ABSF in which macro cells almost mute their transmissions to reduce interference on users associated with the small cell through CRE.

In the context of VLC, our proposed C-LiAN architecture allows CoMP and eICIC techniques to mitigate the interference in the environment. In order to demonstrate the superiority of centralized approach in VLC networks over distributed approach, we consider two different indoor scenarios (see Fig. 3). In Scenario I, there are four APs on the ceiling and constitute four different cells. In this scenario, we utilize CoMP with C-LiAN to increase the spectral efficiency. In Scenario II, there are five APs; one ceiling light and four desk lights located on the top of four tables at each corner of the room. In the second scenario, the smaller coverage areas of the desk lights stay inside the wider coverage area of the ceiling light which constitutes an architecture similar to the HetNets. The room dimensions are 5 m × 5 m × 3 m and same for both scenarios. In both scenarios, UEs with the height of 0.8 m are assumed to be uniformly distributed inside the room. The coordinates of APs are provided in Table 1. The origin (0, 0, 0) is taken as the centre of ground.

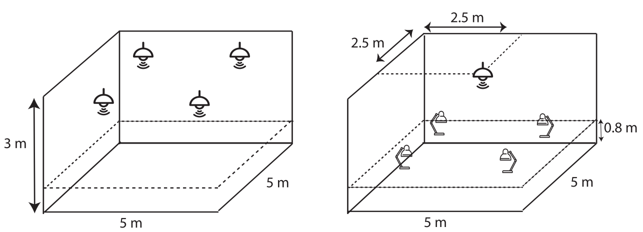

FIGURE 3. The room configurations for Scenario I (a) and II (b).

PHY of our system model builds upon direct current biased O-OFDM (DCO-OFDM) [21] which was adopted as the mandatory PHY mode in IEEE 802.15.13. In DCO-OFDM, in order to satisfy the intensity modulation / direct detection (IM/DD) requirements, only half of the available subcarriers (resource elements) can be used for data transmission. We assume that the resource elements are allocated to UEs through Round Robin scheduler which shares the resources fairly assuming same quality-of-service (QoS) class identifier level for each UE.

TABLE 1. Coordinates of the light sources in Scenario I and Scenario II.

Scenario I	
Transmitter	**Location**
1^{st} ceiling light	$(-1.00, -1.00, +3.00)$
2^{nd} ceiling light	$(-1.00, +1.00, +3.00)$
3^{rd} ceiling light	$(+1.00, -1.00, +3.00)$
4^{th} ceiling light	$(+1.00, -1.00, +3.00)$
Scenario II	
Transmitter	**Location**
ceiling light	$(+0.00, +0.00, +3.00)$
1^{st} desk light	$(+1.25, +1.25, +1.50)$
2^{nd} desk light	$(-1.25, -1.25, +1.50)$
3^{rd} desk light	$(+1.25, -1.25, +1.50)$
4^{th} desk light	$(-1.25, +1.25, +1.50)$

We assume line-of-sight (LoS) propagation where the channel gain between the i^{th} AP ($i \in 1, \ldots L$ where $L = 4$ for Scenario I and $L = 5$ for Scenario II) and the j^{th} UE, $j \in 1, \ldots U$ can be calculated as [22]

$$h_{i,j} = \begin{cases} \frac{(k+1)A}{2\pi d_{i,j}^2} \cos^k\left(\phi_{i,j}\right)\cos\left(\psi_{i,j}\right), & 0 \le \psi_{i,j} \le \Psi_{\frac{1}{2}} \\ 0, & \psi_{i,j} \ge \Psi_{\frac{1}{2}}, \end{cases} \quad (1)$$

where $k = -\ln(2)/\ln\left(\cos\left(\Phi_{\frac{1}{2}}\right)\right)$, $\Phi_{\frac{1}{2}}$ is the transmitter semiangle, $\Psi_{\frac{1}{2}}$ is field-of-view (FOV) semiangle of receiver, A is the detector area of the receiver, $\phi_{i,j}$ is the angle of emergence with respect to transmitter axis, $\psi_{i,j}$ is the angle of incidence with respect to receiver axis, and $d_{i,j}$ is the distance between the i^{th} AP and j^{th} UE.

