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New Construction of OVSF-OZCZ Codes in Multi-Rate Quasi-Synchronous CDMA VLC Systems for IoT Applications

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ABSTRACT Internet of Things (IoT) has become an emerging vision for next-generation network and attracts many researchers' attention. In this paper, we propose a novel quasi-synchronous code division multiple access (QS-CDMA) visible light communication (VLC) system for IoT network. A new construction of optical zero correlation zone (OZCZ) code set with orthogonal variable spreading factor (OVSF) is presented for this system, which can meet the multi-rate requirement and tolerate time delay. After deriving the construction and properties of the proposed code set, the maximum numbers of simultaneous users and multiple access interference (MAI) characteristic are analyzed. Furthermore, the signal noise ratio (SNR) and bit error rate (BER) performance of this system are also investigated while taking into account the effects of phase-induced intensity noise (PIIN), shot noise, and thermal noise. The numerical results indicate that the new construction can eliminate MAI and PIIN, which can achieve high quality transmission in the multi-rate QS-CDMA-VLC system for IoT applications.

INDEX TERMS Visible light communication, Internet of Things, quasi-synchronous code division multiple access, orthogonal variable spreading factor.

I. INTRODUCTION

With the rapid development of wireless communication and intelligent user, Internet of Things (IoT) has been emerging as a promising vision for future networks through realizing smart manufacture, smart grid, and smart city [1]–[3]. The next-generation IoT network will require a very large number of connections per unit area, high aggregate bandwidth, ubiquitous coverage, sustainable energy resources, and a high level of security [4], [5]. With the tremendous progress and widespread application of light-emitting diodes (LEDs) in illumination, visible light communication (VLC) as an attractive technology can be integrated with IoT [6], [7]. The lighting LEDs are so ubiquitous that they can provide high-density communication for a large number of IoT users. Furthermore, while energy-efficient communication is preformed, high-precision indoor position is also supported, which can make IoT open up to a wide range of applications [8]. A VLC based IoT architecture was proposed in [9], which provided a tiered IoT system based on VLC and enhanced many VLC services in different sectors more efficiently.

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Due to the wide range and diversity of IoT applications, diverse traffic characteristic exhibits in the network, which requires multi-rate wireless communications [10], [11]. VLC utilizing unregulated spectrum, specifically from 428 to 750 THz, can meet multiple rate transmission requirements [12]–[14]. Recently, there are some VLC multi-rate schemes including using photodetectors (PDs) and image sensors simultaneously [15], hybrid OOK (on-off keying) and ACO-OFDM (asymmetrically clipped optical orthogonal frequency division multiplexing) modulation [16], and WDM (wavelength division multiplexing) technology [17], [18], but these schemes may increase the system complexity. It is reported that the VLC scheme combining code division multiple access (CDMA) with orthogonal variable spreading factor (OVSF) can also be a potential and suitable candidate for IoT network to handle multimedia rates [19]–[21].

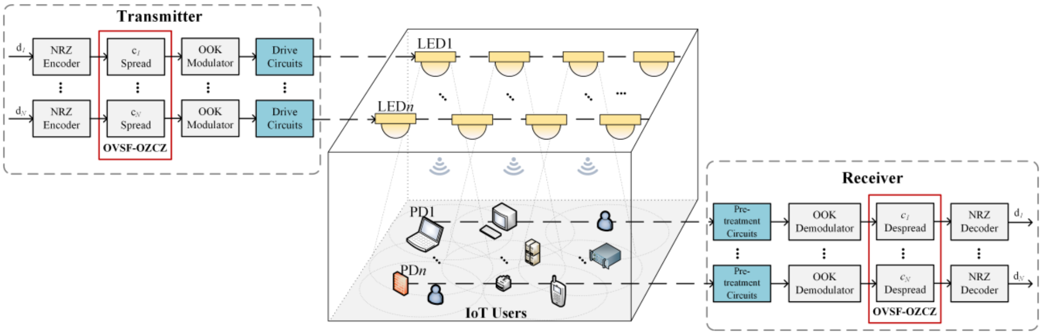

FIGURE 1. The multi-rate QS-CDMA VLC system model for IoT network.

