A Robust Channel Processor for Faster-than-Nyquist Non-Orthogonal FDM Visible Light Communication Systems

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Abstract We propose and experimentally characterize a modified fractional DFT matrix and a robust channel processor for FTN-NOFDM visible light communication systems without complex up-conversion. A 1.76-Gb/s FTN-NOFDM signal with 20% reduced bandwidth achieves ~6-dB sensitivity improvement over 2-m free-space transmission.

Introduction

Visible light communication (VLC) is a promising technology for short-range communication due to its low cost, high security and immunity to electromagnetic interference. However, the severe frequency-selective power fading limits the available system bandwidth. Various schemes were proposed to mitigate this issue\(^2\). Recently, faster-than-Nyquist non-orthogonal frequency division multiplexing (FTN-NOFDM) system has been proposed\(^3,4\). With closer carrier frequency separation than the conventional orthogonal frequency-division multiplexing (OFDM), FTN-NOFDM further improves the spectral efficiency and transmission performance in bandwidth-limited VLC systems without increasing the complexity at transmitters.

In this paper, we propose a novel modified fractional discrete Fourier transform (mFrDFT) based FTN-NOFDM technique without requiring up-conversion and demonstrate a robust channel processor (RCP) for improving signal detection. As VLC is an intensity-modulation/direct-detection optical system, the transmitted signal must be real-valued. Compared to the conventional implementation of a real-valued FTN-NOFDM signal that requires analog or digital signal up-conversion\(^3,5\), the proposed scheme adopts quadrature amplitude modulation (QAM) formats and employs Hermitian symmetry so as to directly obtain a real-valued FTN-NOFDM signal in the baseband with reduced bandwidth requirement. Meanwhile, the compatibility to QAM formats makes it more flexible to various advanced signal processing techniques. Furthermore, we propose an RCP that comprises a robust channel estimator and a frequency domain equalizer for channel fading compensation. Our experiments have shown that the proposed mFrDFT enabled FTN-NOFDM baseband signal with RCP shows better performance than the recently proposed Joint Channel Equalization and Detection (JCED)\(^6\).

Principle

In the conventional generation of an FTN-NOFDM signal, inverse fractional Fourier transform (IFrFT) is utilized. The \(k\text{th}\) time sample \(\{k\tilde{=}0,1,\ldots,N-1\}\) of one FTN-NOFDM symbol \(X\) can be represented as

\[
X[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} S_n e^{j\frac{2\pi nk\alpha}{N}},
\]

where \(S = [s_0, s_1, \ldots, s_{N-1}]\) denotes the mapped symbols in the frequency domain, \(N\) is the number of subcarriers, and \(\alpha (\lt 1)\) denotes the compression factor. The orthogonality principle is purposely violated to accommodate faster than the Nyquist rate. When \(\alpha=1\), it is equivalent to a conventional OFDM signal, and the corresponding electrical spectrum is depicted in Fig. 1(a). However, when \(\alpha\lt 1\), such IFrFT changes the frequency distribution of subcarriers. Hence, as shown in Fig. 1(b), a real-valued FTN-NOFDM signal cannot be obtained by performing Hermitian symmetry. Although several FTN-NOFDM baseband transmitters have been proposed recently\(^4\), the ratio of \(N\) to \(\alpha\) has to be an integer value, and Hermitian symmetry cannot be employed directly, as well.

To cope with these issues, we propose an mFrDFT-based FTN-NOFDM modulation method. The modulated signal can be expressed by \(X=FS\), where \(F\) is an \(N\times N\) inverse modified fractional discrete Fourier transform (ImFrDFT) matrix as given in the following:

\[
F = \frac{1}{\sqrt{N}} \begin{bmatrix}
1 & e^{j2\pi k_1} & \ldots & e^{j2\pi k_1(N/\alpha-N-n_1)} \\
\vdots & \vdots & \ddots & \vdots \\
1 & e^{j2\pi k_2} & \ldots & e^{j2\pi k_2(N/\alpha-N-n_2)}
\end{bmatrix},
\]

where \(\beta=\frac{2\pi \alpha d}{N}\). \(k_1=0,1,\ldots,N/2-1\) and \(k_2=\frac{N/2+1}{N/2+2},\ldots,N-1\) denote the row indices. \(n_1=0,1,\ldots,N/2-1\) and \(n_2=N/2+1, N/2+2,\ldots,N-1\)
denote the column indices. From Eq. (2), it should be noted that $F$ is divided into four submatrices partitioned by the $(N/2)$-th row and the $(N/2)$-th column. To ensure the symmetry of the frequency distribution of the subcarriers, the elements of such row and column are set to the zero-frequency region, i.e., $e^{j\pi n/2}$ and $e^{j\pi k/2}$, respectively. It can be noticed that $F$ is equivalent to the standard inverse discrete Fourier transform (IDFT) matrix when $\alpha = 1$. After performing Hermitian symmetry and ImFrDFT, the modulated subcarriers are centered around the DC carrier, as presented in Fig. 1(c). Hence, the generated signal is real-valued. For demodulation, the mFrDFT matrix defined as the conjugate matrix $F^*$ is employed.