Based on the channel gain between the i^{th} AP and the j^{th} UE provided in (1), SINR for the j^{th} UE can be written as

$$\mathrm{SINR}_j = \frac{R^2 \sum_{i \in S} P_i \left|h_{i,j}\right|^2}{R^2 \sum_{i \in I} P_i \left|h_{i,j}\right|^2 + N_0 B}, \quad (2)$$

where R is the optical-to-electrical (O/E) conversion coefficient, N_0 is noise power spectral density (PSD) and B is system bandwidth, and P_i is the power level of i^{th} AP. In (2), S denotes the set of APs which serve the j^{th} UE and I denotes the set of APs which do not serve the j^{th} UE.

In a conventional distributed network, a UE is generally served by the i^{th} AP that has the strongest downlink RSRP, i.e.,

$$i = \underset{v \in \Omega}{\operatorname{argmax}} \left[\mathrm{RSRP}_v\right] \quad (3)$$

where Ω includes the APs in S and I. However, in the proposed centralized access network, SINR for the UEs can be increased by proper selection of the serving APs with CoMP

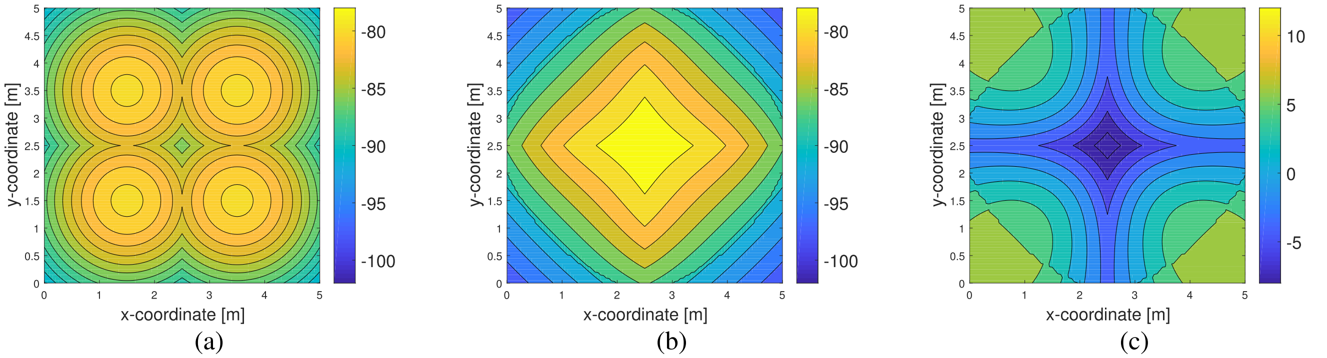

FIGURE 4. **(a) Received signal level [dBm], (b) interference level [dBm] and (c) resulting SINR [dB] without CoMP transmission.**