Besides, precise synchronization among users is difficult to be achieved in IoT network due to non-perfect clock or multi-path transmission [22]. That is, quasi-synchronous CDMA (QS-CDMA) should be considered for the IoT network based on VLC technology [23]. Optical zero correlation zone (OZCZ) codes with ideal correlation properties in the zero correlation zone have been designed for QS-CDMA-VLC system, which can effectively tolerate the inevitable time delay and eliminate multiple access interference (MAI) and phase-induced intensity noise (PIIN) [24]–[26]. Some reported OVSF-ZCZ code sets such as Z-complementary set [27], [28] and ternary complementary pair (TCP) [29], [30] can both support multi-rate transmission and tolerate time delay, but three polar sequences do not fit for intensity modulation of VLC system [31].

To solve the above problems, we present a new construction of OVSF-OZCZ code set to improve the performance of IoT network. The main contributions of this paper are outlined as follows.

- A novel multi-rate QS-CDMA VLC system model is introduced according to the characteristic of IoT applications.
- A new construction of a unipolar OVSF-OZCZ with zero correlation zone properties and variable spreading factors is first proposed and used in the multi-rate QS-CDMA VLC system. Compared with existing code set, it can both enhance multi-rate transmission performance and overcome the effect of time delay.
- We evaluate the performance of the proposed multi-rate QS-CDMA-VLC system by numerical analysis and simulation. The results show that it can effectively support multi-rate communication with more users, and eliminate MAI and PIIN in IoT network.

The rest of the paper is organized as follows. Section II introduces the novel multi-rate QS-CDMA-VLC system model. The new construction and properties of the OVSF-OZCZ code is presented in Section III, together with a specific example. The corresponding performance analysis and results discussions are elaborated in Section IV. Finally, Section V draws the conclusions.

II. A MULTI-RATE QS-CDMA VLC SYSTEM MODEL

To support the multi-rate traffic in IoT network, a novel multi-rate QS-CDMA VLC system model with N active users has been shown in Fig. 1. The number of different traffic with different data rates is set to V, and the number of active users for each traffic is set to N_v $\left(v = 1, \ldots, V; \sum_{v=1}^{V} N_v = N\right)$. At the transmitter, the original data first perform non-return to zero (NRZ) encoding, and then spreading according to the assigned spreading codes, with shorter (or longer) code-length for users with higher (or lower) rate. After that, on-off keying (OOK) modulated signals added proper bias drive LED to generate optical signal for transmission. The total transmitted optical signal from multiple LEDs can be written as

$$S(t) = \sum_{n=1}^{N} s_n(t) = \sum_{v=1}^{V} \sum_{n_v=1}^{N_v} s_{v,n_v}(t), \tag{1}$$

where $s_{v,n_v}(t)$ denotes the transmitted signal of the n_v-th user with v-th data rate, defined by

$$s_{v,n_v}(t) = P_0 \sum_{i=-\infty}^{+\infty} d_{v,n_v}(i) c_{v,n_v}(t - iT_v) \quad 0 \le t \le T = L_{lcm} T_c, \tag{2}$$

where P_0 is the light power emitted from LEDs, T_c denotes the chip time interval, $d_{v,n_v}(i)$ and $c_{v,n_v}(t)$ represents the binary data transmitted sequence and the assigned spreading code waveform of n_v-th user with v-th data rate respectively. The symbol period with v-th data rate is $T_v = L_v T_c$, where L_v denotes the period of each spreading code. Each user's $c_{v,n_v}(t)$ can be written as

$$c_{v,n_v}(t) = \sum_{i=-\infty}^{+\infty} u_{v,n_v}(i) P_{T_c}(t - iT_c), \tag{3}$$

where $P_{T_c}(t)$ is a unit rectangular pulse of duration T_c, and $u_{v,n_v}(i) \in \{0, 1\}$ is the corresponding spreading code with a period L_v.

