IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 1 Issue 2, April 2014.
www.ijiset.com

ISSN 2348 - 7968

Comparative Study of FLIP-OFDM and ACO-OFDM for Unipolar Communication System

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Abstract

Recent advances in wireless communication systems have increased the throughout over wireless channels. Unipolar communications systems can transmit information using only real and positive signals. We consider two unipolar OFDM techniques such as FLIP-OFDM and ACO-OFDM. This includes a variety of physical channels ranging from optical, to RF wireless using amplitude modulation with non-coherent reception, to baseband single wire communications. Both the techniques enable to efficiently compensate frequency selective distortion in the unipolar communication systems. In this paper, FLIP-OFDM and ACO-OFDM have been compared and it has shown that both techniques have the same spectral energy, SNR and BER but FLIP-OFDM offers fifty percent saving in hardware complexity over ACO-OFDM.

Keywords: *Unipolar baseband communication, OFDM, non-coherent communication, FLIP-OFDM, ACO-OFDM.*

1. Introduction

A modulation that efficiently deals with selective fading channels is orthogonal frequency division multiplexing (OFDM). Specifically, it has inherent resistance to dispersion in the propagation channel. In unipolar communication, intensity modulation with direct detection (IM/DD) technique is commonly used for data transmission. However, IM/DD communication is non-coherent and transmit signal must be real and positive. These additional constraints require some special care, if OFDM is to be used in unipolar communications, since the equivalent baseband time-domain OFDM signal is usually complex. Channel dispersion or multipath fading may cause the inter-symbol interference and degrade the performance of such unipolar communication systems. To compensate these effects, unipolar OFDM can be used.

Three different unipolar OFDM techniques are described below:

- DC-offset OFDM (DCO-OFDM) [1], uses the Hermitian symmetry property with a DC-bias to generate a *real* and *positive* time domain signal. However, the DC bias depends on the PAPR of the OFDM symbol. Since OFDM has a high PAPR, the amplitude of the DC bias is generally significant. It was shown in [2] that the requirement of large DC-bias makes DCO-OFDM optically power inefficient. Conversely, the use of lower DC bias can lead to frequent clipping of the negative parts of the time-domain signal. This can cause inter-carrier interference and create out-of-band optical power.
- Asymmetrically clipped optical OFDM (ACO-OFDM) was proposed in [3] and does not require any DC bias. ACO-OFDM uses odd subcarriers to transmit information symbols, and the negative part of the time-domain signal is clipped. It was shown in [3] that this clipping does not distort information symbols in odd subcarriers, although their amplitudes are scaled by half. In [2], [4], [5], the performance of ACO-OFDM was compared to other modulation schemes such as on-off keying and DC biased OFDM (DC-OFDM); and it was shown that ACO OFDM has better power efficiency over optical wireless channels [2]. Performance of ACO-OFDM can be further improved by using bit loading and diversity combining schemes, as discussed in [6], [7], [8]. Different from the above comparison over optical wireless channels, in [9], the power efficiency comparison between ACO-OFDM, on-off keying and DC-OFDM are presented specifically for single-mode fiber optical communications.
- FLIP-OFDM [10], positive and negative parts are extracted from the real bipolar OFDM symbol generated by preserving the Hermitian symmetry property of transmitted information symbols. Then the polarity of negative parts are inverted before transmission of both positive and negative parts in two consecutive OFDM symbols. Since the transmitted signal is always positive, so FLIP-OFDM that can be used for unipolar communications.

2. Model for Unipolar Communication

A non-coherent communication system can be modeled as a linear baseband equivalent system, as shown in Fig.1. Let $x(t)$, $h(t)$ and $z(t)$ represent the transmit signal (e.g. intensity or amplitude signal), the channel impulse response, and the noise component, respectively. Then the non-coherent communication is said to be unipolar if the following two conditions are satisfied:

1. $x(t)$ is real and $x(t) \geq 0$ for all t.
2. if the equivalent received signal y(t) can be modeled as

$$y(t) = h(t) \otimes x(t) + z(t) \qquad (1)$$

where $\otimes$ represents convolution, $h(t) \geq 0$ for all t and $z(t)$ is Gaussian noise with zero mean and power σ_z^2. If the channel is normalized such that $\int_{-\infty}^{+\infty} |\mathrm{h(t)}|^2 \mathrm{dt} = 1$, then the equivalent signal-to-noise ratio (SNR) is defined as [11]

$$SNR = \frac{E[x^2(t)]}{\sigma_z^2} \qquad (2)$$

where $E[\cdot]$ is the expectation operator.