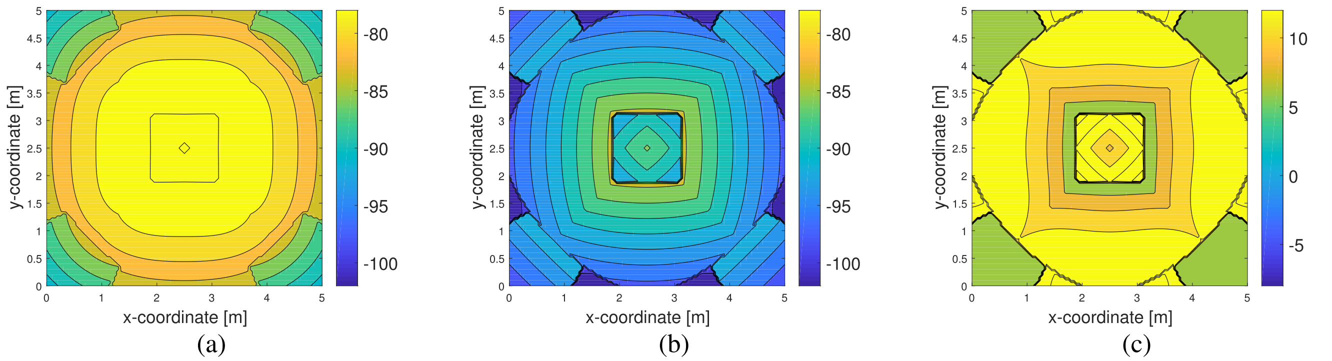

FIGURE 5. **(a) Received signal level [dBm], (b) interference level [dBm] and (c) resulting SINR [dB] with CoMP transmission.**

transmission and reception mechanism that is managed by the centralized controller running in the CU. In the CoMP, for instance, a UE can receive or transmit data through multiple APs. In selection of serving APs, each UE first reports the received signal levels from all APs to CU, then using (2), CU determines the serving set with the least number of APs for each UE that satisfies predefined SINR target.

eICIC, on the other hand, is usually applicable for the networks that are comprised of different size cells (e.g., desk light and ceiling light of Scenario II). In such networks, the large difference between the transmit power levels of the available APs causes load imbalance. In order to balance active UE number on desk and ceiling lights, the UEs are connected to the i^{th} AP based on the following decision criteria

$$i = \underset{v\in\Omega}{\operatorname{argmax}} \left[\mathrm{RSRP}_v + \mathrm{CRE}_v\right], \tag{4}$$

where CRE is equal to 0 for ceiling lights. However, CRE leads higher interference level for the UEs connected to desk light through this offset value, thereby, the critical point is to determine the ABSFs where these type UEs are served by desk lights and ceiling lights only transmit their control signals. Specifically, the centralized controller decides the number of UEs which are served by ceiling light, desk light and desk light through CRE then, select ABSFs in order to maximize the system throughput.

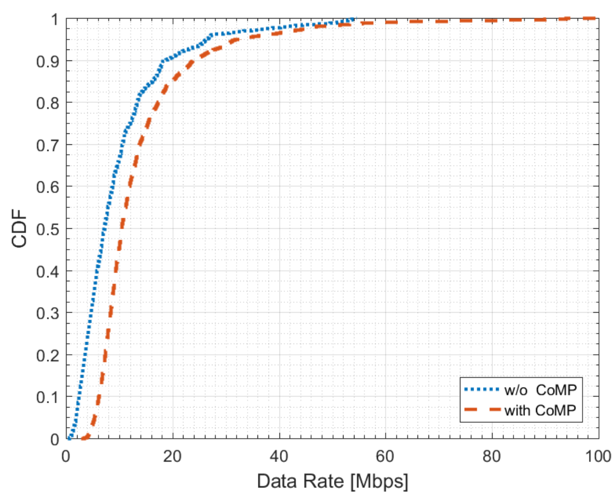

FIGURE 6. **CDF of achievable data rate with and without CoMP transmission and reception mechanism.**

Based on Shannon capacity formula, the achievable data rate (C) for the j^{th} UE can be written as

$$C_j = B_j \log_2\left(1 + \mathrm{SINR}_j\right) \;[\mathrm{bps}], \tag{5}$$

where B_j is allocated bandwidth to j^{th} UE. Numerical values for system and channel parameters are provided in Table 2.