To simplify the analysis, we mainly focus on the LOS (Line-of-sight) case in this system. At the receiver, optical signals are received by PD. Pre-treatment circuits are designed and utilized to achieve photoelectric conversion and analog-to-digital (A/D) conversion in VLC system. The following receiving process performs in the exact opposite way to the transmitting process. The signals are demodulated, and then despread by corresponding correlator to identify the desired user and reduce MAI, and decoded to recover the original data.

III. NEW CONSTRUCTION OF OVSF-OZCZ CODE SET

In this section, a new construction of OVSF-OZCZ code set has been proposed. The proposed code set is applied in the multi-rate QS-CDMA VLC system model as spreading codes. The new construction and the derivation of properties are elaborated, together with a specific example.

A. PRELIMINARIES

Assuming two codes $\boldsymbol{x}_i = [x_{i,1}, x_{i,2}, \ldots, x_{i,L}]$ and $\boldsymbol{x}_j = [x_{j,1}, x_{j,2}, \ldots, x_{j,L}]$ with length L, their periodic cross-correlation function (PCCF) [22] is defined as follows:

$$\theta_{\boldsymbol{x}_i,\boldsymbol{x}_j}(\tau) = \sum_{l=1}^{L} x_{i,l} x_{j,(l+\tau) \bmod L} \quad \forall \tau \geq 0 \tag{4}$$

when $i = j$, it becomes the periodic auto-correlation function (PACF). When $\theta_{\boldsymbol{x}_i,\boldsymbol{x}_j}(0) = 0 (i \neq j)$, the codes are orthogonal to each other.

Definition 1: Let a combination of subset $\{\boldsymbol{x}_{k_n}\}_{k_n=1}^{K_n}$ $(1 \leq n \leq N)$ with different code lengths have $\sum_{n=1}^{N} K_n$ codes. When all codes in the same subset are orthogonal to each other and codes in different subset are orthogonal to each other, the set can be called OVSF code set [21]. The spreading factor denotes the length of each code.

Definition 2: Let $X = \{x_i\}_{i=1}^{K} (x_{i,j} \in \{0, 1\}, 1 \leq j \leq L)$ denote a code set with K codes, each has length L and zero correlation zone Z_{cz}. The set is called OZCZ code set [24], [25] if the following correlation properties satisfy

$$\theta_{\boldsymbol{x}_i,\boldsymbol{x}_j}(\tau) = \begin{cases} w & i = j, \tau = 0 \\ 0 & i \neq j, \tau = 0 \\ 0 & 0 < |\tau| \leq Z_{cz}, \end{cases} \tag{5}$$

where w denotes the code weight, which is the number of '1' in the code.

B. NEW CONSTRUCTION

The new construction of the OVSF-OZCZ code set is described as the following steps.

Step 1: Let I be an identity matrix of order-K $(K \geq 2)$. Then we need to construct an OZCZ code set $H_K^{w,Z_{cz}} = \{\boldsymbol{h}_k\}_{k=1}^{K} (h_{k,l} \in \{0, 1\}, 1 \leq l \leq Kw(Z_{cz} + 1))$. We insert Z_{cz} columns of zeros behind each column, making I become an OZCZ code set $H_K^{1,Z_{cz}}$ with $L = K(Z_{cz} + 1)$. If the code weight w needs to be changed, we then do w times concatenation operations, that is

$$H_K^{w,Z_{cz}} = \underbrace{\left[H_K^{1,Z_{cz}} : H_K^{1,Z_{cz}} : \ldots : H_K^{1,Z_{cz}}\right]}_{w}. \tag{6}$$

Step 2: For constructing the OZCZ code set with variable spreading factors, we choose an OZCZ code set as an initial code set. We employ the matrix M consisting of $(1, L_{zero}) = (1, wK(Z_{cz} + 1))$zeros to generate new code $\boldsymbol{h}_{k,1} (1 \leq k \leq K)$ as follows

$$\boldsymbol{h}_{k,1} = [\boldsymbol{h}_k : \underbrace{M : M : \ldots : M}_{S(k-1)}], \tag{7}$$

where $S(1 \leq S \leq N^{+})$ is variable rate factor. The combination of all codes $\boldsymbol{h}_{k,1}$ can be called an OVSF-OZCZ code set. Each user would adopt an identical code $\boldsymbol{u}_n = \boldsymbol{h}_{k,1}$ with different spreading factor.

