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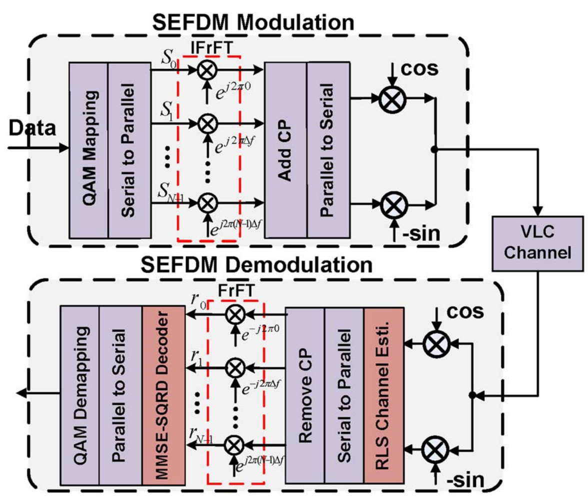

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Efficient MMSE-SQRD-Based MIMO Decoder for SEFDM-Based 2.4-Gb/s-Spectrum-Compressed WDM VLC System

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Abstract: A spectrally efficient frequency division multiplexing (SEFDM) modulation has been proposed to improve system spectral efficiency, particularly for bandwidth-limited visible-light communication (VLC) systems. It employs non-orthogonal subcarriers to achieve bandwidth savings at the expense of serious intercarrier interference (ICI); thus, complicated detectors are required at the receiver to extract signals from the ICI. In this paper, we carry out an analysis of SEFDM modulation and establish a quasi-multiple-input multiple-output (MIMO) model for SEFDM-based systems. Based on this quasi-MIMO system model, for the first time, we propose to use an MMSE-sorted QR decomposition (MMSE-SQRD)-algorithm-based MIMO decoder to efficiently eliminate the ICI in a high-speed SEFDM-based wavelength-division multiplexing (WDM) VLC system. Using the MMSE-SQRD decoder, the WDM VLC system at an aggregate data rate of 2.4 Gb/s is experimentally demonstrated over a 2-m indoor free-space transmission, and up to 20% of bandwidth savings is achieved compared with that of the orthogonal frequency-division multiplexing (OFDM). The results clearly validate the effectiveness of the proposed MMSE-SQRD detector for SEFDM-based spectrum-compressed VLC system.

Index Terms: Visible-light communication (VLC), spectrally efficient frequency division multiplexing (SEFDM), MMES-OSIC.

1. Introduction

Light-emitting diode (LED) based visible light communication (VLC) has been considered as a promising technology for future wireless communication, since LEDs can be used for both illumination and data transmission simultaneously. Compared with traditional wireless communication at radio frequency, VLC offers several unique advantages such as low cost, no need for a license, and high security. A lot of investigations have been carried out for different VLC applications especially indoor high-speed wireless access [1], [2]. So far, the feasibility of VLC has been demonstrated by employing red-green-blue (RGB) LED and phosphor-based white LED. However, the 3-dB bandwidth of a commercially available LED is commonly less than 10 MHz; therefore, the available modulation bandwidth of a VLC system is seriously limited. To achieve high-speed transmission in such a bandwidth-limited VLC system, advanced modulation formats have been utilized for high spectral efficiency (SE), such as carrier-less amplitude and phase (CAP) [3], discrete multi-tone (DMT) [4], and Nyquist single carrier (N-SC) [5].

Recently, relaxing the orthogonality of the subcarriers in frequency domain or the symbol period in time domain has been found to be an effective way to further improve spectrum utilization. Darwazeh has proposed a novel spectrally efficient frequency division multiplexing (SEFDM) modulation in optical fiber systems [6]. SEFDM employs non-orthogonal overlapped subcarriers where the SE is improved by reducing the spacing between subcarriers. Compared to orthogonal frequency-division multiplexing (OFDM), SEFDM is a kind of fast than Nyquist (FTN) in frequency domain, which further compresses signal bandwidth (less than symbol baudrate). In our previous work, we have experimentally demonstrated the feasibility and superiority of SEFDM for the bandwidth-limited VLC system due to its bandwidth saving [7].