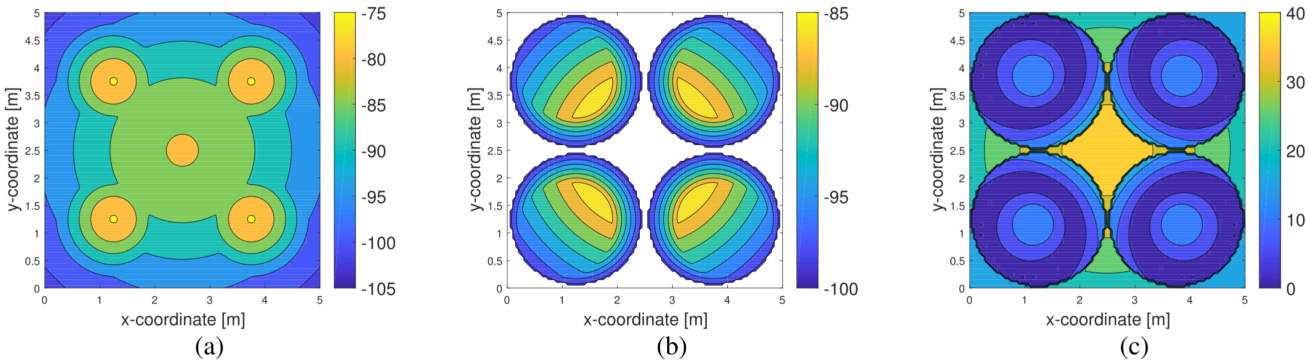

FIGURE 7. (a) Received signal level [dBm], (b) interference level [dBm] and (c) resulting SINR [dB] without eICIC.

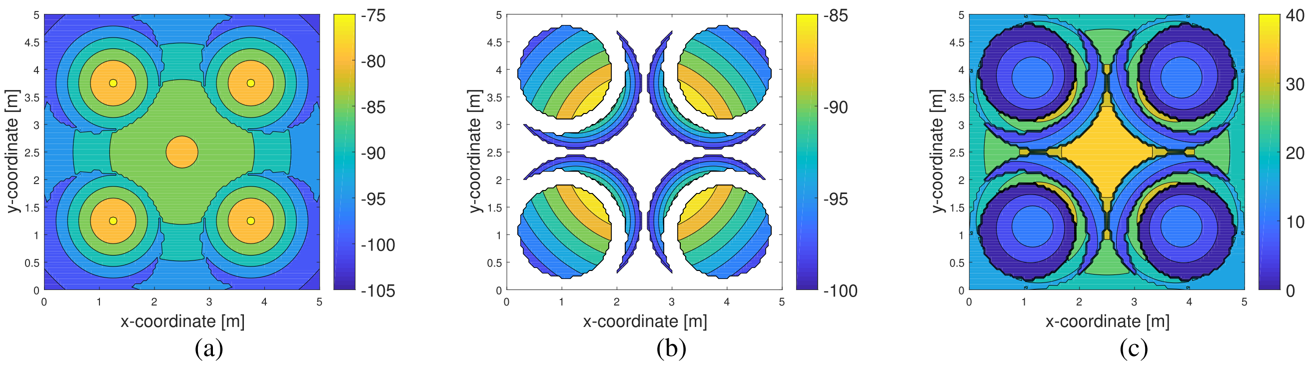

FIGURE 8. (a) Received signal level [dBm], (b) interference level [dBm] and (c) resulting SINR [dB] with eICIC at CRE of 6 dB.

TABLE 2. Simulation parameters.

Parameter	Value
Noise PSD (N_0)	10^{-22} W/Hz [23]
Average Electrical Signal Power (P)	35 dBm (ceiling light)
	20 dBm (desk light)
System Bandwidth (B)	20 MHz
FFT size	256
O/E Conversion Coefficient (R)	0.28 A/W [23]
Detector area of the receiver (A)	1 cm^2 [24]
Transmitter semiangle ($\Phi_{\frac{1}{2}}$)	60^o [23]
FOV semiangle of receiver ($\Psi_{\frac{1}{2}}$)	60^o

In the following, we first demonstrate the C-LiAN with CoMP for Scenario I and then with eICIC for Scenario II.

