Integration of Visible Light Communication and Positioning within 5G Networks for Internet of Things

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Abstract

With the widespread deployment of internet of things (IoT), more and more devices are involved in wireless networks, and the fifth generation (5G) network requires to support the massive connectivity and diverse services for the huge number of IoT devices. Visible light communications (VLC) and visible light positioning (VLP) are two promising supplementary technologies to assist 5G networks to support the massive connectivity, high reliability, high data rate, high positioning accuracy, low latency, low power consumption and improved security of IoT. Hence, this article presents a multi-layer network architecture by integrating VLC and VLP within 5G networks, in order to support the above mentioned diverse requirements of IoT devices. In the multi-layer network, the macrocell and picocell layers support better coverage and reliability via the radio frequency (RF) spectrum, while the optical attocell layer provides the high-speed transmission and high-accuracy positioning services operating at the visible light spectrum. We then briefly describe some key technologies for the performance improvement of the multi-layer network, including energy harvesting, modulation and multiple access schemes. Furthermore, an exemplary case study and simulation analysis are provided to demonstrate the advantage and significance of the presented multi-layer network for IoT. Finally, we point out some future research directions.

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I. INTRODUCTION

With the widespread development of the wireless communication technologies and internet of things (IoT), more and more devices are involved in IoT, and the fifth generation (5G) wireless network needs to support various communication connectivity and diverse services of the massive number of IoT devices [1], [2]. Pervasive IoT will require the massive connectivity, high reliability, high data rate, high positioning accuracy, low latency, low power consumption and improved security. In this case, it is not easy for current radio frequency (RF)-based wireless networks to support the massive connectivity due to limited RF spectrum, guarantee the high-accuracy positioning because of the severe multipath reflections, and satisfy colorful requirements of IoT devices [3].

Visible light communications (VLC), also known as Li-Fi, has been identified as a promising candidate technology for 5G networks to address these challenges [3]. While RF-based wireless networks can support the seamless coverage and reliability for devices in outdoor environments, VLC is capable of serving devices in indoor environments because of the following main advantages [3]: 1) low cost due to the use of the existing lighting infrastructure; 2) high-speed transmission with the abundant license-free visible light spectrum; 3) guaranteeing communication security, since visible light signals cannot penetrate walls; 4) offering high-accuracy localization visa visible light positioning (VLP) for object tracking and navigation; 5) no interference between RF communications due to the different spectrum, and it cannot generate the electromagnetic interference so VLC can be employed in electromagnetic interference-sensitive scenarios; 6) energy harvesting from visible light for power-constrained devices to extend their battery life.

Thanks to the above benefits of VLC, densely deployed light emitting diodes (LEDs) points can be employed into access points (APs) to support the high density of indoor IoT devices and satisfy the diverse services, since many studies have reported that wireless devices will spend about 80% of their time indoors [4]. Compared with existing low-accuracy and high-cost indoor RF-based positioning systems, VLP can achieve sub-meter positioning accuracy level and even centimeter level accuracy in some cases [5]. Nevertheless, VLC-only systems have some key challenges, such as lack of uplink support, susceptibility to line-of-sight (LoS) blocking and small coverage area. However, the challenges can be solved by combining RF into VLC, where the co-deployment of RF and VLC architecture has the ability to addressed these shortcomings and highlight their advantages [6], [7].

The use of VLC and VLP for IoT has been investigated recently to enhance both communication and positioning performance. The literature [8] proposed light energy harvesting models, where energy transmitted from light signals can be harvested at receivers over VLC downlinks and the harvested energy is then employed to support data transmissions over RF links. The heterogeneous RF/VLC network architecture was proposed to support better services for devices [3], [5]-[7], [9], where VLC network provide high data rate and RF network support wide-area coverage. In addition, Zhuang *et al.* in [10] experimentally demonstrated the proposed positioning approach by adopting the received signal strength (RSS) algorithm for indoor devices with low positioning error. Moreover, a new visible light positioning technique is presented to perform the high positioning accuracy with the low power consumption at IoT devices [11]-[13].

In this article, we provides a comprehensive analysis of integrating VLC and VLP within 5G networks for IoT devices, describing how the multi-layer network is suited to guarantee the diverse IoT requirements. The colorful services of IoT devices and the challenges in support of IoT are first discussed in Section II. Section III presents a multi-layer network architecture by integrating VLC and VLP within 5G networks, in order to support the massive connectivity and diverse of IoT devices. In Section IV, we outline some key technologies employed in the multi-layer network to improve the IoT performance, including energy harvesting, modulation and multiple access schemes. Section V provides exemplary case study and evaluates the performance improvement accordingly. Finally, the conclusion of this article and future research directions are presented in Section VI.