Step 3: For supporting more users, we shift the code $\boldsymbol{h}_k$ to get a new matrix H_k as follows

$$H_k = \{\boldsymbol{h}_{k,i}\}_{i=1}^{k} = \begin{bmatrix} \boldsymbol{h}_k & M & \cdots & \cdots & M \\ M & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \boldsymbol{h}_k & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & M \\ M & \cdots & \cdots & M & \boldsymbol{h}_k \end{bmatrix}_{k \times SkL_{zero}} \tag{8}$$

where $H_1 = \boldsymbol{h}_{1,1} = \boldsymbol{h}_1$. The combination of all H_k with different code lengths is also OVSF-OZCZ code set, from which a unique spreading code can be selected for each user.

C. PROPERTIES OF THE NEW CONSTRUCTION

For simplicity, we consider the worst case that each user's transmitted data is '1'. We define that L_{lcm} is the least common multiple (LCM) of different code length, and U_k consists of $\frac{L_{lcm}}{L_{zero}(1+(k-1)S)}$ replication of subset H_k.

Theorem 1: Let $U = \{\boldsymbol{u}_n\}_{n=1}^{N_{\max}} = [U_1; U_2; \ldots; U_K]$ denote a code set with K codes, each has length L and zero correlation zone Z_{cz}, the properties of this code set is as follows:

$$\theta_{\boldsymbol{u}_i,\boldsymbol{u}_j}(\tau) = \begin{cases} w_i & i = j, \tau = 0 \\ 0 & i \neq j, \tau = 0 \\ 0 & 0 < |\tau| \leq Z_{cz} \end{cases} \tag{9}$$

where w_i denotes the number of '1' in the code $\boldsymbol{u}_i$.

Proof : It is easy to be proved that the code set H_k still keep OZCZ properties according to [22]. And the replication of matrix would not change the correlation properties, so U_k is still OZCZ code set. The properties between $\boldsymbol{u}_i$ and $\boldsymbol{u}_j$ in the combination code set $U = \{\boldsymbol{u}_n\}_{n=1}^{N_{\max}} = [U_1; U_2; \ldots; U_K]$

can be derived by

$$\begin{aligned}\theta_{\boldsymbol{u}_i,\boldsymbol{u}_j}(\tau) &= \sum_{l=1}^{L'} u_i(l)u_j(l+\tau)\forall\tau\geq 0\\ &= \sum_{l=1}^{L} u_i(l)u_j(l+\tau) + \sum_{l=L+1}^{2L} u_i(l)u_j(l+\tau)\\ &\quad +\ldots+\sum_{l=L'-L+1}^{L'} u_i(l)u_j(l+\tau)\\ &= \begin{cases} w_i & i=j,\tau=0\\ 0 & i\neq j,\tau=0\\ 0 & 0<|\tau|\leq Z_{cz}.\end{cases}\end{aligned} \tag{10}$$

where w_i denotes the number of '1' in the code $\boldsymbol{u}_i$. Therefore, the code set U is still an OZCZ code set with length $L' = L_{lcm}$.

All codes in the same H_k are orthogonal to each other and codes in different H_k are orthogonal to each other. It can be proved that the combination of all subset H_k with different spreading factors is OVSF-OZCZ code set.

Besides, the system with N active users can support V different user data rates, whose ratio can be calculated by

$$1 : \frac{1}{1+S} : \frac{1}{1+2S} : \ldots : \frac{1}{1+(K-1)S}. \tag{11}$$

The maximum number of users in the system is given by

$$N_{\max} = \frac{S}{2}K^2 + (1-\frac{S}{2})K. \tag{12}$$

The data rate difference among users and N_{max} can be increased by increasing order K of initial identity matrix and variable rate factor S. It can be concluded that K and S should be selected properly according to different requirements for the IoT network.