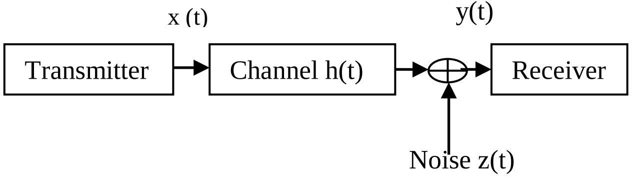


Fig. 1 Model for unipolar communication system.

Following are common examples for such unipolar communication systems:

- Optical communications (fiber or free space)
- Amplitude Modulated RF Wireless
- Baseband digital communication

3. Techniques for Unipolar OFDM

Two techniques, we compare FLIP-OFDM and ACO-OFDM for unipolar communication systems.

3.1 FLIP-OFDM

A block diagram of FLIP-OFDM transmitter is shown in Fig.2. Let X_n be the transmitted QAM symbol in the n-th OFDM subcarrier. The output of Inverse Fast Fourier Transform (IFFT) operation at the k-th time instant is given by

$$x(k) = \sum_{n=0}^{N-1} X_n \exp(\frac{j2\pi nk}{N}) \qquad (3)$$

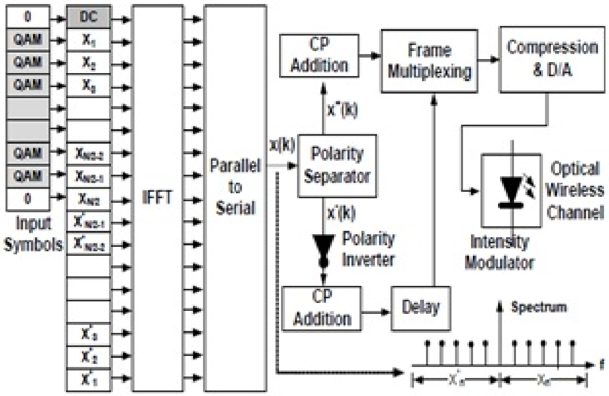


Fig. 2 Block diagram of FLIP-OFDM transmitter.

where N is the IFFT size and $j^2 = -1$. If the symbol X_n transmitted over each OFDM subcarrier is independent, the time-domain signal $x(k)$ produced by the IFFT operation is complex. A real signal can be then obtained by imposing the Hermitian symmetry property

$$X_n = X_{N-n}^*, \qquad n = 0,1,2, \dots \dots, \frac{N}{2} - 1 \qquad (4)$$

where * denotes complex conjugation. This property implies that half of the OFDM subcarriers are sacrificed to generate the real time-domain signal. The output of IFFT operation in (3) can be rewritten as [11]

$$x(k) = X_0 + \sum_{n=0}^{\frac{N}{2}-1} X_n \exp(\frac{j2\pi nk}{N}) + X_{N/2} \exp(j\pi k) + \sum_{n=\frac{N}{2}+1}^{N-1} X_{N-n}^* \exp(\frac{j2\pi nk}{N}) \qquad (5)$$

where X_0 is the DC component. To avoid any DC shift or any residual complex component in the time domain signal, we let

$$X_0 = X_{N/2} = 0. \qquad (6)$$

In such a way, the output of the IFFT operation is a real bipolar signal. We can then decompose the bipolar signal as

$$x(k) = x^+(k) + x^-(k) \qquad (7)$$

where the positive and negative parts are defined as

$$x^+(k) = \begin{cases} x(k) & if\ x(k) \geq 0 \\ 0 & otherwise \end{cases}$$

$$x^-(k) = \begin{cases} x(k) & if\ x(k) < 0 \\ 0 & otherwise \end{cases} \qquad (8)$$