II. CHALLENGES IN SUPPORT OF IOT

As the massive number of IoT devices are involved in wireless networks, 5G wireless networks will support various connectivity and diverse services of IoT devices [2]. This section describes the main types of IoT devices and analyzes the challenges in support of IoT.

In wireless networks, different IoT devices have different service requirements, traffic characteristics and resource constraints. Generally, these IoT devices can be classified into the following five groups based on their required services [1], [2], as illustrated by Table I.

TABLE I
TYPES OF IOT DEVICES

Types of IoT devices	**Service characteristics**	**Applications**
Massive IoT	Delay-tolerant and low data rates, but energy-constraint.	Smart city, smart grid, and smart home.
URLLC-IoT	Needs strict low latency, high reliability and stable connectivity, but with low date rates.	Industrial automation, emergency response, and real-time control.
HAP-IoT	Requires high-accuracy positioning and real-time tracking services.	Shopping mall localization and robot navigation.
HSR-IoT	Needs high data rates, even has latency constraints.	Video surveillance, software downloading, and webpage surfing.
S-IoT	Requires communication security and privacy protection.	Industrial manufacturing and automatic payment.

- Massive IoT: This class of IoT refers to serve a large number of low-cost, long range and low-energy consumption devices. They are less latency sensitive and require relatively low data rates, e.g., smart home, smart grid, smart city, and smart industry.
- IoT with ultra-reliable and low latency communications (URLLC-IoT): This kind of IoT devices have strict low latency, high reliability and stable connectivity requirements, but do not need the high date rates, e.g., industrial automation, emergency response and real-time control.
- IoT with high-accuracy positioning (HAP-IoT): These IoT devices require the high positioning accuracy, and they are used for indoor tracking and navigation.

- IoT with high-speed data rates (HSR-IoT): These devices have the high data rate requirements but are less interested in the strict latency constraints, e.g., video surveillance, software downloading, and webpage surfing.
- IoT with security (S-IoT): This class of IoT devices requires high communication security. Examples of devices are those envisioned for industrial manufacturing and automatic payment.

The challenges to support the above mentioned different types of IoT devices for the 5G network can be summarized as follows in detail.

- High-speed data rate challenge: For future communication, many work have reported that wireless devices will spend about 80% of their time indoors and 20% of their time outdoors [4]. The demands for the high-speed data transmission to support the various application services of devices, things and machines in both indoor and outdoor environments are rapidly ever growing, such as various Internet access, video/voice conferencing, high-definition television, and so on. Even though the millimeter wave (mmWave) spectrum can support high speed short-range communications, wireless networks will finally face a skyrocketing capacity explosion that could even overstretch the millimeter wave spectrum and other limited radio frequency spectrum.
- Severe interference challenge: Small cells have been presented in 5G wireless networks to improve network capacity/coverage for massive IoT devices. However, densely deployed small cells lead to severe co-channel interference. Although heterogeneous 5G cellular architecture over radio frequency (RF) spectrum can address this issue to some degree, the cross-layer interference over the same RF frequency still degrades network performance. How to mitigate severe interference is a key challenge.
- High-accuracy localization challenge: For localization systems, the global positioning system (GPS) has been most widely used for outdoor localization, but it has poor localization accuracy in indoor environments due to line-of-sight blockage. RF-based positioning systems, infrared-based systems and ultrasonic-based systems also have been widely applied for indoor positioning. However, the RF-based positioning systems (such as Wi-Fi, Bluetooth etc.) are not safe to be used in some environments (hospitals and airplanes), and the negative effects of the

multipath reflections and shadowing on the positioning performance degradation are significant. Infrared-based and ultrasonic-based positioning systems are capable of achieving high-accuracy positioning performance, but ultrasonic systems pose high installation cost and the coverage range of infrared systems is limited.

- Security challenge: Since some IoT devices require high communication security, e.g., industrial manufacturing and automatic payment. This is one of the most key challenges that 5G networks require to meet the protection of personal data, as RF waves easily penetrate the walls and buildings, so they suffer from security issues. In addition, the projected increase in connected IoT devices will bring a corollary increase in potential attack vectors.
- Cost and energy efficiency challenge: 5G networks need to support the massive number of devices, which may consume a large amount of power. At the same time, mmWave communication requires to be equipped with advanced complementary metal oxide semiconductor chips, and high-gain and steerable antennas at both transmitter and receiver, which mandates nontrivial hardware costs and implementation complexity. Hence, it is important to search economic and high energy efficiency architecture to support IoT for 5G networks.