However, the key challenge for SEFDM systems is the serious inter-carrier interference (ICI) which is caused by the deliberate violation of the orthogonality between subcarriers. Therefore, complicated detection techniques are required at the receiver to extract signals from ICI. The truncated singular value decomposition (TSVD) has been proposed to eliminate ICI [8], but its performance is far from the optimal maximum likelihood (ML). Heydari has proposed an iterative detection (ID) with soft decision which is a nearly optimal detection method [9], and Xu has designed a hybrid detector combining ID and fixed sphere decoding (FSD) [10]. However, the ID detection needs several iterations for convergence before getting the final output, and the required iteration number is significantly increased at larger bandwidth compression, which will no doubt increase the computation complexity. Therefore, it is important to find an efficient detection technique to achieve a better performance/complexity trade-off.

In this paper, we first carry out analysis of SEFDM modulation and establish a quasi-MIMO model for SEFDM based systems. Based on this quasi-MIMO system model, for the first time we propose to use a minimum-mean-square-error sorted QR decomposition (MMSE-SQRD) algorithm based MIMO decoder [11] to efficiently eliminate the ICI in a high-speed SEFDM based wavelength division multiplexing (WDM) VLC system. Using the MMSE-SQRD decoder, the WDM VLC system at an aggregate data rate of 2.4 Gb/s is experimentally demonstrated over 2-m indoor free space transmission with the bit error rate (BER) below the 7% forward error correction (FEC) limit of 3.8×10^{-3}, and up to 20% bandwidth saving is achieved. Compared with ID detector, MMSE-SQRD detector can achieve nearly the same output performance at lower computation complexity. The results clearly validate the feasibility and benefit of the proposed MMSE-SQRD based MIMO detector for SEFDM based spectrum compressed VLC system.

2. Principle

2.1. SEFDM System Model

Fig. 1 shows the schematic diagram of the SEFDM modulation. At the transmitter, the original bit sequence is first mapped into QAM symbols. Then inverse fractional Fourier transform (IFrFT) is applied to the QAM symbols for SEFDM modulation [6]. The SEFDM non-orthogonal signal is presented as

$$x(t) = \frac{1}{\sqrt{T}} \sum_{l=-\infty}^{\infty} \sum_{n=0}^{N-1} s_{l,n} \exp\left[\frac{j2\pi n\alpha (t - lT)}{T}\right] \tag{1}$$

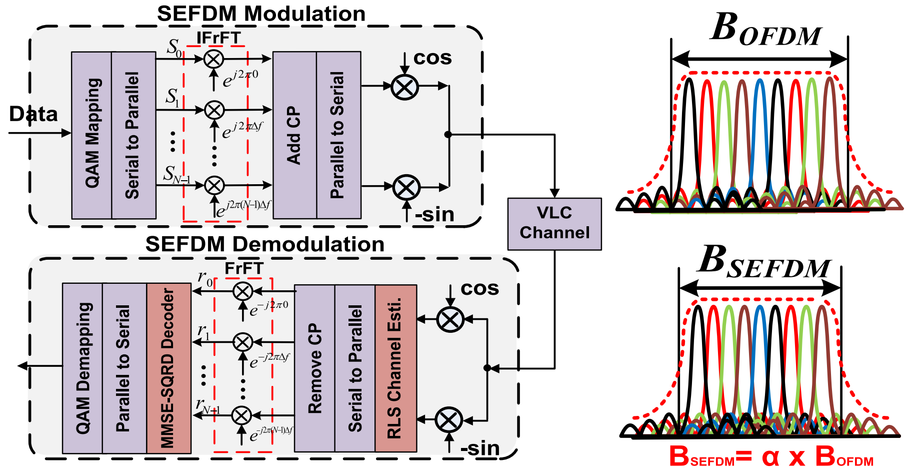

Fig. 1. Schematic of SEFDM modulation.

where α is the bandwidth compression factor defined as $\alpha = \Delta f \cdot T$, and Δf is the frequency distance between adjacent subcarriers. N is the number of subcarriers, and $s_{l,n}$ is the QAM symbol modulated on the nth subcarrier. The OFDM signal corresponds to $\alpha = 1$, and $\alpha < 1$ for SEFDM. Therefore, given the same data rate, SEFDM offers higher SE than OFDM. For the sake of simplicity, the signal in (1) can be expressed in a matrix form as

$$X = F_\alpha^{-1} S \tag{2}$$

where S is a N-dimensional vector of transmitted symbols, X is a N-dimensional vector of time samples of $x(t)$, and F_α^{-1} is the IFrFt matrix. After adding cyclic prefix (CP), the baseband signal is up-converted to a RF carrier to generate real-value SEFDM signal. Then, the SEFDM signal transmits through a VLC channel and reaches the receiver.