Based on above analysis, the new construction of OVSF-OZCZ code set satisfies the ideal auto-correlation and cross-correlation properties within Z_{cz}, which is helpful to reduce the effect of time delay between different users compared with the construction in [21], [32]. The transmitter and receiver both employ the unipolar code set for the intensity modulation directly in VLC system compared with the construction in [28], [29]. Furthermore, compared with the construction in [24], [25], the proposed code set with different spreading factors can enhance the multi-rate system performance significantly.

D. EXAMPLE

Step 1: An OZCZ code set $H_3^{2,1}$ can be constructed as follows

$$\begin{aligned} I &= \begin{bmatrix} 1\,0\,0\\ 0\,1\,0\\ 0\,0\,1\end{bmatrix}_{3\times 3} \rightarrow H_3^{1,1} = \begin{bmatrix} 1\,0\,0\,0\,0\,0\\ 0\,0\,1\,0\,0\,0\\ 0\,0\,0\,0\,1\,0\end{bmatrix}_{3\times 6}\\ &\rightarrow H_3^{2,1} = \begin{bmatrix} 1\,0\,0\,0\,0\,0\,1\,0\,0\,0\,0\,0\\ 0\,0\,1\,0\,0\,0\,0\,0\,1\,0\,0\,0\\ 0\,0\,0\,0\,1\,0\,0\,0\,0\,0\,1\,0\end{bmatrix}_{3\times 12}. \end{aligned} \tag{13}$$

Step 2: If the system supports 3 users with different data rates, $H_3^{1,1}$ is adopted as initial code set and S=1, the spreading code $\boldsymbol{u}_k$ of each user can be obtained by

$$\begin{cases} \boldsymbol{u}_1 = \boldsymbol{h}_{1,1} = [1\,0\,0\,0\,0\,0]\\ \boldsymbol{u}_2 = \boldsymbol{h}_{2,1} = [0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0]\\ \boldsymbol{u}_3 = \boldsymbol{h}_{3,1}\\ = [0\,0\,0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0]. \end{cases} \tag{14}$$

Step 3: For supporting more users, each user with different rates uses different spreading codes $\boldsymbol{u}_n$ from H_1, H_2 and H_3 respectively as follows

$$\begin{cases} H_1 = [\boldsymbol{u}_1] = [1\,0\,0\,0\,0\,0]_{1\times 6}\\ H_2 = \begin{bmatrix}\boldsymbol{u}_2\\ \boldsymbol{u}_3\end{bmatrix} = \begin{bmatrix} 0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0\\ 0\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0\,0\end{bmatrix}_{2\times 12}\\ H_3 = \begin{bmatrix}\boldsymbol{u}_4\\ \boldsymbol{u}_5\\ \boldsymbol{u}_6\end{bmatrix} = \begin{bmatrix} 0\,0\,0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\\ 0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0\,0\,0\,0\,0\,0\\ 0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,1\,0\end{bmatrix}_{3\times 18} \end{cases}. \tag{15}$$

The maximum number of supporting users is 6 and there can be up to 3 different data rates in the system. The ratio of different data rates is 6:3:2. The PCCF of $(\boldsymbol{u}_2, \boldsymbol{u}_3)$, $(\boldsymbol{u}_2, \boldsymbol{u}_4)$, and PACF of $\boldsymbol{u}_2$ are shown in Fig. 2.

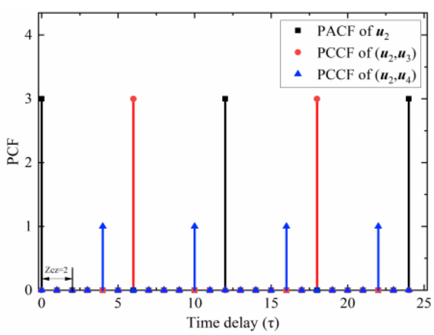

FIGURE 2. The periodic correlation function (PCF) of codes $\boldsymbol{u}_2$, $\boldsymbol{u}_3$ and $\boldsymbol{u}_4$.