When more and more devices are involved in 5G networks, it is difficult for current RF-based 5G wireless networks to support the massive connectivity, provide high-speed transmission data rate, guarantee communication security, and satisfy varying quality of services (QoS) requirements of the massive number of devices [3]. Central issues in designing a new network architecture include how to support the massive connectivity of massive IoT devices, how addressed the above mentioned challenges and how to satisfy their colorful service requirements.

III. INTEGRATION OF VLC AND VLP WITHIN 5G NETWORKS FOR IOT

There is a need to integrate VLC and VLP within 5G networks to support massive connectivity and meet the diverse service requirements of IoT devices. In this section, we propose a multi-layer network (integrating VLC and VLP within 5G networks) with the objective to address the challenges mentioned in the previous section.

A. Integration of VLC and VLP within 5G Networks

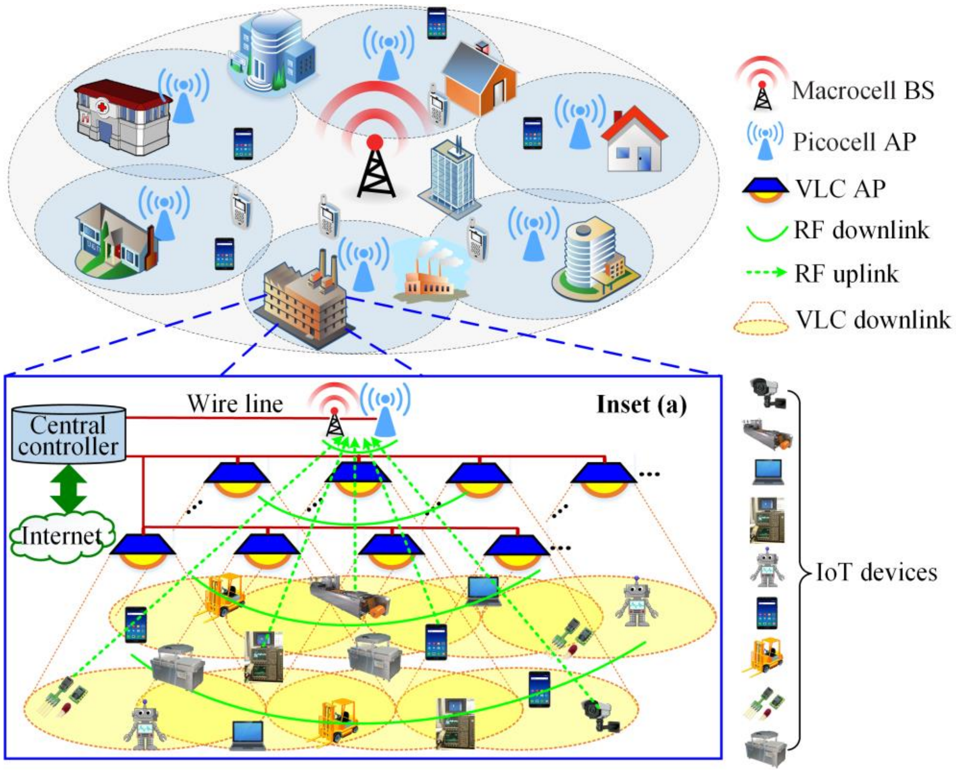

Fig. 1. The architecture of integrating VLC and VLP within 5G networks for IoT.

The presented multi-layer network architecture is shown Fig. 1, which mainly consists of three layers: macrocell layer, picocell layer and optical attocell layer, which are classified by their coverage ranges. The macrocell layer is associated with macrocell base stations (BSs) operating in low RF frequencies, which supports the seamless coverage. The picocell layer is associated with picocell access points (APs) with smaller coverage areas (e.g., factory, home or building). The optical attocell layer is the lowest layer which is composed of VLC APs (refer to femtocells), and it is mainly employed for indoor services. The former two layers operate in the RF spectrum while the bottom layer is on the visible light spectrum. The objective of the presented multi-layer network is to increase data rate and improve indoor positioning accuracy via VLC APs while the larger cells (macrocells and picocells) support the better coverage and reliability.

