International Journal of Electronics and Electrical Engineering

Volume 3 | Issue 4 Article 14

April 2015

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Mrs. Ranjita Rout
GIET, Gunupur, ranjita.rout@gmail.com

Jagan Bihari Padhy
GIET,Gunupur, jbpadhy@gmail.com

Recommended Citation
Rout, Mrs. Ranjita and Padhy, Jagan Bihari (2015) "DEMULTIPLEX THE SSB SIGNAL WITHOUT THE INTERFERENCES BETWEEN THE EVEN AND THE ODD SUBCHANNELS," *International Journal of Electronics and Electical Engineering*: Vol. 3 : Iss. 4 , Article 14.
DOI: 10.47893/IJEEE.2015.1173
Available at: https://www.interscience.in/ijeee/vol3/iss4/14

DEMULTIPLEX THE SSB SIGNAL WITHOUT THE INTERFERENCES BETWEEN THE EVEN AND THE ODD SUBCHANNELS

Mrs. Ranjita Rout
Asst. Prof
GIET,Gunupur

Mr. Jagan Bihari Padhy
Asst. Prof
GIET,Gunupur

Abstract— This letter studies the interference between the even and the odd subchannels in the interleaved multiplexing optical fast orthogonal frequency-division multiplexing system, which is caused by the non-orthogonal demultiplexing transform at the receiver. To eliminate this interference, frequency and timing off-sets are introduced deliberately at the receiver to form orthogonal bases, which coincide with the discrete cosine and sine transforms of type- IV. Thus, the symbols can be demultiplexed at the receiver without any interference between subchannels, and the proposed receiver design can be implemented efficiently. Finally, analysis and simulation are provided to verify its feasibility and the ability to eliminate such interference.

Index Terms— Discrete cosine transform, discrete Fourier transform, optical fast orthogonal frequency division multiplexing (OFDM).

I. INTRODUCTION

ORTHOGONAL frequency division multiplexing

(OFDM) is a multicarrier system in which the information- bearing symbols are transmitted over the orthogonal and overlapped narrowband subchannels [1]. It is spectrally efficient and able to compensate the dispersive channel by a single-tap equalizer easily. To provide high capacity and robust transmission, it has been adopted for optical systems and exhibits attractive resilience to both chromatic dispersion and polarization mode dispersion, especially in long-haul optical transmission [2]—[5].

In the OFDM systems, the minimum subchannel space $Qf = 1/T$, (T is symbol period) ensures the orthogonality between subchannels. Recently it is found that, if the symbols are real-valued and the phases of the overlapped subcarriers are aligned to the multiple of *n/2*, the minimum subchannel space can be reduced to 1/2T [6]-[12]. In [7], the amplitude- shift keying (ASK) modulated OFDM with subchannel space $Qf = 1/(2T)$ is proposed, and its feasibility and efficiency are validated by using discrete cosine transforms (DCTs) of type- II and -III for modulation and demodulation rather than the discrete Fourier transform (DFT) in the conventional OFDM systems. It is also adopted for the optical systems, as fast

Manuscript received September 18, 2012; revised December 17, 2012; accepted December 18, 2012. Date of publication December 24, 2012; date of current version January 29, 2013.

X. Ouyang, J. Jin, G. Jin, and Z. Wang are with the School of Information Science and Engineering, Dalian Polytechnic University, Dalian 116034, China (e-mail: jiyu.jin@dlpu.edu.cn; jiyu.jin@dlpu.edu.cn; guiyue.j in@dlpu. edu.cn; z_s_wang@dlpu.edu .cn).

Y. Park is with the Department of Information and Communication Engineering, Yeungnam University, Gyeongsan 712-749, Korea (e-mail: ywpark@yu.ac.kr).

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OFDM (FOFDM) [8], and has been demonstrated in the single- mode and multimode fiber systems experimentally more recently [9]—[12]. Although precise timing synchronization is required in FOFDM [13], it is shown in [14] that, if a multi-tap equalizer is applied, the FOFDM is more tolerant to the carrier frequency error since the inter-carrier interference is more concentrated in FOFDM than in conventional OFDM.

In these optical FOFDM systems, optical filters and Hilbert transform are required to get the single sideband (SSB) signal [8]. As a result, in [15], a SSB optical FOFDM based on DFT is proposed by halving the redundant samples at the output of inverse DFT (IDFT) since the symbols are real-valued. In [16], an interleaved multiplexing optical FOFDM is proposed where the SSB optical FOFDM signal is generated by multiplexing the two OFDM signals obtained by two IDFTs with 1/(2 T)frequency shift with low complexity.