IV. PERFORMANCE ANALYSIS

A. SYSTEM PERFORMANCE ANALYSIS

To better analyze the multi-rate QS-CDMA-VLC system in IoT network, we assume the following conditions:

1) Each user's power at the transmitter and the receiver are equal.
2) The spectrum of each light source is flat over the bandwidth $[\nu_0 - \Delta\nu/2, \nu_0 + \Delta\nu/2]$, where ν_0 and $\Delta\nu$ denotes the central optical frequency and the optical source bandwidth.
3) Power spectral components have the same spectrum width.
4) The first user is considered as the desired user. The permitted multiple access time delay is $\tau_n = t_n T_c$, where $1 \leq n \leq N, 0 \leq t_n \leq T_n$ and $t_1 = 0$.

Based on above assumption that light sources have flat broadband spectrum, the influence on performance of

VLC-CDMA system mainly comes from the PIIN, shot noise, and thermal noise. PIIN noise can be introduced to the received signal when incoherent light fields are mixed and incident upon a PD. To suppress PIIN, the value of cross-correlation should be kept as small as possible. In our system, the properties of OVSF-OZCZ code set show that each code has the ideal cross-correlation properties in zero correlation zone and there is no overlapping of '1' between any users. Therefore, PIIN can be suppressed directly. The total noise can be expressed as the sum of the variance of the shot noise and the thermal noise:

$$\left\langle i^2 \right\rangle = 2eIB + 4K_bT_nB/R_L, \tag{16}$$

where I denotes the average photocurrent of PD, the first item and the second item describe the shot noise and thermal noise respectively.

When adopting Gaussian approximation in this system, the following (17) gives the average signal-to-noise ratio (SNR) for l-th desired user in N active users system when the probability of data bit for each user is $1/2$ [23], [26].

$$\begin{aligned} SNR &= \frac{I^2}{\langle i^2 \rangle} \\ &= \frac{(\Re w P_{sr}/L)^2}{2eB\Re P_{sr}/L(w + MAI(T_n)/T_n) + 4K_bT_nB/R_L}, \end{aligned} \tag{17}$$

where MAI with the worst synchronous scenario can be defined as

$$MAI(T_n) = \sum_{n=1, n\neq l}^{N} \sum_{t_n=0}^{T_n} \sum_{i=1}^{L} c_n(i - t_n)c_l(i). \tag{18}$$

And, P_{sr} denotes the effective power of a broadband source at each receiver, B is noise bandwidth equal to the value of chip rate R_c, and $\Re$ is the responsivity of the PD, calculated by $\Re = \eta e/h\nu_0$ [33]. When time delay does not exceed the OZCZ length ($T_n \leq Z_{cz}$), $MAI(T_n) = 0$ and the SNR becomes

$$SNR = \frac{I^2}{\langle i^2 \rangle} = \frac{(RwP_{sr}/L)^2}{2eBRwP_{sr}/L + 4K_bT_nB/R_L}. \tag{19}$$

The rest of the parameters have listed in Table 1 below.

TABLE 1. Parameters used in the calculation.

Symbol	Quantity	Value
v_0	Blue light center frequency	480nm
Δv	Modulation bandwidth	650MHz
η	Photo detector quantum efficiency	0.6
T_n	Receiver noise temperature	300K
R_L	Receiver load resistor	1030Ω
e	Electronics constant	1.602189×10^{-19}
K_b	Boltzmann's constant	1.3806505×10^{-23}
h	Planck's constant	6.626196×10^{-34}

To analyze the performance of this system using proposed OVSF-OZCZ code set and NRZ-OOK modulation, the BER for N active users can be calculated by

$$P_e = \frac{\sum_{n=1}^{N} 0.5erfc(\sqrt{SNR_n/8})/L_n}{\sum_{n=1}^{N} 1/L_n}, \tag{20}$$

where L_n and SNR_n represent the code length and SNR for n-th user, respectively. Furthermore, data rate of the n-th user in the system can be obtained by $R_{b,n} = R_c/L_n$.

B. RESULTS AND DISSCUSSIONS

In this section, we investigate and discuss the MAI and BER performance of multi-rate QS-CDMA-VLC system using the new OVSF-OZCZ construction. The system supports N_{max} active users. We consider that the time delay is within Z_{cz}. and the chip rate is 300 Mbit/s.

