Visible Light Communications Relying on Cell-Free Amorphous Networks

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Abstract. The user-centric architecture is the trend for constructing future networks. To improve user experience, visible light communication system adopts user-centric cooperative transmission technology, which breaks the traditional concept of network-centric. Generating user-centric cells for each user can make the best of network resources, which is of great significance in the 5G era with the design concept of small unit scenes. However, it is still in the initial stage, and the basic theories and key technologies need to be further studied. This paper expounds the new design concept, describes the characteristics and the forming process of user-centric virtual community centering on users, and introduces the key technologies of multi-user processing, channel estimation and network resource management combined with the unique features of visible light. This new mode of transmission can provide the user with the service of the network and improve the user's peak rate and edge user performance.

1. Introduction
Visible light communications (VLC) comprises a speedily developing research field that has attracted the attention of academia and industry, due to its tremendous wide bandwidth, high data rate, energy-saving lighting etc. [1]. Apart from their varietal benefits, spontaneously, VLC systems also have several defects, such as lessened performance in non-line-of-sight scenarios, lack of local up-link support, limited coverage etc. For a particular optical cell, the coverage is determined by the lighting requirements and the FoV(field of view) of the VLC receivers. When there are a large number of virtual cells in the VLC system, inter-cell interference (ICI) implemented by the LoS ray and non-los (NLoS) link must be carefully handled, because ICI will cause the performance of the edge of the virtual cell to decrease significantly. The decline of ICI's performance at the edge of the cell may lead to a sharp decline in the Quality of Service (QoS) in the VLC downlink system.

In view of the above problems, the concept of user-centric virtual cell design has been proposed in recent years [2-6]. The network allows each user to select several preferred APs for transmission in a coordinated manner according to their QoS requirements and channel conditions. Because smartphone its widespread use, mobile cloud computing is also gradually arisen, user-centric design using the change of the user terminal location and diversified service demand, the user terminal to participate in virtual light district planning, resource management, mobility control work, services, such as signal processing, the end of the terminal is no longer simple, but as an element in the network to participate actively. Therefore, the user-centric design concept is likely to become one of the disruptive technologies in the 5G era. User-centric focuses more on the performance of each user. Users are the center of the community. Each user can be served by one or more APs.

2. Review of User-Centric Concept
In visible light communication network, the user-centric design concept is caused by cell boundary problems, such as ICI and frequent handover while moving, which will lead to a substantial decrease in QoS of VLC communication network downlink, so the design of virtual cell becomes crucial. Considering a specific VLC virtual cell, the propagation of light has some restrictions, its coverage is dependent on the FoV of the VLC receivers. As a result, VLC network may need a new structure to solve the cell boundary problem, relying on user-centric VLC network, APs follow user, not the user follows the APs.

In the existing literature, the Coordinated Multipoint (COMP) technology, also known as the network Multiple input Multiple output (MIMO) technology, has been widely applied in the construction of virtual cell [2-4]. Multiple base stations jointly provided services to users and converted the strong interference signal at the edge of the cell into a useful signal. Considering the return trip restrictions and training costs in the real network, the virtual cell containing only a few APs is ideal [7]. In the traditional collaborative network, the network provides network coverage for fixed positions. In order to improve the spectral efficiency, virtual cells are formed from the perspective of the network, which are non-overlapping [8]. Cell configuration is usually fixed, and network resources are allocated to users according to the preset algorithm. While the user-centric network is formed from the perspective of each user to ensure QoS. This inevitably leads to overlapping clusters. Ideally, regardless of the user's physical location, the performance gap between the center of the cell and the edge of the cell would disappear, breaking the traditional boundary of the cell to better serve the user and improve the performance of the communication network. In order to support seamless network connection and user mobility, the network adaptively provides users access to the APs associated with the virtual cell, with the purpose of enabling the virtual cell to track users' movement and provide continuous QoS. User-centric virtual cell design considers user distribution. A virtual cell includes service APs, users and related optical links. The shape of the cell is usually irregular and amorphous. The formation of user-centric community is combined with resource allocation. During the formation of virtual community, users are scheduled and resources are allocated at the same time. In addition, the network-centric network switching mechanism is triggered by the user, which usually sends the switching request when the user moves, while in the user-centered network, the switching is triggered by AP, which dynamically updates the virtual cell by tracking the user.