and k = 1, 2, ...,N. These two components are separately transmitted over two successive OFDM symbols. The positive signal $\mathrm{x}^+(\mathrm{k})$ is transmitted in the first subframe (positive subframe), while the flipped (inverted polarity) signal $-\mathrm{x}^-(\mathrm{k})$ is transmitted in the second subframe (negative subframe). Since the transmission is over a frequency selective channel, the cyclic prefixes composed of Δ samples are added to each of the OFDM subframes. Hence, the negative OFDM subframe is delayed by (N + Δ) and transmitted after the positive subframe.

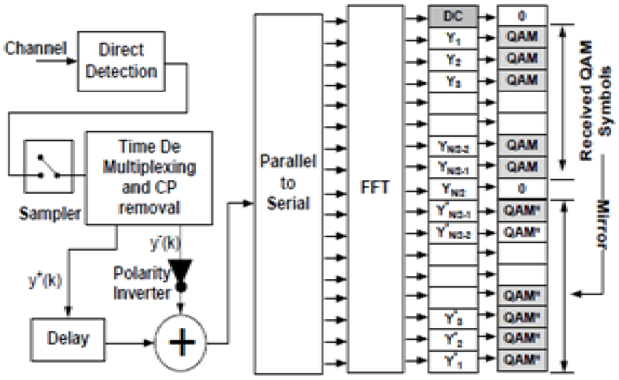


Fig. 3 Block diagram of FLIP-OFDM receiver.

The reconstruction of the bipolar OFDM frame and the detection process at the receiver are illustrated in Fig.3. The cyclic prefixes associated with each OFDM subframe are removed. Then the original bipolar signal is reconstructed as [11]

$$y(k) = y1(k) - y2(k) \qquad (9)$$

where $y1(k)$ and $y2(k)$ represent the time-domain samples received in the positive and negative subframes, respectively. The Fast Fourier Transform (FFT) operation is performed on the bipolar signal to detect the transmitted QAM information symbols.

3.2 ACO-OFDM

A block diagram of an ACO-OFDM transmitter is shown in Fig.4. At the transmitter, the QAM information symbols are first mapped into the first half of the odd subcarriers, X_{2n+1}, where $n = 0, 1, 2, ..., N/4 - 1$. The even subcarriers are set to zero, i.e.

$$X_{2n} = 0, \quad n = 0,1,2,\ldots,N/2 \qquad (10)$$

Using the above equation, the DC component and the symbol of the $\frac{N}{2}$-th subcarrier become zero. The Hermitian symmetry property in (4) is used to construct a real signal. After the IFFT operation, the time-domain OFDM symbol $x(k)$ can be computed using (5) and has an odd symmetry property

$$x(k) = -x(k + \frac{N}{2}) \qquad (11)$$

This allows clipping of the negative time samples of $x(k)$ right after the DA conversion at the transmitter without destroying the original information. The clipped signal $x_c(t)$ is a unipolar signal, defined as [11]

$$x_c(t) = \begin{cases} x(t) & if\ x(t) \geq 0 \\ 0 & otherwise \end{cases} \qquad (12)$$

The cyclic prefix is then added to the clipped unipolar OFDM symbol before the transmission.

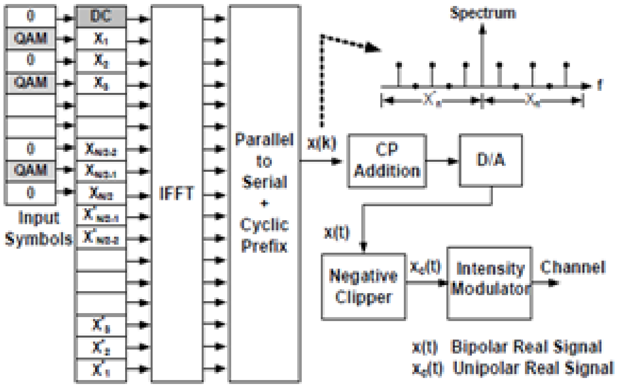


Fig. 4 Block diagram of ACO-OFDM transmitter

The direct detection (DD) of the received signal $y(t)$ is performed at the receiver, as illustrated in Fig.5. The cyclic prefix of the OFDM symbol is removed and the serial-to-parallel conversion is performed. The FFT operation is performed and finally the QAM information symbols contained in the odd subcarriers can be detected.