We take one unit of the multi-layer network to show the working principle. As illustrated in Fig. 1 (inset (a)), a number of VLC APs are uniformly equipped on the room celling, while the RF BSs/APs also support communication services for IoT devices. Each VLC AP has a LED lamp to support the lighting requirements, communication and positioning services, and each VLC AP covers a small area to generate an optical cell. In contrast, RF BSs/APs provide full coverage for the entire room. Both the VLC APs and RF BSs/APs connect to the central controller to support the application services of indoor IoT devices, where VLC APs transmit information to devices by visible light signals and RF BSs/APs provide communication services over RF spectrum. Since it is difficult for VLC to support uplink wireless communications [3], VLC mainly provides downlink service while RF supports both uplink and downlink data transmission.

In addition to communication services, positioning services are provided via the optical layer based on VLP systems. So far, many methods have been proposed for VLP systems, such as angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), and RSS [5]. In the network, for TOA, TDOA and RSS, each VLC AP has its unique frequency identification (F-ID) which is utilized to perform positioning at devices according to the received optical signals. These three methods mainly evaluate the distances from the selected VLC APs to its equipped photodetector (PD) by measuring the received optical signal strengths or the propagation times. After that, the location of the device can be estimated by using the trilateration and triangulation. AOA realizes positioning based on the angles between the VLC APs and devices, where it uses optical channel model or trigonometric relationship of light beacons to calculate the radiation angle.

Due to the mobility behaviors and dynamic service requests of IoT devices in RF/VLC networks, handover processes need to be implemented to satisfy both connectivity and QoS requirements of indoor IoT devices. Generally speaking, there exist two types of the handover mechanisms: vertical handover and horizontal handover.

Vertical handover: The handover mechanism takes place between different access layers, such as the handover between the RF AP and the VLC AP. For example, the mobile device connects the RF links when the VLC LoS link is blocked or it may connect the VLC links if it needs the high transmission data rate. The handover mechanism can be implemented based received signal intensity (RSI) or non-LoS conditions at IoT devices. In addition, downlink traffic is dynamically adjusted between RF and VLC spectrum, in order to improve the system throughput and QoS satisfaction levels.

Horizontal handover: The handover mechanism allows the devices to transfer from one AP to another AP in the same layer while moving, such as switching the current VLC AP to another VLC AP seamlessly. The horizontal handover can be executed in the network to avoid the effect of inter-cell interference and maintain the connectivity of mobile devices. In addition, the VLC APs selection is also processed to perform positioning at devices when they move in indoor environments, where devices regard the positioning parameters with corresponding VLC APs as references to select the available VLC APs to estimate their locations.

Both the vertical and horizontal handovers need to be triggered when the mobile IoT devices move in indoor environments, in order to improve connectivity and guarantee the QoS requirements of indoor IoT devices.

B. Integration of VLC and VLP (VLCP)

In indoor environments, high-speed transmission data rate and high-accuracy positioning need be deployed simultaneous in certain scenarios, hence, the integration of VLC and VLP needs to be performed to support simultaneous communication and positioning services for IoT devices. As shown in Fig. 1, some IoT devices need communication services, some devices (i.e. indoor vehicles) require positioning services and other devices (i.e. robots) may require both communication and positioning services.

Here, we describe the existing and proposed integrated VLCP system models as follows, as illustrated in Fig. 2. The system has L APs, so L subcarriers are employed for positioning (note: each AP has one unique identified positioning subcarrier which is used for indoor positioning).

1. Orthogonal frequency-division multiple access (OFDMA)-based VLCP [12]: The method directly combines orthogonal frequency-division (OFDM) modulation and two dimensional (2D) positioning algorithms for integrated VLCP systems, as represented in Fig. 2 (a). However, as shown in Fig. 2 (a), OFDM signals usually leak high out-of-band interference (OOBI) to adjacent subcarriers, which degrades the communication and positioning performance. In addition, this system needs a large guard band (GB) to mitigate OOBI, which decreases the bandwidth utilization efficiency.