In SEFDM demodulation, the received signal is firstly down-converted to baseband. RLS adaptive equalizer is proposed for SEFDM time-domain channel estimation in our previous work [7]. After removing CP, FrFT is employed for SEFDM demodulation. The whole SEFDM modulation/demodulation process is expressed as

$$R = F_\alpha X + F_\alpha Z = CS + Z_{F_\alpha} \tag{3}$$

where R is an N-dimensional vector of distorted symbols after FrFt, and Z is additive white Gaussian noise (AWGN). F_α is FrFt matrix, and $C = F_\alpha \cdot F_\alpha^{-1}$ is an $N \times N$ correlation matrix representing interference between subcarriers

$$C[m,n] = \frac{1}{N}\sum_{k=0}^{N-1} \exp\left(\frac{j2\pi mk\alpha}{N}\right) \cdot \exp\left(\frac{-j2\pi nk\alpha}{N}\right). \tag{4}$$

For OFDM, C is an identity matrix which means no ICI, while the cross correlation between subcarriers is not zero for SEFDM so that serious ICI will be induced. Therefore, a decoder is used to eliminate ICI subsequently, and QAM demapping is followed to recover the original bit sequence.

From (3), it is found that the SEFDM system can be regarded as a quasi multiple input multiple output (MIMO) system. N-dimensional vector $S = [s_0, s_1, \ldots, s_{N-1}]^T$ and $R = [r_0, r_1, \ldots, r_{N-1}]^T$ are respectively the N transmitters and N receivers, while the correlation matrix C becomes the $N \times N$ channel matrix which is perfectly known by the receiver. Fig. 2 describes the quasi-MIMO model for the SEFDM based VLC system. Therefore, the ICI between subcarriers can be

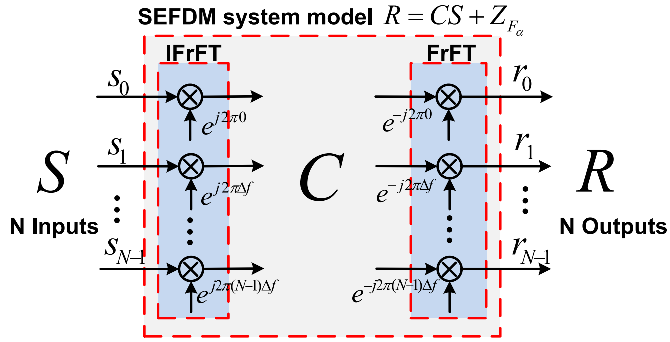

Fig. 2. Quasi-MIMO SEFDM system model.

considered as the interference between the receiver antennas so that some efficient MIMO detection algorithms can be utilized here for ICI cancellation.

2.2. MMSE-SQRD-Based MIMO Detector

As mentioned above, SEFDM system is a quasi-MIMO system, and advanced MIMO detection algorithms can be used to eliminate the ICI. In [11], D. Wubben has introduced a novel, computationally efficient algorithm called MMSE-SQRD detection for successive interference cancellation (SIC) in MIMO systems. In this paper, we propose to utilize this MIMO detector to eliminate ICI in SEFDM systems. A brief description about this algorithm is presented below.

At first, we consider a quasi-MIMO SEFDM system given as

$$X = HS + n \tag{5}$$

where $X = [x_0, x_1, \ldots, x_1]^T$ and $S = [s_0, s_1, \ldots, s_{N-1}]^T$ are $N \times 1$ transmitted and received signal vectors. H is the $N \times N$ channel matrix, corresponding to the correlation matrix C. For MMSE detector, the resulting output is given as

$$\tilde{S}_{MMSE} = \left(H^H H + \sigma_n^2 I_N\right)^{-1} H^H X. \tag{6}$$

With the definition of an extended channel matrix $\underline{H} = \begin{bmatrix} H \\ \sigma_n I_N \end{bmatrix}$ and an extended receive vector $\underline{X} = \begin{bmatrix} X \\ 0_{N,1} \end{bmatrix}$, the output of MMSE can be rewritten as

$$\tilde{S}_{MMSE} = (\underline{H}^H \underline{H})^{-1} \underline{H}^H X = \underline{H}^{+} \underline{X}. \tag{7}$$