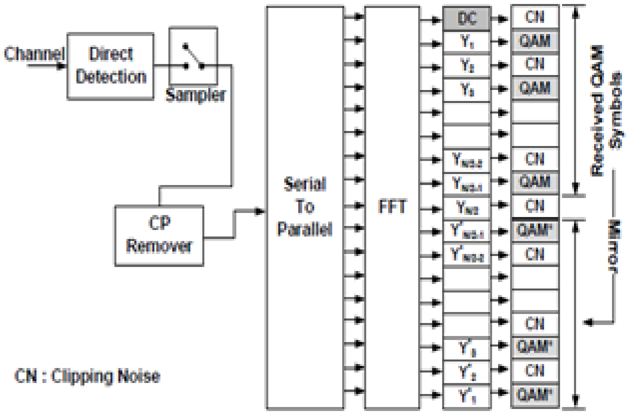


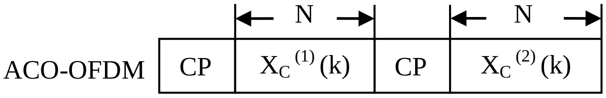
Fig. 5 Block diagram of ACO-OFDM receiver

3.3 Comparison between FLIP-OFDM and ACO-OFDM

We use the same optical channel model with the same delay spread.

3.3.1 Modification to FLIP-OFDM:

Note that the original FLIP-OFDM [10] uses the compression of time samples to be compliant with the standard bipolar OFDM symbol length. Given the same bipolar OFDM symbol length for both systems, this compression in FLIP-OFDM leads to half length of each cyclic prefix, when compared to that of ACO-OFDM. This implies that both systems have different capabilities to combat delay spread distortion of the channel.



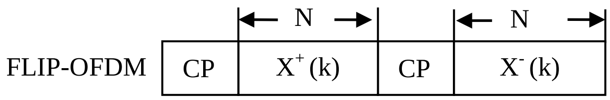


Fig. 6 OFDM symbol structure used to compare FLIP-OFDM and ACO-OFDM. We assume FFT and IFFT sizes of both ACO-OFDM and FLIP-OFDM are the same. N denotes the FFT and IFFT size for each case.

Here, we do not compress the time scale and two consecutive OFDM symbols of FLIP-OFDM have the same bandwidth and the same cyclic prefix as those of ACO-OFDM, as shown in Fig.6.

3.3.2 Spectral Efficiency: In ACO-OFDM, each OFDM symbols (i.e. $x_c^{(1)}$ *and* $x_c^{(2)}$) has N/4 information symbols.

However, in FLIP-OFDM, even though each symbol has twice of the number of information symbols (i.e. N/2), both positive and negative OFDM subframes are required to extract the original transmitted information symbols.

Given the same bandwidth, the spectral efficiencies of both schemes are indeed the same [11].

3.3.3 Symbol Energy: In FLIP-OFDM, the energy of an information symbol is spread across the positive and negative OFDM subframes during the flipping process, as shown in Fig.7. However, this spread energy is fully recovered at the receiver by the recombination of the subframes.

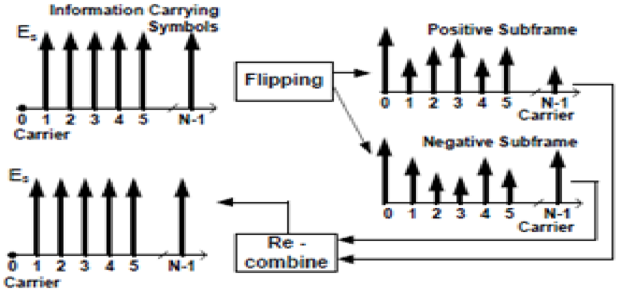


Fig. 7 FLIP-OFDM: Effects on symbol energy during the flipping and the recombination process

In ACO-OFDM, since the OFDM symbol is symmetric around time axis, the clipping preserves half of the original signal energy and scales the amplitude of the original symbols by half

$$X_{2n+1}^{c} = \frac{1}{2} X_{2n+1} \qquad (13)$$

Where, X_{2n+1}^{c} denotes the information carrying symbol after the asymmetric clipping process.