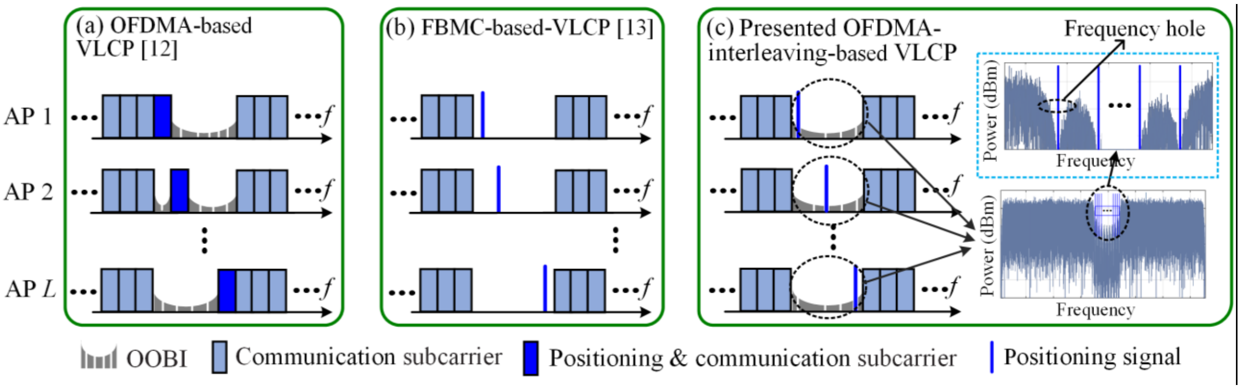

Fig. 2. The spectrum structures of the integrated VLCP system models.

2. Filter bank multicarrier (FBMC)-based VLCP [13]: This scheme applies the FBMC technique to mitigate the OOBI by filtering the interference leakage of each communication subcarrier, as shown in Fig. 2 (b), which can effectively minimize the negative effect of OOBI and improve the positioning accuracy compared with OFDMA-based VLCP. However, it needs extra signal processing complexity compared with OFDMA-based VLCP.

3. OFDMA-interleaving-based VLCP: As shown in Fig. 2 (c), when the L subcarriers are not adopted to transmit any communication signal (L idle subcarriers), we can find there has L specific frequency holes in frequency domain, which have negligible OOBI from OFDM signal. Let N

denote the size of the Inverse Fast Fourier Transform (IFFT), then the bandwidth of each subcarrier is $B_{\mathrm{sub}} = B / N$. When we set the first positioning subcarrier is the *n*-th subcarrier, its corresponding frequency hole is at the middle frequency of this subcarrier with being at $nB_{\mathrm{sub}} - 0.5B_{\mathrm{sub}}$, the second frequency hole is at $(n+1)B_{\mathrm{sub}} - 0.5B_{\mathrm{sub}}$, similarly, the L frequency holes can be detected at $\left[nB_{\mathrm{sub}} - 0.5B_{\mathrm{sub}}, (n+1)B_{\mathrm{sub}} - 0.5B_{\mathrm{sub}}, \cdots, (n+L-1)B_{\mathrm{sub}} - 0.5B_{\mathrm{sub}}\right]$. In this case, the positioning signals (blue color) can be put into these frequency holes, which is capable of avoiding the OOBI on positioning subcarriers from the adjacent communication subcarriers as well as achieves the higher positioning accuracy and bandwidth utilization performance compared with OFDMA-based VLCP. Moreover, it has the lower complexity than FBMC-based VLCP, because FBMC needs filters to filter each subcarrier at transmitters.

IV. KEY TECHNOLOGIES FOR MULTI-LAYER NETWORKS

Based on the above presented multi-layer network architecture, we describe some promising key technologies that can enable the network to fulfill the performance requirements.

A. Energy Harvesting Designs

In indoor rooms, some energy-constrained IoT devices, e.g., sensors for monitoring, date collecting and alarming, etc. Therefore, extending the lifetime of these devices is important as their energy battery is limited. In our proposed multi-layer network, at each IoT device, light energy harvesting can be realized by adopting photodetector (PD) and the harvested energy can be used for packet transmission over RF links [8].

Recently, the paradigm of energy harvesting was investigated in hybrid RF/VLC networks to prolong the life time of indoor devices, where devices equipped with PDs are designed to harvest the energy from the visible light. In indoor scenarios, the devices, like sensor nodes, can directly harvest the energy from the light transmitted from LED lamps over the downlink, which is used for the data transmission over the uplink [8]. In addition, in dual-hop heterogeneous RF/VLC networks, the relay harvests energy from the first-hop VLC link, and uses it to support the communication services over the second-hop RF link.

B. Modulation Schemes

Different from RF-based systems, flicker and dimming control need to be taken into account the modulation schemes for VLC systems. On-off keying (OOK) and pulse position modulation (PPM) are the two simple modulation schemes that have been used in VLC systems, but the data rate of these two modulation schemes are very low. Then, some VLC-specific modulation schemes are presented, such as pulse width modulation (PWM), variable PPM (VPPM), differential PPM (DPPM) and color shift keying (CSK) [14], where additional designs require to be considered to take care of the dimming control.