For Scenario I, Figs. 4 and 5 show the distribution of received useful signal level, interference level from neighbouring APs, and corresponding SINR values inside the room for distributed and centralized approaches respectively. When the APs operate in a distributed manner (i.e., no coordination among the APs), maximum received signal power within the room is -79.7 dBm and this power level is achieved by the UEs that are right below the APs (see Fig. 4a). At these points, total interference caused by the other three APs is -82.29 dBm (see Fig. 4b) and this yields 2.59 dB SINR level (see Fig. 4c). In C-LiAN with CoMP feature (see Fig. 5), where UEs are served by multiple APs in a coordinated manner, the received signal power at these points becomes -77.42 dBm (a gain of 2.28 dB) and interference level decreases to -86.79 dBm (a gain of 4.5 dB) which corresponds to 9.36 dB SINR level.

In Fig. 6, we present the cumulative density function (CDF) of achievable data rate per UE with and without CoMP technique. The analysis is carried out using Monte Carlo simulations by averaging 10^6 different realizations of UE distribution in the room. In each realization, a random number of UEs, uniformly distributed distributed between 1 and 20 is chosen. It is observed that the data rate values lower than 13.4 Mbps can be achieved with a probability of 0.8 in distributed manner and the mean achievable data rate is equal to 9.7 Mbps. When C-LiAN is implemented with CoMP, the achievable data rate is increased to 17.4 Mbps for the same probability of 0.8 and the mean value becomes 13.7 Mbps.

In Scenario II, we demonstrate serving area extension and throughput improvement for low power APs (desk lights). In the analysis, ABSF ratio is determined through brute force search in order to maximize the achievable data rate. Similar to Scenario I, we first provide the received signal, interference and corresponding SINR levels for distributed approach (without eICIC) in Fig. 7, then present the same results for C-LiAN with eICIC for CRE of 6 dB and 9 dB in Figs. 8 and 9, respectively. As seen in Fig. 7, the maximum received signal power level obtained from the ceiling light is -79.7 dBm as in Scenario I for distributed approach (CRE of 0 dB). For the users connected to desk lights, this level is -74.8 dBm

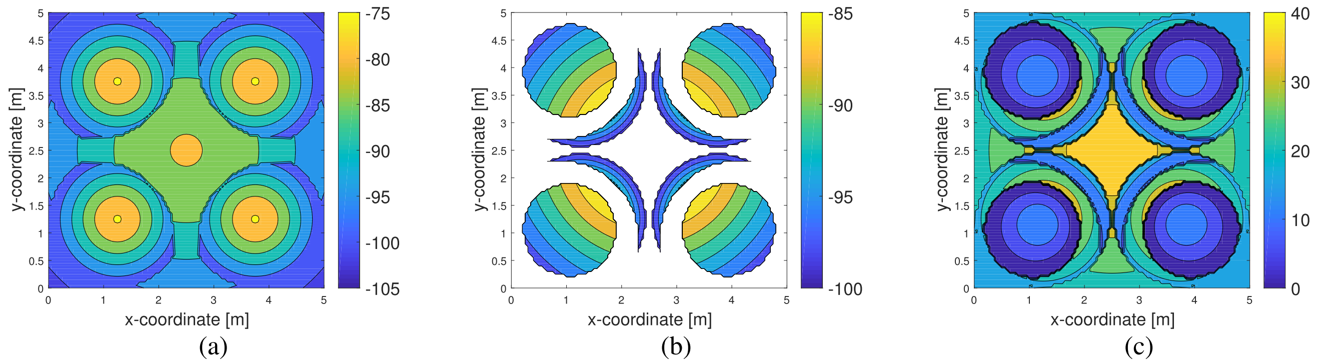

FIGURE 9. (a) Received signal level [dBm], (b) interference level [dBm] and (c) resulting SINR [dB] with eICIC at CRE of 9 dB.