For the user-centric design concept, Ping-Heng et al [9] proposed design mechanism about VLC virtual cell. In user-centric cell, users can be served by multiple APs, and the network can also institute user-centric virtual cells by affording services jointly through multiple APs. There are three main characteristics of irregular virtual cells in user-centric VLC network for data transmission.

- **Signal overlapping coverage:** We define the concept of VLC cells, for overlapped regions, interference signals are converted into useful signals by cooperative transmission or eliminated by precoding algorithm.

- **Data/Control Separation:** We develop the relationship between data and control by developing the naturally parted downlink and uplink transmissions. Connections at the control level are possible through a more extensive optical AP, and users are less likely to miss critical control information in the network. Therefore, when the user moves at a higher level, the virtual cell of that user can be composed of a separate control plane and a data plane connection.

- **Service provision:** Through the structure of optical virtual cell, We improve the QoS from a user-centric perspective. It enables users in different locations to acquire high rate and low delay communication services, and meanwhile insures that users have high-quality service experience when moving within the cell.

In user-centric network, user can choose several APs to form an amorphous cell, which can be transmitted jointly to the user terminal through MIMO technology or independently to the user terminal through beam forming. As multiple user equipments have different QoS requirements and channel conditions, they also choose APs differently, which ineluctably leads to overlap between virtual cells. In other words, each AP may belong to a different virtual cell, as shown in figure 1, where AP3 belongs to both virtual cell 1 and virtual cell 3. When the cells change, the adjusted results
between updated cells are sent to the Center Unit (CU) for further coordination by CU. Ideally, in order to avoid causing a large amount of signaling overhead, virtual community has the average channel gain, in particular, each user is measured first, and then report to the CU, takes several adjacent APs average channel gain to CU, CU based on the system resources and the QoS requirements of each user terminal to determine each user terminal is connected the APs.

![Diagram](image)

**FIGURE 1.** A brief explanation of the user-centric concept.

### 3. User-centric Cooperative Transmission Technology

#### 3.1 Channel Estimation

APs cooperative transmission performance is largely affected by Channel quality. When joint precoding of multiple APs, instantaneous Channel State Information (CSI) of all users in the virtual cell needs to be obtained, and the process of obtaining CSI is Channel estimation (CE). However, the channel model in VLC, channel Impulse Response (CIR) and RF are different. The significant difference is that the CIR in VLC is not affected by the doppler effect, and there are a lot of reflected waves in the VLC channel model, and the reflected waves have considerable power. This makes it difficult to estimate VLC channel. The traditional estimation using pilot signal will lead to the decrease of efficiency.

Training resources allocation directly affects the results of channel estimation, mainly due to the length of the orthogonal pilot sequence limited by the length of the channel coherence time. The crucial of channel estimation in VLC communication system is to allocate pilot sequence reasonably and avoid pilot contamination. Pilot contamination is mainly caused by the superposition of the expected channel and the interfering channel, which leads to the low accuracy of channel estimation. In order to optimize downlink precoding channel estimation in collaborative networks, training signals sent from APs in the same cluster or from users who choose the same AP should be orthogonal to each other, which has been widely recognized in 3GPP.

For non-overlapping virtual cells, only a set of orthogonal training resources need to be allocated for each virtual cell, and resources can be reused among virtual cells. However, in a user-centric network, virtual cells overlap, and the orthogonal requirements of one virtual cell are coupled in another. In order to meet the demand of all virtual cells, an orthogonal training resource can be allocated for each AP or each user terminal. The total training cost increases linearly with the increase of APs or the total number of user terminals, which will offset the benefits of cooperation and lead to the decrease of net throughput. The second method can greatly reduce the cost by properly scheduling the training resource reuse scheme between APs or users.

The problem of training signal design has been extensively studied in the literature related to wireless resources, mainly focusing on the design of training sequence, training duration, power distribution, etc., mainly for single-input single-user system. If orthogonal training resources can be allocated to avoid multiple interference in channel estimation, these techniques can be used for...
reference in user-centric networks. At the same time satisfy the VLC visible light energy requirements in communication system and indoor users use eye safety requirements, how to don't cause a lot of distribution under the condition of orthogonal training resources, training for multi-cell network cooperation with overlapping clusters, its cost is still unknown, this to improve the user-centric VLC spectrum efficiency of communication network is very important.