For CSK, the transmitted bit corresponds to a specific color in the color space chromaticity diagram. In practice, CSK is not applicable to VLC systems where phosphor-based LEDs are used and moreover, the implementation of CSK requires a very complex circuit structure. Unfortunately, the above mentioned modulation schemes generally cannot provide the high spectrum efficiency in VLC systems.

In order to support high transmission data rate, and decrease the inter-system interference (ISI) and multipath fading effect, OFDM has been widely applied in VLC systems, where multiple orthogonal subcarriers are utilized to simultaneously transmit parallel data streams. Different from RF systems, due to the intensity modulation/direct detection (IM/DD) nature of LEDs, Hermitian symmetry is usually imposed on VLC systems to obtain LED-compatible real-valued OFDM signals. OFDM surfers from the high peak-to-average power ratio (PAPR) which degrades the system performance, but several schemes (e.g., commanding transform and selected mapping techniques) have been proposed for the PAPR reduction. Moreover, some modified OFDM schemes were proposed for VLC systems, including direct current (DC) biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM) and asymmetrically clipped DC biased optical OFDM (ADO-OFDM).

C. Multiple Access Schemes

In the multi-layer network, OFDMA, code-division multiple access (CDMA), spatial-division multiple access (SDMA) and non-orthogonal multiple access (NOMA) are four main multiple access techniques to improve the network performance for IoT devices.

OFDMA: OFDMA can be regarded as the multi-user version of OFDM, which has the ability to provide flexible subcarrier and power allocation to guarantee QoS requirements of devices. It is capable of eliminating both intra-cell and inter-cell interferences by flexibly allocating the subcarriers to devices.

CDMA: CDMA is widely used in RF systems, where several transmitters can send information simultaneously over a single communication channel or over the same frequency band. Optical CDMA (O-CDMA) has the similar basic structures to CDMA with the difference that O-CDMA requires optical codes [6]. O-CDMA can deal with the multi-user and multipath interference problems in VLC systems, and it flexibly supports adding devices and asynchronous access.

SDMA: SDMA is a key multiple access technique for 5G networks by exploiting the spatial diversity, which enables frequency-time resources to be shared among a group of devices. However, SDMA cannot be applied to VLC directly, because it is an IM/DD system. Fortunately, LEDs have the limited field-of-view (FOV) feature, which can be employed to generate directional light beams, resulting in the application of SCMA for VLC systems.

NOMA: NOMA multiplexes a number devices in the power domain over the same band and it can greatly improve the spectral efficiency compared with OFDMA, which has been widely investigated in RF systems. NOMA is an valuable multiple access technique for VLC systems for the following reasons [15]: 1) It is efficient and flexible in multiplexing a small number of devices, which is applicable in VLC systems where each small optical cell only serves a few devices in its close proximity; 2) NOMA needs channel state information, which can be estimated accurately in VLC systems due to the constant channel gains for most of the time.

V. SIMULATION–BASED EVALUATION

This section mainly evaluates and analyzes the performance of the proposed integrated network architecture for IoT devices. A typical indoor room is considered with the area of 20m×20m×4.0m, where 5×5 VLC APs and 2×2 RF APs (Wi-Fi APs) are uniformly distributed at the height of 3.5 m. K IoT devices are randomly distributed on the floor with the height of 0.5 m. $K/4$ devices need both the normal communication and positioning services with 0.5 Mbps per device, $K/4$ devices require URLLC services and other $K/2$ devices only require the normal communication services with high data rate requirement (5 Mbps in downlink and 0.5 Mbps in uplink per device). For URLLC services, the maximum latency and transmission reliability are 1 ms and 99.99% with each message size being 500 bits, respectively. The number of subchannels of each AP is 12. The fixed power consumption of each RF AP and VLC AP are 6.7 W and 4W [7], respectively. The maximum transmit power of each AP is 250 mW. The available bandwidth of each AP is 10 MHz. Other parameters can be found in [9].

A. Communication Performance Comparisons

We compare the performance of the following network architectures: 1) the presented multi-layer network including the three layers (RF-RF-VLC); 2) the presented multi-layer network including the picocell layer and the optical attocell layer (RF-VLC); 3) the RF-based network including the macrocell layer and the picocell layer (RF-RF).