In [17], it is revealed that in [16] the symbols on the even or the odd subchannels suffer the interference from the odd or the even subchannels, and it becomes severer as the number of subchannels decreases. Considering that the interference imposed on the even or the odd subchannels is identical, some subchannels are intentionally set to be zeros to estimate the interferences. Thereby, the interferences can be removed. For accurate estimation, however, a number of subchannels are required to be zeros without bearing information. As a result, data rate loss occurs, which is pronounced when the number of subchannels is small. And the interference cannot be removed completely due to the estimation errors.

In this letter, we investigate the interleaved multiplexing optical FOFDM system and such interference [16]. It is shown that the demultiplexing transform at receiver is non-orthogonal to the multiplex transform at transmitter, which lies behind the interference. In order to eliminate the interference completely, frequency and timing offsets are introduced at the receiver to form orthogonal bases which coincide with the DCT and discrete sine transform (DST) of type-IV. Consequently, the proposed receiver scheme can be implemented efficiently, and it is capable of demultiplexing the optical SSB FOFDM signal without any interference.

II. PRELIMINARIES AND PROBLEM STATEMENT

The detailed mathematic model of the FOFDM system is provided in [16]. Given $\_f = 1/(2T)$, the baseband signal is

(t) 1/N N2-1 x (2k) e ... + TX (2k ... N/2 k 0 ... 1) e^{1} T 2n where $s(t)$ is the baseband signal and $x(k)$ is the k-th frequency symbol. The discrete baseband signal $s(n)$ can be obtained with two IDFTs by sampling $s(t)$ at t = nT_s ($T_s = T/N$), as

$j Nn^n$ -

(2)

$s(n)$= IDFT [x $(2k)$, N] + $e^{J Nn}$ IDFT [x $(2k + 1)$,N] (3)

where IDFT [x (k) N] denotes the N-point normalized IDFT of a sequence $x(k)$. At the receiver, inverse operation is performed to recover the transmitted symbols as

- $J N_n n$

$y(m)$ = DFT [s $(2n)$,N] + $e^{J Nn}$ DFT [s $(2n + 1)$,N] where $y(m)$ is the demodulated symbol on the m-th subchannel.

In [17], it is found that the symbol on the m-th subchannel, $y(m)$, is the desired m-th symbol x (m) impaired by the symbols on the odd subchannels if m is even or by the symbols on the even subchannels if m is odd. Substituting Eq. (2) into Eq. (3)

$G(m\ k)$ $y(m)$ — - x)e-J Nnm-k) j N-1 N-1 n

κ) +S((m k 1))2 (4)

-N k=0 n=0

where the second summation satisfies

N-1 _e~ J N n(m-k) n=0

_N S (m

$y(2m)$ [y (2m) x $(2m)$ 1) (6)

(5)

• 1 + J cot 2N $(m - k)$ 2 -1 1 x N (2k). + k=0

where cot() denotes cotangent function, $S(n)$ is the Kronecker

and

(2 m y^1 1) [y (2m 1) x (2m 1)

+ = _ + = +

(7) From Eqs. (6) and (7), the interference on the even or the odd subchannels is identical. If the symbols have zero mean and are mutually independent, the interference approaches to zero as the number of subchannels increases. In [17], the interference is estimated and mitigated by leaving some subchannels being nulls. However, this method leads to data rate loss, especially when the number of subchannels is small.

III. Proposed Optical Fast OFDM Receiver

Based on Eqs. (4) and (5), it is obvious that the interference occurs since the transforms in Eqs. (2) and (3) are not unitary. The main idea of the proposed algorithm is to introduce timing and frequency offsets on the received signal deliberately to form orthogonal bases so that the symbols can

delta, and $(\bullet)_2$ denotes the modulo-2 operator. Considering that the symbols $x(k)$ are real modulated, the received even and odd symbols can be derived by discarding the imaginary part as

— x (2k N N · 1 _ 2-1 + k=0 +

be demodulated by the DCT and/or DST of type-IV without any interference. The proposed system scheme is illustrated in Fig. 1. To achieve this purpose, the received signal is first frequency