Then, the QR decomposition is used for the extended channel matrix as $\underline{H} = \underline{Q}\underline{R}$, where $\underline{Q}$ has orthogonal columns with unit norm, and $\underline{R}$ is upper triangular. Due to the upper triangular structure of $\underline{R}$, successive interference cancellation is used to eliminate interference layer by layer. However, the detection sequence is crucial due to the risk of error propagation. Wubben proposed a modified approach of arranging the order of detection into the QR decomposition [11]. This sorted QR decomposition is basically an extension to the modified Gram-Schmidt procedure by reordering the columns of the channel matrix. The description of the whole MMSE-SQRD algorithm based signal detection is given in Table 1. Utilizing this MMSE-SQRD MIMO detector, the ICI between SEFDM subcarriers can be efficiently eliminated.

3. Experimental Setup

Fig. 3 shows the experimental setup of the SEFDM based VLC system. Tektronix AWG 7122C is used to generate the 4QAM SEFDM signal with 16 subcarriers for an RGB LED. We use the output of channel 1 for the red chip, while the output of channel 2 and its inverted output are

TABLE 1

MMSE-SQRD algorithm and signal detection

SQRD Algorithm	Signal Detection
$\underline{R}=0,\ \underline{Q}=\underline{H},\ P=(1,\ldots,N)$	$Y=\underline{Q}^H\cdot\underline{X}$
$for\ \ i=1,\ldots,N$	$for\ \ k=N,\ldots,1$
$k_i=\arg\min_{l=i,\ldots,N}\left\Vert \underline{q}_l\right\Vert^2$	$d_k=\sum_{i=k+1}^{N} r_{k,i}\cdot c_i$
$exchange\ \ col.\ i\ \ and\ k_i\ in\ \underline{Q},\underline{R},\underline{P}$	$z_k=y_k-d_k$
$r_{i,i}=\left\Vert \underline{q}_i\right\Vert$	$c_k=Quantization[z_k/r_{k,k}]$
$\underline{q}_i=\underline{q}_i/r_{i,i}$	end
$for\ l=i+1,\ldots,N$	$Permutate\ c\ according\ to\ P$
$r_{i,l}=\underline{q}_i^H\cdot\underline{q}_l$	
$\underline{q}_l=\underline{q}_l-r_{i,l}\cdot\underline{q}_i$	
end	
end	

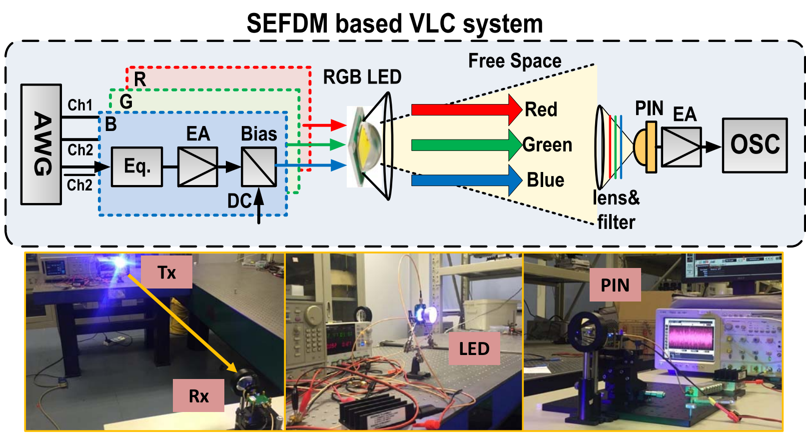

Fig. 3. Experimental setup of the WDM VLC system employing SEFDM.

applied to the green and blue chip respectively. The baud rate of generated SEFDM signal is 400 MBaud/s. The signal is then pre-amplified by an in-house designed bridged-T based pre-equalizer to compensate LED frequency attenuation at high frequency [12]. After an electrical amplifier (EA, Mini-circuits, 25-dB gain), the electrical signal and DC-bias voltage are combined by a bias tee, and, respectively, applied to the three color chips of a commercially available RGB LED (LED Engine, output power: 1 W). A reflection cup with 60° divergence angle is applied to reduce the beam angle of the RGB LED for longer transmission distance.