Fig. 3 compares the network energy efficiency (EE), the satisfied service levels of normal services and URLCC services versus the device density. We can observe that the EE performance of RF-RF-VLC and RF-VLC architectures is much better than the performance of the RF-RF architecture because of the energy efficient nature of VLC. Furthermore, relying on the abundant bandwidth resource of VLC as well as by exploiting the better channel conditions of small optical cells, the two RF/VLC architectures significantly outperforms the RF-RF architecture in terms of both the normal and URLLC services satisfied levels, especially the performance advantage gradually increases as the increased number of served IoT devices.

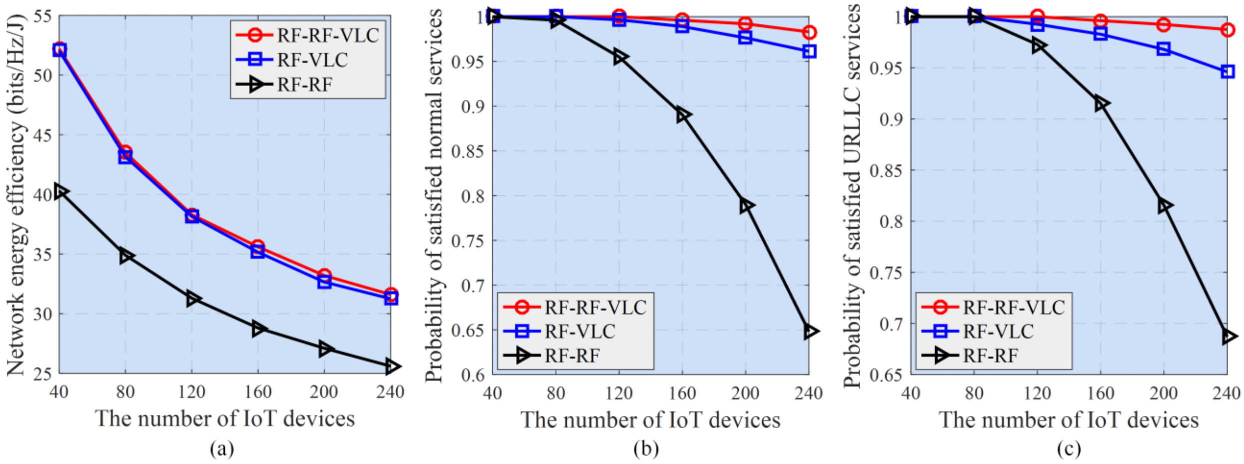

Fig. 3. The performance comparisons versus the number of IoT devices.

We would like to mention that RF-RF-VLC has the similar EE performance to RF-VLC, but it achieves the higher satisfied service levels than that of RF-VLC because of the flexible service provisioning by the multi-layer architecture. The performances of all the network architectures decrease with the increased number of devices due to the fixed spectrum and power resource, but the presented RF-RF-VLC still achieves the best performance.

B. Positioning Performance Comparisons

This subsection compares the indoor 2D positioning performance of the following positioning schemes in the RSS-based positioning system: 1) OFDMA-interleaving-based VLCP; 2) OFDMA-based VLCP [12]; 3) Wi-Fi fingerprint; 4) Wi-Fi positioning.

The indoor positioning results and the Cumulative Distribution Function (CDF) of the positioning errors by using the above mentioned positioning schemes are shown in Fig. 4 (a) and (b), respectively. From Fig. 4 (a), as we can see, the positioning accuracy of the two VLCP schemes is much higher than that of the two Wi-Fi based positioning schemes, especially the advantage is obvious at the room edges and corners. Because the negative effects of multipath reflections and shadowing on the positioning performance degradation are significant in Wi-Fi based positioning systems. Although fingerprint can greatly enhance the positioning accuracy, it requires a large amount of labeled data to train the positioning model which requires extra computation and storage space at IoT devices.