3.2 Multiuser Signal Processing

Limited by LED modulation bandwidth, spatial multiplexing is usually used to provide high data rate transmission in the actual deployment of VLC system. Therefore, Multiple input Multiple output (MIMO) schemes are widely used in indoor VLC systems. However, this also brings challenges such as multi-user interference (MUI). In order to support multiple user terminals to be active in the network at the same time, multi-user signal processing technology, namely precoding technology, is needed to form virtual cell. For user-centric cooperation, the same AP can be added to multiple virtual cells, during cooperation, the exchange of information accelerates dramatically. Meanwhile, there is no obvious boundary between communities, which increases the complexity of cooperation. Furthermore, precoding technology has been widely investigated in traditional Radio Frequency (RF). However, there are basically different between VLC signal and RF signal. RF signal has complex value, while in VLC, the modulation method is intensity modulation/direct detection (IM/DD). Light emitting diode (LED) by the intensity modulation, instantaneous optical radiation power is determined by the signal amplitude, so the modulation signal is positive and the real value, leading to the input signal amplitude is limited, with average power constraints, obtain VLC channel capacity is relatively complex, in addition, due to the safety of the eye, signal also is limited by the average optical power. Therefore, IM/DD channels are usually modeled as additive white gaussian noise channels, and the classical Shannon formula is no longer suitable in VLC systems. However, for the input signal amplitude constraint, there is no accurate closed expression of channel capacity at present, only a few tight capacity boundaries can be used to approach channel capacity.

Compared with single-input single-output (SISO) system, multiple input multiple output (MIMO) system can provide higher data rate. The research of advanced MIMO transmission technology in the field of optics has also been strengthened [12]-[18]. In particular, M. Biagi et al. Designed multiple laser and Photo detectors (PDs) of free space optical MIMO system, and based on the VLC system of MIMO system has also been studied [15]-[19]. In the literature [17], T. Q. Wang et al., analyze the designed using a half spherical lens imaging receiver MIMO system, to improve the space diversity order, using hemispherical lens to achieve a wide viewing angle, so as to make the effective separation of the light of the received signal, therefore, the correlation between each element channel matrix is relatively low, the signal for MIMO system provides a favorable diversity gain effective decoding. In addition, Azhar et al. [18] were the earliest authors, who demonstrated an imaging receiver based on MIMO-OFDM, realizing the transmission rate of 220 Mbit/s. Previous studies [20]-[24] on single cell VLC systems focused on the designs of Minimum Mean Square Error (MMSE), Block Diagonalization (BD) and Zero-Forcing (ZF) precoding techniques to maximize the interest in performance indicators. However, there is no research about how user-centric cooperation can be precoded. In general, studies on MU-VLC systems considered two different configurations: single photodiode (PD) (i.e. MU-MISO) and multiple PDs (i.e. MU-MIMO) at receiver. It should be noted that the study by T. V. Pham et al. [22] is the first design of MU-MISO VLC system BD technology that takes non-negative constraints into account. For single PD receiver, or MU-MISO configuration, precoding matrix based on MSE criterion is designed to minimize MSE [23] or minimize the maximum MSE among users. However, these studies have two important limitations. In fact, the sum rate of channel capacity is not taken into account. It is simply defined as the maximum mutual information between input and output that can achieve the minimum bit error rate (BER). Given in reference [24] the sum-rate optimization problems, especially pointed out that a given minimum ber threshold of multistage pulse amplitude modulation (M-ary pulse amplitude modulation, PAM) IM/DD channel can achieve data rate, due to the achievable data rate expression...
depends on the ratio of the amplitude of signal and noise standard deviation, thus form a convex optimization problem was solved.

In VLC, for user-centric cooperative transmission, the same AP can be added to multiple virtual cells. In the process of collaboration, information exchange will be greatly increased, and there is no obvious boundary between cells, further increasing the complexity of user-centric collaboration. To study the precoding scheme design in cooperative transmission, not only the precoding constraint conditions should be considered, but also the visible light non-negative constraint and the maximum optical power constraint should be combined to establish the optimization objective and realize the maximization of the overall network performance.

3.3 Resource Management
When there are multiple user terminals in VLC system, fair and efficient multi-user scheduling and resource management is a prominent problem. In RF systems, this problem has been studied extensively, but in VLC-based networks, there is little research on the scheduling and resource allocation of cooperative communication transmission in multi-user VLC systems.