Assuming there are 6 active users in this system, the desired user is with highest rate. By the limitation of the transmission distance and rates, the time delay is always small, which fits well for the proposed OVSF-ZCZ code set. Fig. 3 illustrates the normalized MAI of the multi-rate QS-CDMA-VLC system adopting the OVSF-OZCZ code set with parameters $K = 3$, $w = 1$, $S = 1$, and $Z_{cz} = 2$, 4, and 6. The results show that the MAI can be eliminated effectively inside the Z_{CZ}. When the time delay exceeds the ZCZ, the MAI would increase gradually due to the higher cumulative PCCF values. Besides, the results indicate that we can extend zero correlation zone length to eliminate MAI and tolerate larger time delay, when synchronization condition in IoT network gets worse.

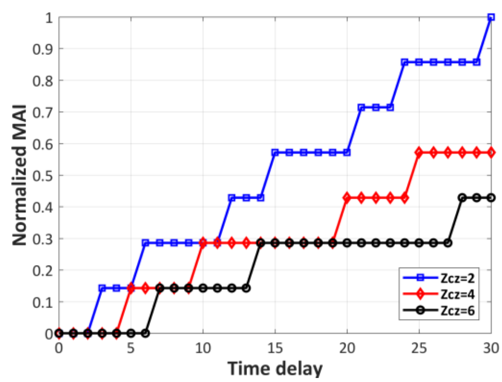

FIGURE 3. The normalized MAI of the desired user versus time delay T_n for the QS-CDMA-VLC system using OVSF-OZCZ code set with parameters $K = 3$, $w = 1$, $S = 1$, and $Z_{cz} = 2$, 4, and 6.

As we know, increased order of initial identity matrix K and variable rate factor S would increase the maximum number of active users and rates, while the ability to tolerate larger time delay can be enhanced by extended Z_{cz}. Fig. 4 gives the BER performance of this system adopting the proposed code set with different construction parameters. We find that all the increased parameters K, Z_{cz} and S would degrade BER performance of the system at a given received power, due to the decreased ratio of code weight to code length. As a result, for the higher system performance, the bigger received power and ratio of code weight to code length are needed. We should make a trade-off between BER performance and IoT network requirements of time delays, users and rates. Besides, the results in Fig. 4 (a) show that with fixed K and P_{sr}, the number of active users has slight influence on BER performance.

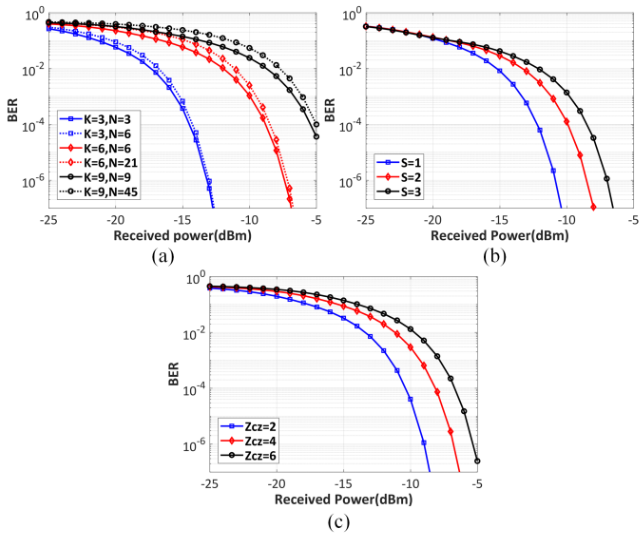

FIGURE 4. BERs performance varying with the received power for the QS-CDMA-VLC system using OVSF-OZCZ code set with parameters (a) Z_{cz} = 1, w = 1, S = 1, and K = 3, 6, and 9, (b) K = 4, Z_{cz}=1, w = 1, and S = 1, 2, and 3, (c) K = 4, w = 1, S = 1, and Z_{cz} = 2, 4, and 6.