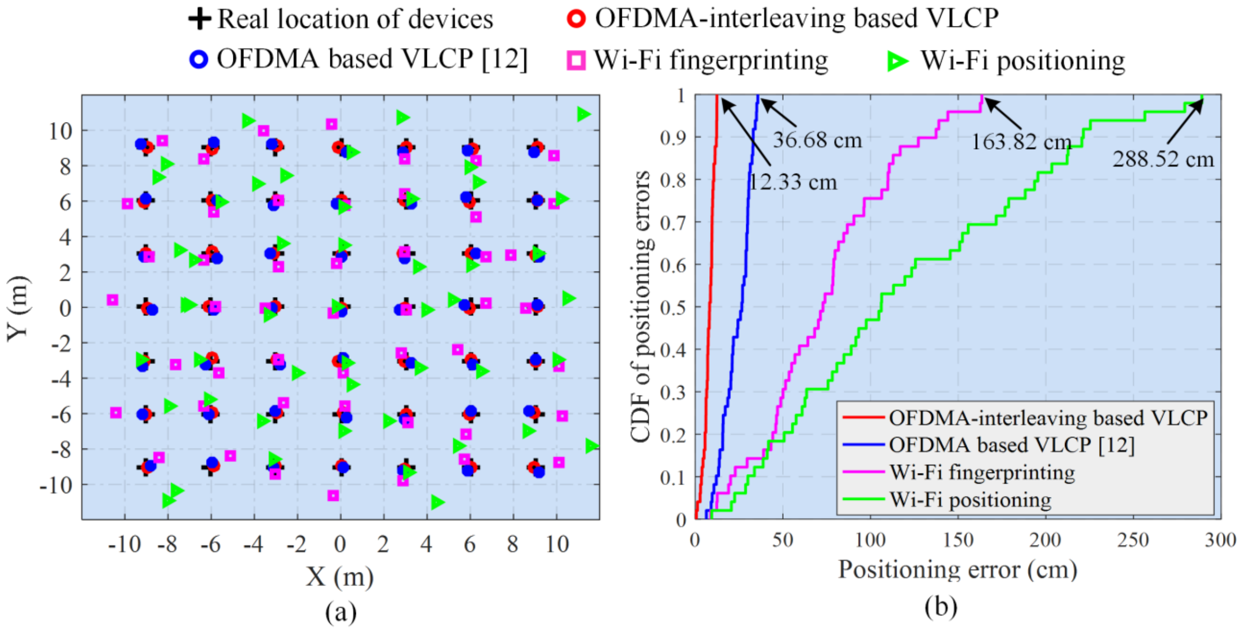

Fig. 4. Comparisons of (a) positioning errors and (b) positioning errors' CDF

In addition, the mean position errors of OFDMA-interleaving-based VLCP, the OFDMA-based VLCP, Wi-Fi fingerprint and Wi-Fi positioning are 7.19 cm, 19.75 cm, 68.76 cm and 113.54 cm, respectively. In Fig. 4 (b), in our presented integrated VLCP system, most of the positioning errors in the room are below 10 cm, and only a few locations are over 12 cm. The performance evaluation indicates the higher positioning accuracy achieved by our presented integrated VLCP system, because it puts positioning signals into frequency holes, which avoids OOBI on the positioning subcarriers from adjacent communication subcarriers. In the existing OFDMA based integrated VLCP system [12], the high OOBI from OFDM signal leads to the severe interference on adjacent positioning subcarriers, which degrades the positioning accuracy.

VI. CONCLUSION AND RESEARCH DIRECTIONS

This article presents a multi-layer network architecture by integrating VLC and VLP into 5G networks for IoT, in order to support massive IoT connectivity and satisfy diverse service requirements of devices. Key technologies are discussed for the performance improvement, including energy harvesting, modulation and multiple access schemes. Furthermore, an exemplary case study and simulation analysis are provided to demonstrate the advantage of the presented multi-layer network for IoT. Possible future research directions are:

- LoS blocking is a key problem in VLC or VLP systems due to movements of IoT devices and obstructing objects, which significantly decreases the network performance. Thus, it is important to study robust handover mechanisms to guarantee the communication connectivity, and present new positioning schemes to maintain the positioning accuracy under LoS blockages.
- Achieving both energy harvesting and communication in VLC systems might violate the illumination requirements, because VLC systems need to provide energy and information to indoor devices. As a result, the investigation of the above mentioned functions in multi-layer RF/VLC networks by formulating optimization problems that allocate direct DC bias, transferred energy, and available resources is needed.
- Since the transmission power at LED lamps is fixed, transmission power allocation is a key issue that affects the tradeoff performances between VLC and VLP. Allocating power for one metric with larger value will lead to the less power value allocated to another metric. In this case, the performance of the one metric improves while the performance of another metric decreases. Hence, how to balance the tradeoff is important.
- In the multi-layer network, different IoT devices may have different QoS requirements, ranging from high reliability and low-latency, high positioning accuracy to high transmission data rates. The varying requirements expect to search an efficient resource management strategy or network architecture to guarantee different QoS requirements.

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