At the receiver, a PIN photodiode (Hamamatsu 10784) are used to detect the optical signals. Before the PIN, a lens (50-mm diameter, 50-mm focus length) is used to focus light, and optical R/G/B filters are also employed to filter out different colors. The outputs of the PIN is amplified by an EA and recorded by a digital storage oscilloscope (Agilent DSO54855A) for offline SEFDM demodulation and MMSE-SQRD detection.

4. Experimental Results and Discussions

To render the RGB LED working at the optimal condition, we firstly study the influence of different bias voltages and input signal peak-to-peak values (Vpp). The bandwidth compression factor is set at 0.8 here. The BER performance of the red chip versus different bias voltages is shown in Fig. 4(a). At this time, the input signal Vpp is fixed at 0.4 V. Then, the BER

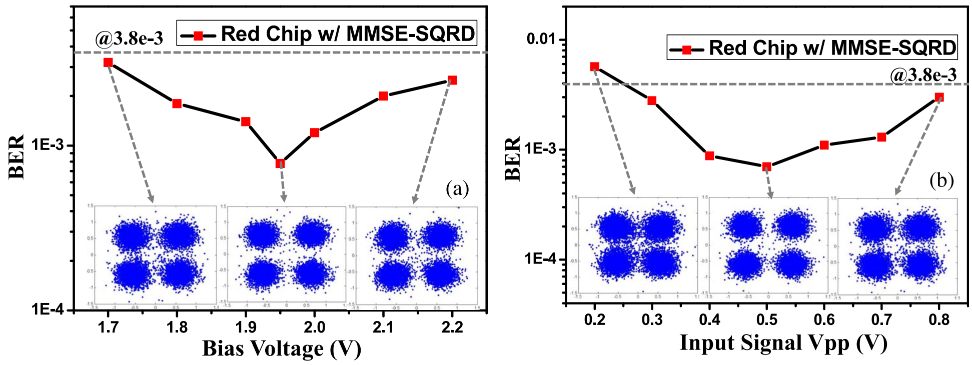

Fig. 4. Measured BER of the red chip versus (a) bias voltages and (b) input signal peak-to-peak voltages.

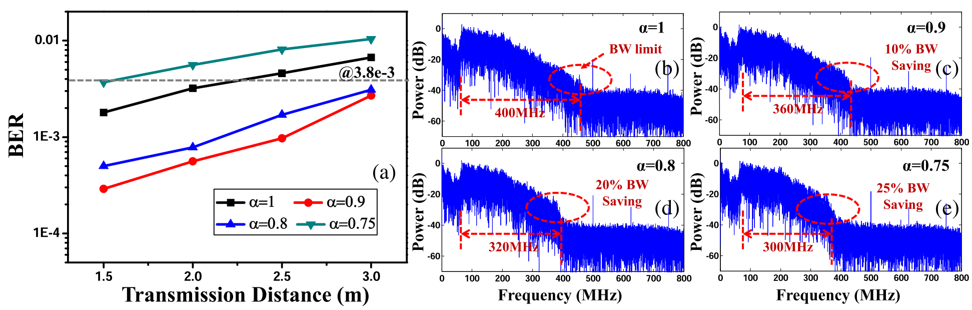

Fig. 5. (a) BER of the red chip at different compression factors. (b)–(e) Signal spectrum at different compression factors.

performance versus different input signal Vpps is measured at the fixed bias voltage of 1.95 V, as shown in Fig. 4(b). We also measure the BER performances versus bias voltages and input signal Vpps of the other two color chips. According to the measurements, the optimal working point of the red, green, and blue chip is, respectively, at (1.95 V bias voltage, 0.5 V input signal Vpp), (3.15 V, 0.6 V), and (3.15 V, 0.7 V).

