A Modified Fractional DFT based FTN-NOFDM Technique for IM/DD Optical Systems

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Abstract

We propose a novel modified fractional DFT based FTN-NOFDM technique for IM/DD optical fiber communication systems. It does not require up-conversion and reduces signal bandwidth. For 22.41-Gbit/s, 20-km transmission, 20% bandwidth can be saved.

I. INTRODUCTION

Recently, faster-than-Nyquist non-orthogonal frequency division multiplexing (FTN-NOFDM) system has been proposed to achieve better bandwidth utilization, compared to orthogonal frequency-division multiplexing (OFDM) [1]. The conventional implementation of the FTN-NOFDM in an intensity-modulation/direct-detection (IM/DD) optical system requires signal up-conversion, which leads to increased system complexity. Fractional Hartley transform (FrHT) [2] and fractional cosine transform (FrCFT) [3] based FTN-NOFDM have been reported to tackle this issue, but only pulse amplitude modulation (PAM) format was supported. This constraint would limit the application of some advanced signal formats, such as set-partitioned quadrature amplitude modulation (SP-QAM) and offset-QAM.

In order to make the FTN-NOFDM more flexible to various signal formats, in this paper, we propose a novel modified fractional discrete Fourier transform (mFrDFT) based FTN-NOFDM technique which gives better signal compatibility. The proposed scheme can adopt QAM formats and employs Hermitian symmetry so as to obtain a real-valued signal directly, which is necessary in IM/DD optical systems. No increase in system complexity nor power penalty is induced. In addition, no signal up-conversion is required. In this work, a 22.41-Gbit/s FTN-NOFDM signal with 20% bandwidth saving has been experimentally demonstrated over 20-km standard single mode fiber (SSMF), while keeping the bit error rate (BER) below \(3.8 \times 10^{-3}\).

II. PRINCIPLE

An FTN-NOFDM signal generated by the conventional method can be represented as [1]

\[
X[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} s_n e^{j2\pi n k / N}
\]  

(1)

where \(s_n\) denotes the mapped symbols in the frequency domain; \(X[k]\) is the \(k\)th time sample \((k=1, 2, ..., N)\) of one FTN-NOFDM symbol \(X\); \(N\) is the number of subcarriers, and \(\alpha < 1\) denotes the compression factor. The violation of the orthogonality principle is consciously induced to make it faster than the Nyquist rate. Basically, it is equivalent to a conventional OFDM signal when \(\alpha = 1\). With such signal generation method, a real-valued signal cannot be obtained by performing Hermitian symmetry, as shown in Fig. 1(a). Although several available FTN-NOFDM baseband transmitters [4] have been proposed recently, the ratio of \(N\) to \(\alpha\) has to be an integer value, and Hermitian symmetry cannot be employed directly, as well.

In view of the issues discussed above, we propose an mFrDFT based FTN-NOFDM system, which can be expressed by \(X = FS\), where \(F\) is \(N \times N\) inverse modified fractional discrete Fourier transform (ImFrDFT) matrix, given by

\[
F = \frac{1}{\sqrt{N}} \begin{bmatrix}
\cdots & e^{\beta N} & \cdots & e^{\beta (N-2 N + N+n)} \\
\cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
2 \pi n & \cdots & \cdots & \cdots \\
\end{bmatrix}
\]  

(2)

where \(\beta = j 2 \pi \alpha / N\); \(k = 0, 1, ..., N-1\) and \(n = 0, 1, ..., N-1\) denote the row index and the column index, respectively. It should be noted that, to ensure the symmetry of the frequency distribution of the subcarriers, the elements of the \((N/2)\)-th row and the \((N/2)\)-th column are set to zero-frequency region, i.e., \(e^{j2 \pi n}\) and \(e^{j2 \pi k}\), 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, the modulated subcarriers are centered around the DC carrier, which is
depicted in Fig. 1 (b). Hence, the generated signal is real-valued.

III. EXPERIMENTAL SETUP AND RESULTS

Fig. 2 (a) depicts the block diagram of the experimental setup and the digital signal processing (DSP) used in this work. After mapping the input data into 4-QAM symbols, Hermitian symmetry and ImFrDFT were performed to implement a real-valued FTN-NOFDM signal, where 127/256 subcarriers were efficiently modulated. Before parallel-to-serial conversion, the cyclic prefix (CP) was set to 1/16 of the length of an FTN-NOFDM symbol to combat chromatic dispersion (CD). Then, the obtained signal was converted to an analog signal by using a 24-GSa/s arbitrary waveform generator (AWG). Hence, the net bit rate of the signal was about 22.41 (=2×127/256×16×17/24) Gb/s. The signal was then fed into a Mach-Zehnder modulator (MZM) to generate an optical signal before being launched into a piece of 20-km SSMF. At the receiver side, before detection by a photodiode (PD), a variable optical attenuator (VOA) was used to emulate different received optical power (ROP) values. Then, the electrical signal was sampled by using a real-time oscilloscope at a sampling rate of 50 GSa/s for offline DSP. To compensate the channel fading and the inherent inter-carrier interference (ICI) induced by FTN-NOFDM, we respectively employed a modified frequency-domain equalization (FDE) and iterative detection (ID) before demapping and BER calculation.

Fig. 2(b) depicts the transmission performance of the proposed FTN-NOFDM signal with different values of $\alpha$. Despite the ICI induced, it shows that the back-to-back (B2B) BER curve of the FTN-NOFDM signal with $\alpha=0.9$ is almost the same as that of the conventional OFDM signal ($\alpha=1$). This can be attributed to its saved bandwidth and consequently higher tolerance to the bandwidth limitation from devices. Similar relative performance is also observed after 20-km SSMF transmission. The FTN-NOFDM signal with $\alpha=0.85$ shows almost no performance degradation compared to the conventional OFDM signal ($\alpha=1$). It should be noted that the FTN-NOFDM signal with 20% bandwidth saving ($\alpha=0.8$) can still keep its BER below the forward error correction (FEC) threshold of $3.8\times10^{-3}$ after 20-km SSMF transmission.

As shown in Fig. 2 (c), the tolerance to system bandwidth limitation for FTN-NOFDM signals with different $\alpha$ has also been investigated. We used an optical bandpass filter before PD to emulate different system bandwidth values. We can see that all these signals with employing FTN-NOFDM outperform the conventional OFDM signal in the bandwidth-limited region, and can save about 2-GHz optical bandwidth at the FEC threshold.

IV. SUMMARY

In this paper, we have proposed and experimentally demonstrated a novel mFrDFT based FTN-NOFDM technique for IM/DD optical communication systems. To the best of our knowledge, it is the first time generating a real-valued FTN-NOFDM by employing Hermitian symmetry, which shows better compatibility and lower complexity. A 22.41-Gbit/s FTN-NOFDM signal has been successfully implemented over 20-km SSMF. The experimental results have indicated that the proposed technique can save 20% bandwidth compared to the conventional OFDM, while keeping the BER below $3.8\times10^{-3}$. The proposed scheme also shows a higher tolerance to narrow-bandwidth filtering.

REFERENCES