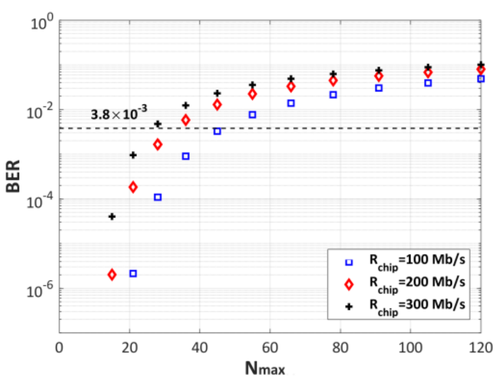

FIGURE 5. BERs performance versus the maximum number of active users for the QS-CDMA-VLC system using OVSF-OZCZ code set with parameters P_{sr} = −10dBm, Z_{cz} = 1, w = 1, and S = 1.

We also investigate the BERs performance of this system adopting OVSF-OZCZ code set with $P_{sr} = -10$dBm, $Z_{cz} = 1$, $w = 1$, and $S = 4$. The chip rate of this system R_c is 100 Mbit/s, 200 Mbit/s and 300 Mbit/s respectively. The 7% FEC threshold of 3.8×10^{-3} is shown by a horizontal line. From the results in Fig. 5, we can see that the BER performance of this system is degraded with the increasing chip rate and user numbers. The reason is that the transmitted LED signals with the higher chip rate corresponds to larger noise bandwidth in the VLC system and more users need larger P_{sr}. When the chip rate R_c is 100 Mbit/s, this system would support 45 active users transmission with 5 different user rate for 7% FEC limit, where the highest user data and lowest user data is 10 Mbit/s and 0.59 Mbit/s respectively. The difference between users' rates can meet the diverse traffic requirement of IoT users.

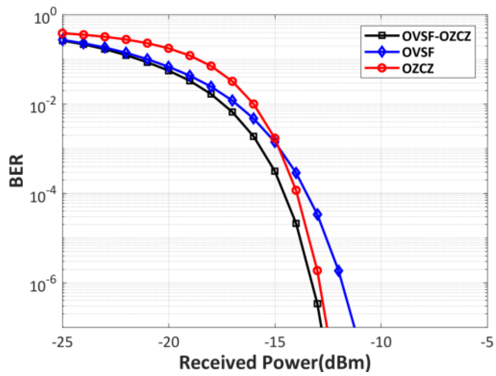

FIGURE 6. BERs performance varying with the received power for the QS-CDMA-VLC system using OVSF-OZCZ code set, OVSF code set [32] and OZCZ [22] with parameters K = 3, Z_{cz} =1, w = 1, and S = 1.

Fig. 6 compares the BERs performance of this system adopting OVSF-OZCZ code set, OVSF code set generated by [32] and OZCZ code set [22] with $K = 3$, $Z_{cz} = 1$, $w = 1$, and $S = 1$. We assume that the time delay is 2 and the lowest user rate is the same in all systems. Due to the proposed code set having ideal correlation properties within Z_{cz}, MAI can be effectively eliminated resulting in better BER performance compared with OVSF without zero correlation zone. Besides, the proposed code set with different code lengths can support multi-rate transmission with better BER performance compared with OZCZ code set, due to its larger ratio of code weight to code length corresponding to better SNR. Therefore, it is benefit for improving multi-rate QS-CDMA-VLC system performance for IoT network.

V. CONCLUSION

In this paper, a new construction of OVSF-OZCZ code set is proposed for a novel multi-rate QS-CDMA-VLC system model in IoT network, which can significantly enhance the multi-rate transmission performance and reduce the effect of time delay. The maximum number of simultaneous user and rates can be increased by adjusting construction parameters. We investigate and compare the transmission performance of the QS-CDMA-VLC system employing different code sets. The numerical results show that PIIN and MAI can be suppressed effectively if the time delay within zero correlation zone. Furthermore, a system with 45 active users and 5 different rates has been successfully achieved below 7% FEC limit, when the chip rate is 100 Mbit/s with OOK modulation. In summary, the proposed OVSF-OZCZ code set used in multi-rate QS-CDMA-VLC systems can be considered as a potential and appropriate candidate for IoT network.

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