In recent years, some valuable studies have been performed in network-centric single AP VLC cells. Particularly, in order to improve the total throughput, D. Bykhovsky et al. [25] studied a heuristic scheme for allocation of subcarriers subject to interference constraints in a multi-access VLC system based on discrete multi-tone (DMT) modulation. M. Biagi et al. [26] carefully designed a logical framework for localization, access, scheduling, and transmission in a VLC system, capable of achieving considerable throughput with moderate complexity. However, similar to the literature on resource allocation in most VLC-based systems, [25] and [26] both aim to improve achievable throughput without considering the fairness of the user experience. Huang X. et al. [27] proposed a incremental scheduling scheme (ISS) based on fairness, in which the global scheduling stage is responsible for allocating resources to users, while the local scheduling stage adjusts resource allocation regularly by tracking the movements of users. In addition, O. Babatundi et al. [28] designed a scheduling algorithm based on proportional Fairness (PF) for a centralized control VLC system, which is superior to the maximum rate scheduling strategy in balancing throughput and user experience. Generally, most of the researches on MUS problems encountered in VLC systems are based on single AP VLC units. Instead, we will address MUS and user-centric clustering that rely on vector transport (VT).

Furthermore, while most VLC research focuses on improving achievable throughput, the research focuses on the energy efficiency of user-centric VLC networks that have not yet been developed. Xuan et al. [29] proposed an amorphous cell from the user-centered perspective, considering the user's position, but didn't consider the user service type, and the system bandwidth was not fully used. In addition, the two technologies of combined transmission (CT) and vector transmission (VT) are used. Although VT has the characteristics of high bandwidth utilization, the system load is too heavy due to its dependence on advanced signal processing technology and the need to share CSI information between AP. Xuan et al. [30] further studied the formation of user-centric dynamic clusters, designed scalable video streams, and realized the purpose of energy saving in the indoor VLC system. Rong et al. [31] study a user associated design based on position and delayed perception, in indoor VLC, by adopting estimated method to reduce the system within the scope of the average delay, considering the user positioning and tracking method in reality, a variety of mobile model, hybrid user distribution will be further research. Rui et al. [32] proposed a joint user and power distribution solution in an amorphous VLC network to solve load balancing and power control problems. Simeng et al. [33] studied modulation mode allocation and power allocation strategy by using heuristic dynamic programming algorithm, and the proposed user-centric system throughput and interrupt probability were better than traditional network-centric system.

In addition, compared with radio frequency communication, VLC has some unique characteristics to consider, such as blocking is one of the most significant physical characteristics of VLC. Kim et al. [34] proposed three service modes based on resource allocation for VLC downlink channel to maintain
high system throughput and meet lighting requirements. In order to maximize the spectral efficiency of the system, Park et al. [35] designed an optical MIMO system and proposed an optical power distribution scheme. In order to improve the throughput [36], the concept of non-orthogonal multiple access (NOMA) is introduced in VLC downlink (VLC DL), and a novel power allocation strategy based on user channel conditions is proposed. Jiang et al. [37], as one of the constraints on the sum rate maximization problem, restrict the brightness, signal amplitude and target BER. Specifically, in order to maximize the qualification rate of multi-chip LED based mu-miso VLC system, a light power distribution and evaluation scheme based on the above four constraints is proposed.

In general, previous studies have mostly focused on increasing the maximum throughput of all users in a system, which can be inefficient in practice, especially under the constraints of actual transmission power and return rate. If the channel quality of some users is not satisfied, then it is useless to allocate more energy to them, because it will consume resources and force excessive interference. In addition, if the sum of throughput overcomes the return rate limit, all user packets will be discarded due to the greedy strategy, which means an increased probability of user downtime. In this context, we purpose to allocate resource needing to consider many of these issues under a range of practical restraints.

4. CONCLUSIONS

This column introduces the concept of user-centric access, which allows the network to customize a virtual cell for users by means of multi-point cooperative transmission. For such user-centric network, due to the conflict of the needs of multiple users from different communities and the unique characteristics of VLC compared with RF, it faces many challenges in multi-user signal processing, channel estimation, training signal design, resource allocation and other aspects. This paper briefly reviews the related literature. As one of the most feasible research directions of the new generation communication, the user-centric network cooperative transmission technology has attracted extensive attention, and has some rudimentary research results.

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