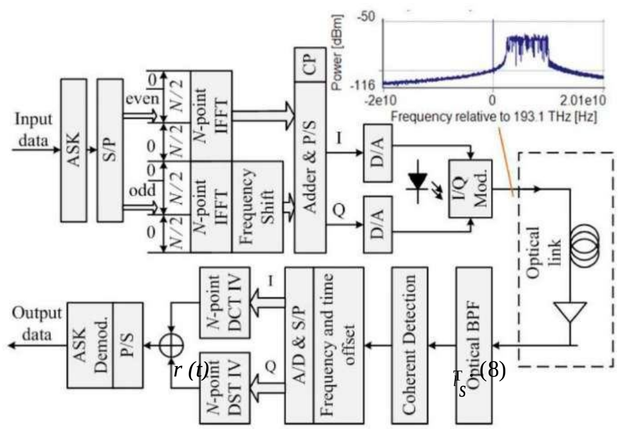

Fig. 1. Diagram of the interleaved multiplexing optical fast OFDM with the proposed receiver scheme based on DCT and DST of type-IV.

shifted by 0.5_f and sampled at t = nT_s + $0.5T_s$ as

$r(t)$ T_s = T / N into (8), (8)

$e^{J\pi t}$ _ $s(t)$ ^{1} Ts +2 N 1

Substituting Eq. (1), and _$f = 1/2T$ and T_s it can be readily deduced that

1 $r(n)$ $r(t,$ _ e j x $(k)H(k, n)$. k=0 (9)

,_rn+ 2 Ts s t = n 1 Ts

_N 1 1 1 - n 1 1 J N _k 2 _n 2

= V~N ~ x (k)e + +

k=0

In the proposed scheme, the sampling point should be aligned precisely with 0.5 T_s sampling offset. Precise timing is required in the proposed scheme, as is the case with other FOFDM systems [13].

In Eq. (9), the term $H(k, n)$ is still not orthogonal, that is, $_n H(k,n)\bullet H(m,n)$ _= $S(m - k)$, while the real and imaginary parts of $H(k, n)$ form the orthogonal bases, respectively, as (10)

$H(k, n)= C(k,n)+ J \bullet S(k,n)$

__ ^{1} cos k J, _ _n ^{1}

= VN N +2 +2

n 1 1

+$^{J \sin}$ $_N$ _k + 2 _ _n + 2 __ such that $C(k, n)$ and $S(k, n)$ satisfy

N -1 N -1 (11)

$C(k,n)C(m,n)=$ $S(k,n)S(m,n)$

n=0 n=0

$= 0.5S(m - k)$.

In Eq. (11), these two terms $C(k, n)$ and $S(k, n)$ coincide with the

$c_0(n)$= DCTiv $[at(k), N]$
_ 2 N-1 1 1
_ $ct(k)$ cos (12)
= $k=0$ N + 2 + 2

(k) sin k 1 n 1 _ (13)

N 2 2

DCT and DST of type-IV [18]

k
N

and
$s_0(n)$= DSTIV $[St(k),N]$
2
N
k= 0
V -

respectively, except to a coefficient 2, where (15)
$ct(k)$ or $st(n)$ is
the input sequences, and $c_0(k)$or $S_0(n)$is the output sequences. Both of the type-IV DCT and DST are real and involutary (being its own inverse). Therefore, the transmitted symbols can be recovered as

y (m) = DCTiV [_ [r (n)] ,N] + DSTiV [_ [r (n)] , N] (14)

where _[•] denotes the imaginary part of a complex number. Considering Eqs. (9) and (10), and $x(k)$being real modulated, Eq. (14) can be further deduced as

$y(m)$= 0.5x (m)+ 0.5x (m) = $x(m)$.

Comparing Eqs. (15) with (6) and (7), the interference in (6), (7) is completely removed by using the proposed receiver scheme.

In Eq. (14), the symbols can be recovered by transforming only one of the quadrature terms of $r(n)$, i.e., either _[r (t) or _[$r(n)$ with a scale 0.5 as indicated in Eq. (15). Thereby, either DST or DCT can be saved for simplicity without degradation of the output signal-to-noise ratio (SNR) since the N samples in either of the quadrature terms are sufficient to demodulate the N real-modulated symbols.