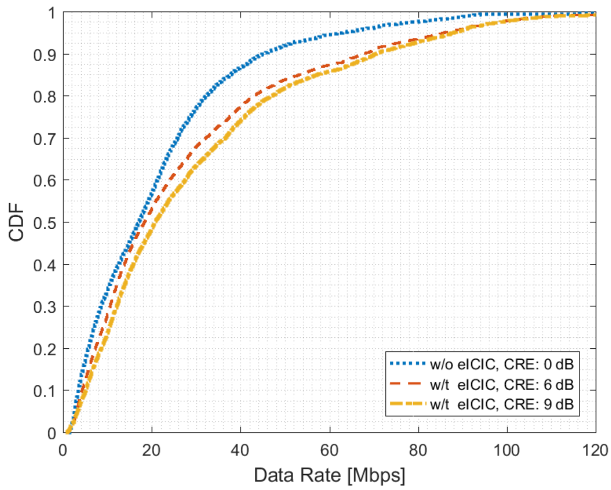

FIGURE 10. CDF of achievable data rate with and without eICIC.

due to less attenuation as a consequence of shorter distance between the AP and UE. The interference level for these locations ((1.25, 1.25, 0.80), (−1.25, 1.25, 0.80), (1.25, −1.25, 0.80), (−1.25, −1.25, 0.80)) served by the desk lights is −88.35 dBm and corresponding SINR becomes 13.54 dB. On the other hand, interference from the desk lights are low at the centre of the room due to the limited FOV, for instance SINR is the highest at 37.29 dB at (0.00, 0.00, 0.80). In centralized case (see Figs. 8 and 9) where eICIC is deployed between ceiling light and desk lights, serving area of each desk light can be increased using an offset value which reduces received signal level, however, interference levels do decrease as well. The advantage here is almost zero interference that compensates the reduced received power for the users which are now connected to desk light with the use of CRE.

In Fig. 10, we present the CDF of achievable data rate per UE with and without eICIC technique. The results reveal that as CRE increases, the achievable data rate increases as well. The mean of the achievable data rate in the distributed case is 21.8 Mbps. For C-LiAN with eICIC, this is increased to 27.8 Mbps and 30 Mbps with the use of 6 dB and 9 dB CRE, respectively. It is also observed that the data rate within the room is less than 32.2 Mbps with a probability of 0.8 in distributed case. On the other hand, at the same probability level, this is increased to 42.9 Mbps and 47.1 Mbps with C-LiAN using CRE of 6 dB and 9 dB, respectively.

IV. CONCLUSIONS AND OPEN RESEARCH TOPICS

In this paper, we have proposed the concept of a centralized network architecture for indoor VLC networks which moves the baseband processing to a central pool and aggregates all AP computational resources into a central pool. Such an approach reduces the associated cost and complexity of each VLC-enabled LED luminary and also allows an efficient implementation of multi-cell signal processing to handle interference from neighbouring cells. Our investigations on CoMP and eICIC techniques originally proposed for LTE-A in the context of indoor VLC networks have demonstrated significant improvements over conventional architectures.

While C-LiAN promises significant advantages over conventional distributed networks, its practical implementation brings some challenges that need to be properly addressed. First of all, the network backbone needs to have sufficiently high capacity to carry OFE input/output and low latency to enable multi-cell processing. Some compression techniques can be applied to adaptively overcome the capacity constraints if required [25]. Another concern is the reliability of BBUs located within the CU. In case of failure of any BBU in the CU, there must be flexible switching mechanism through which baseband signal from any AP can be processed by any other BBU. Third, in case of virtualization of BBUs on a common platform, real-time processing algorithm implementation, virtualization of the baseband processing pool, and dynamic cell loading should be properly handled. In addition, when hardware accelerators are employed, high speed interface is required between the accelerators and the BBU pools.

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