Then we investigate and compare the BER performances for the fixed data rate of 2.4 Gb/s at different compression factors, including $\alpha = 1$ (OFDM) and $\alpha = 0.9$, 0.8 and 0.75 (SEFDM), as shown in Fig. 5(a). The received signal spectrum at different α are presented in Fig. 5(b)–(e). It is found that the best performance is achieved when $\alpha = 0.9$ (BW = 360 MHz), and the performance is degraded slightly for $\alpha = 0.8$ (BW = 320 MHz). While for $\alpha = 1$ (BW = 400 MHz) and $\alpha = 0.75$ (BW = 300 MHz), the BER performances become much worse. It can be explained that for a VLC system, the available modulation bandwidth is a very precious resource because of the serious bandwidth limitation coming from LED. As shown in Fig. 5(b), the VLC signal spectrum is seriously attenuated at high frequency, which dominantly degrades the system performance. Compared to OFDM (signal bandwidth equals to symbol baudrate), SEFDM can further compress the signal bandwidth (less than symbol baudrate), which achieves the faster than Nyquist (FTN) modulation in frequency domain; therefore, the bandwidth limitation of the VLC system can be overcome by using SEFDM. We can see that the performances of SEFDM at $\alpha = 0.9$ and 0.8 are better than O-OFDM at $\alpha = 1$, as shown in Fig. 5(a). By bandwidth compression, SEFDM can effectively save the bandwidth resource. This bandwidth saving overweight the effect of ISI and offers an improvement in the overall system performance for the bandwidth-limited VLC systems. Considering the urgent bandwidth demand for next-generation

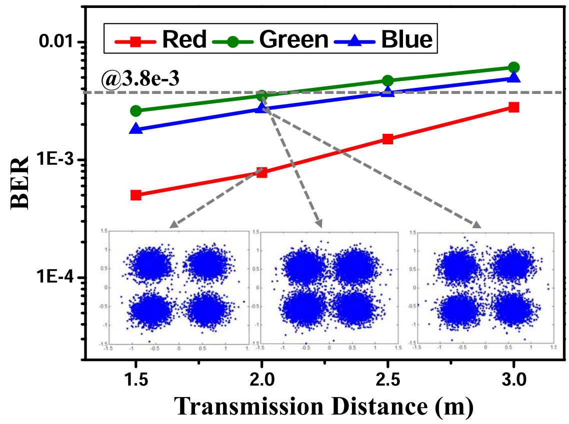

Fig. 6. BER performances versus different transmission distances at a 0.8 compression factor.

TABLE 2
Complexity comparison between MMSE-SQRD and ID

	MMSE-SQRD	ID
Number of operations	$\frac{16}{3}N^3+\frac{7}{3}N^2+\frac{25}{6}N$ [11]	$12\upsilon N^2$ [10]
$N=16,\upsilon=5$	22576	15360
$N=16,\upsilon=10$	22576	30720
$N=16,\upsilon=20$	22576	61440

wireless communications, the investigation of SEFDM and its DSP algorithms is very helpful to achieve high SE beyond-Nyquist transmission.

On the other hand, the reduction of α further increases the SE at the expense of higher BER penalties. Therefore, for $\alpha = 0.75$ the compression penalty is the dominating factor to the degradation of the system performance. Considering the 7% FEC limit, up to 20% bandwidth saving can be achieved at 2-m transmission distance in our VLC system.

At the optimal working point, we measure the BER performances versus different distances for all the three color chips utilizing MMSE-SQRD decoder, as shown in Fig. 6. The compression factor is fixed at 0.8. The SEFDM signals are independently modulated onto the three color chips, and the RGB LED are lighted to simultaneously transmit signals. It can be seen that 2.4 Gb/s aggregate data rate of the WDM VLC system can be achieved at 2-m transmission distance with the BER below the 7% FEC limit. It is worth noting that the red chip has better performance because the best responsivity of the utilized PD is at 620 nm, which is close to the red light wavelength. Moreover, because of the R/G/B filters utilized in front of the PIN, the crosstalk from other color channels has been filtered out before detection.

In order to make a clear comparison between the MMSE-SQRD detector and the ID detector, we first investigate the computation complexity of the two detection algorithms according to [10] and [11]. The comparison results are presented in Table 2. Here, *N* is the number of subcarriers, and υ is the number of iterations. It can be found that the required operation number of ID detection is increased with the iteration number. The operation number of MMSE-SQRD is less than ID with 10 iterations, but larger than ID with five iterations. Although the number of operations of MMSE-SQRD is proportional to N^3 and for ID it is N^2, it is worth noting that for SEFDM modulation more subcarriers result in much larger ICI, which will seriously degrade system performance. Therefore, only 16 or less subcarriers are commonly suggested for SEFDM modulation according to [6]–[10]. Superior to SEFDM, traditional OFDM allows the use of much