Fig. 2(a) shows the block diagram of the offline digital signal processing (DSP) used in this work. At the transmitter (Tx) side, the input bit stream is firstly mapped into QAM symbols. Then, Hermitian symmetry and ImFrDFT are performed to directly obtain a real-valued FTN-NOFDM signal for VLC systems. Before parallel-to-serial conversion, the cyclic prefix (CP) and pilot OFDM symbols are added to combat the frequency-selective channel. At the receiver side (Rx), after serial-to-parallel conversion and CP removal, RCP is employed for channel fading compensation. In JCED, the channel estimation is implemented by transmitting pilot FTN-NOFDM symbols$^6$. However, the accuracy is highly affected by the ill-conditioning of the FTN-NOFDM system. As shown in Fig. 2(b), the proposed RCP uses a pilot OFDM symbols aided channel estimator to combat the inherent ill-conditioning impact. Then, the channel fading is compensated in the frequency domain by a single-tap equalizer. Furthermore, the leakage power, due to the non-orthogonality of such system, is also compensated using the information from the proposed channel estimator.

The reason that we chose OFDM pilots rather than FTN-NOFDM pilots is that the power leakage can be properly accounted for before demodulation. Then, after performing mFrDFT, the hybrid iterative detection and fixed sphere decoding (ID-FSD) are used to eliminate the inherent inter-carrier interference (ICI) induced by FTN-NOFDM. Finally, the recovered symbols are de-mapped for the bit error rate (BER) calculation.

**Experimental setup and results**

Fig. 2(c) shows the experimental setup. The mFrDFT based FTN-NOFDM signal was firstly generated by MATLAB offline. The subcarrier number was set to 32, among which 15 subcarriers effectively carried 4-QAM symbols. The CP length was 1/16 of one FTN-NOFDM symbol period. Then, the FTN-NOFDM signal was loaded to an arbitrary waveform generator (AWG) working at 2 GSa/s, amplified by a 1-GHz bandwidth electrical amplifier (EA), and then coupled with the DC current supply via a laser diode (LD) controller, to directly modulate a blue LD (OSRAM PL450). Hence, the net data rate of the signal was about 1.76 (\(=2\times15/32\times16/17\times2\)) Gb/s. After 2-m free-space transmission, the optical signal was detected by a 1-GHz avalanche photodiode (APD) (APD Hamamatsu C5658). A neutral density (ND) filter in front of APD was used as a variable optical attenuator to attenuate the received optical power (ROP). Finally, the detected signal was sampled by a digital sampling oscilloscope (DSO) at 6.25-GS/s for offline DSP.

The experimental results are given in Fig. 3.
We have proposed and implemented a novel technique for mitigating channel fading in VLC systems. This technique, known as FTN-NOFDM, employs a combination of frequency-time signal modulation and novel equalization schemes. The performance of this scheme is demonstrated through experiments under different conditions.

The performance of the proposed scheme under different AWG sampling rates has also been investigated, as shown in Fig. 3(c). By employing the proposed FTN-NOFDM technique, the maximum achievable sampling rate was increased from 1.95 GSa/s to 2.2 GSa/s, leading to about 12.8% capacity enhancement compared to OFDM. Thanks to the enhanced channel fading compensation from RCP and the consequently accurate decision from ID-FSD, the three FTN-NOFDM signals exhibit almost the same improved BER curve, indicating the enhancement of system capacity in a bandwidth-limited VLC system.

**Conclusions**

In this paper, we have proposed and experimentally demonstrated, for the first time, a novel FTN-NOFDM VLC system by employing Hermitian symmetry. Without the complex up-conversion, the bandwidth requirement can be further reduced. Moreover, an RCP is proposed to overcome the inherent ill-conditioning in FTN-NOFDM systems. Over 2-m free-space transmission, ~6-dB power penalty improvement and ~12.8% capacity enhancement with up to 20% bandwidth saving have been demonstrated, which shows the great potential of the proposed FTN-NOFDM technique for bandwidth-limited high-speed VLC systems.

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**References**