IV. Simulations and Discussion

Numerical simulations are carried out to verify the feasibility and efficiency of the proposed receiver scheme. The electrical system bandwidth is 7.5 GHz, and the sampling rate of the digital-to-analog (D/A) and analog-to-digital (A/D) is 20 Gs/s. The transmitter of conventional optical FOFDM [16] based on interleaved multiplexing is employed to generate the optical signal. There are 16, 64, or 256 subcarriers of which 12, 48 or 192 subcarriers are modulated in 4-ASK with bit rate 30 Gb/s. The optical SNR (OSNR) is defined as OSNR =

$(R_b * \mathrm{SNR}_b)/(2B_{ref})$, where R_b is bit rate, SNR_b is bit SNR,

and B_{ref} is the reference bandwidth measured over a 12.5 GHz optical bandwidth. At the receiver, signal is detected in a back-to-back manner with coherent detection. Perfect timing synchronization is assumed, and the nonlinear effects are ignored. The 3 dB bandwidth of optical filter is 12.5 GHz. After the electrical signal is A/D converted with the deliberate timing offset as in Eq. (9), the real and imaginary

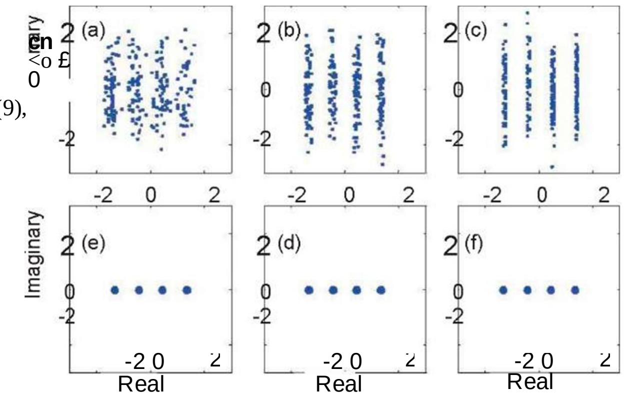

Fig. 2.Received constellations of the interleaved multiplexing optical FOFDM with (a) 16, (b) 64, and (c) 256 subchannels and that of the proposed scheme with (d) 16, (e) 64, and (f) 256 subchannels.

parts of the signal are transformed by DCT and DST of type-IV, respectively, based on Eq. (14).

10 1 1
OSNR (dB) 2 4

Fig. 3. BER performance of the conventional (conv.) [16], the ZS based [17], and the proposed (prop.) optical FOFDM schemes with 16, 64, and 256 subcarriers (4, 8, 16 out of the data subcarriers in ZS-based scheme are set to be zero-subcarrier for interference estimation).

Then, their outputs are added for decision to calculate the bit error rate (BER).

In Figs. 2(a)-(c), the received signal constellations with 16, 64, and 256 subchannels of the conventional optical interleaved multiplexing FOFDM are illustrated separately. As the number of subchannels increases, the variance of interference abates as discussed in Section 2. In Fig. 2(d)-(f), simulations are performed with the same parameters for the proposed scheme. Obviously, the interference is completely avoided irrespective of the number of subcarriers.

Fig. 3 provides the performances of the conventional [16], the zero-subcarrier (ZS) [17], and the proposed optical FOFDM schemes for comparison. In the ZS based scheme, the number of zero-subcarriers used for interference estimation are 4, 8, and 16 out of the 12, 48, and 192 data-bearing subcarriers, respectively, to balance the spectral efficiency and performance. Therefore, compared to the proposed scheme, the data rate loss is 0.34, 0.17 and 0.08, respectively.

The ZS scheme has better performance than the conventional one, especially when the number of subchannels is small, but it is inferior to the conventional scheme at low OSNR. This is because, at low OSNR and with large number of subchannels, the noise is dominant over the interference and degrades the accuracy of estimation. In the proposed scheme, these three BER curves are overlapped since the interference is completely removed irrespective of the number of subcarriers, while the BER performances of the conventional and ZS schemes are improved and approach the proposed scheme as the number of subcarriers increases. The proposed scheme outperforms both of them. For example, for 64 subchannels and at BER = 10^{-4}, the proposed scheme gets about 1 dB improvement to the ZS scheme, and for 256 subchannels and at BER = 10^{-4}, it still outperforms the conventional and ZS based ones about 0.5 dB.

V. Conclusion

In this letter, we propose a trigonometric transform based receiver for the interleaved multiplexing optical FOFDM to demultiplex the SSB signal without the interferences between the even and the odd subchannels. By deliberate frequency and timing offsets, the orthogonal bases are formed to demodulate the symbols to avoid the interference completely; its feasibility and capability are verified by analysis and simulation. By the use of fast algorithms for DCT and DST of type-IV, it provides an efficient approach to receive the SSB modulated optical FOFDM signal in terms of both complexity and performance.

Acknowledgment

The authors would like to thank the anonymous review-ers and editor for their helpful suggestion and comment to improve this letter, especially for correcting the definition of OSNR in Fig. 3.

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