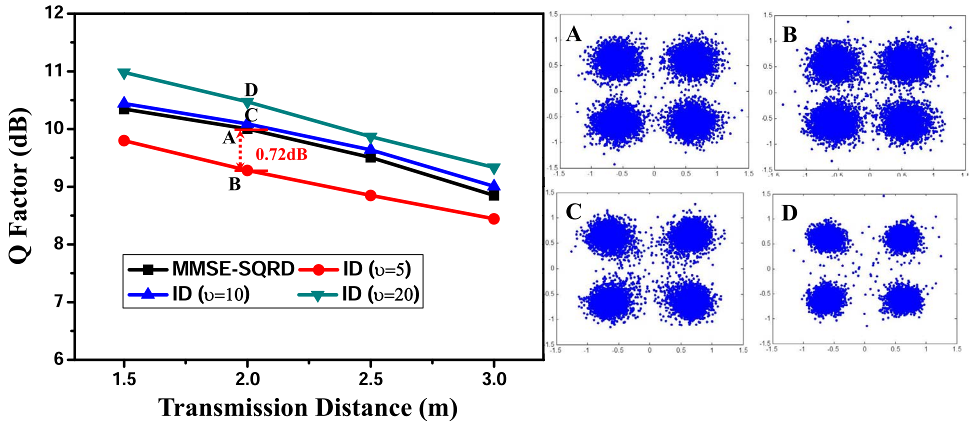

Fig. 7. *Q* factor comparison between the MMSE-SQRD detector and the ID detector of the red chip.

more subcarriers. It means that more precise bit and power loading can be employed to improve the bandwidth utilization. Moreover, more flexible subcarrier allocation for multiusers can be achieved by more OFDM subcarriers. However, a large number of subcarriers lead to a high peak-to-average power ratio (PAPR), which will make the OFDM signals more susceptible to nonlinearity and degrade the system performance. For a fair comparison, the subcarrier numbers of SEFDM and OFDM signals are both fixed at 16 in our experiment. While for larger subcarrier numbers, the required iterations of ID will be significantly increased for convergence due to the larger ICI. Therefore, the complexity of ID will increase greatly with the subcarrier numbers as well.

Finally, we measure the *Q* factor of the red chip versus different transmission distances using MMSE-SQRD detector and ID detector respectively, as shown in Fig. 7. The results show that the MMSE-SQRD detector outperforms the ID detector with five iterations by *Q* factor of 0.72 dB, and the MMSE-SQRD has very similar performance with ID detection using 10 iterations (only about 0.08 Q factor difference), while the required operation number is less than 75% of the ID detection $(22576/30720 = 73.4\%)$. For the ID detector with 20 iterations, it has higher *Q* factor than MMSE-SQRD at the expense of more than two times computation operations. It is worth noting that the required detection techniques of SEFDM are much more complicated than traditional OFDM, because of the serious ICI induced by non-orthogonal subcarriers. Therefore, it is very important to find an efficient and low-complexity detection algorithm to eliminate the ICI. Based on the proposed MMSE-SQRD detector, we can save more than 25% of the required operations to achieve the same performance as ID detection. Therefore, compared to ID, MMSE-SQRD detector can provide better performance/complexity tradeoff for the SEFDM based VLC system.

On the other hand, MIMO detection techniques have been widely used in wireless communications. Based on the established quasi-MIMO model and the preliminary verification of MMSE-SQRD detector, we are able to investigate and find some more efficient MIMO algorithms to further reduce the complexity of the SEFDM detector in our future work.

It should be noted that in VLC system the luminance of the LED is the key factor that can limit the transmission distance. In our experiment, the measured luminance of the RGB LED at 2 m is about 300lx. The illumination level is below the standard value for brightness (500lx). Therefore, it is believed that transmission distance and system performance can be further improved by increasing the optical power of LEDs or deploying LED array.

5. Conclusion

In this paper, we propose for the first time the use of MMSE-SQRD algorithm based MIMO decoder to efficiently eliminate the ICI in a high-speed SEFDM based WDM VLC system. By the

MMSE-SQRD decoder, the WDM VLC system at an aggregate data rate of 2.4 Gb/s is experimentally demonstrated over 2-m indoor free space transmission with the BER below the 7% FEC limit of 3.8×10^{-3}, and up to 20% bandwidth saving is achieved. Compared with the ID detector, the MMSE-SQRD detector can get nearly the same output performance at lower computation complexity. The results clearly validate the feasibility and better performance/complexity trade-off of the proposed MMSE-SQRD based MIMO detector for SEFDM based spectrum compressed VLC system.

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