Hence, the energy of information carrying symbol is reduced by a fraction of four, while the clipping has shifted the other quarter of the signal energy (half of the signal energy is lost during the clipping process) into the odd subcarriers, as illustrated in Fig.8. This energy in the odd subcarriers is known as clipping noise [3], [4].

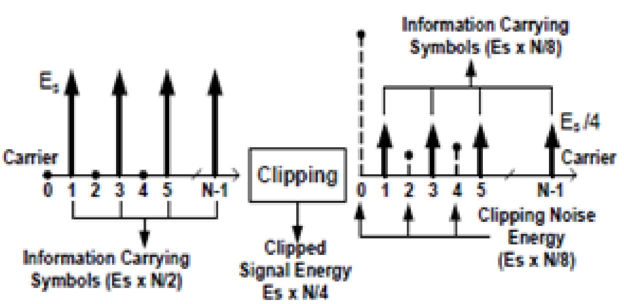


Fig. 8 ACO-OFDM: Effects on symbol energy due to the asymmetric clipping

Therefore, the energy of an information symbol in FLIP-OFDM is twice the amount of ACO-OFDM for a given transmitted power.

3.3.4 Noise Power: In FLIP-OFDM, the noise power of received information symbols is $2\sigma_z^2$[12].

In ACO-OFDM, since there is no recombination, the received information symbol is given by

$$R_{2n+1} = \frac{1}{2} H_{2n+1} X_{2n+1} + Z_{2n+1} \qquad (14)$$

and the noise power is σ_z^2 , which is half of the amount in FLIP-OFDM.

3.3.5 Equivalent SNR: Since half of the transmitted signal energy is preserved in ACO-OFDM and the other half is the clipping noise, the SNRs of both ACO-OFDM and FLIP-OFDM are indeed the same. Using (2), the equivalent SNR per received sample is given by [11]

$$\mathrm{SNR} = \frac{\sigma_x^2}{2\sigma_z^2} \qquad (15)$$

where, σ_z^2 is the transmitted signal power.

3.3.6 Bit Error Rates: The analytical BER expression for both FLIP-OFDM and ACO-OFDM in AWGN channels can be computed as [14]

$$P_b \simeq \frac{2}{\log_2 M}\left(1-\frac{1}{\sqrt{M}}\right) erfc(\sqrt{\frac{3}{2(M-1)}} SNR) \qquad (16)$$

for a rectangular M-QAM constellation, where $erfc(\cdot)$ is the complementary error function.

The simulated BER performance of FLIP-OFDM and ACO-OFDM for the specified optical wireless channel having strong LOS signal (Directed, has AWGN characteristics [13]) and multipath propagation signals (Non directed or Diffused mode), were compared in [12]. It was shown in [12] that both systems have the same BER performance, which can be accurately predicted by (16).

3.3.6 Complexity: We define complexity as the number of FFT/IFFT operations at the transmitter or the receiver. A complexity comparison is given in Table 1. At the transmitter, both schemes have nearly the same complexity for a significant value of N, given the IFFT operation at ACO-OFDM is optimized by zeroing half of subcarriers. However, at the receiver, FLIP-OFDM has a fifty percent of complexity savings compared to ACO-OFDM.

4. Conclusions

This paper focuses on the comparative study of FLIP-OFDM and ACO-OFDM for uni-polar communication systems. It has been observed that FLIP-OFDM is equivalent to the well-known ACO-OFDM in terms of spectral efficiency and error performance, but it can save nearly fifty percent of receiver complexity over ACO-OFDM.

Table 1: Complexity comparison of FLIP-OFDM and ACO-OFDM

Complexity	**ACO-OFDM**	**FLIP-OFDM**
Transmitter	$2\left(\frac{N}{2}\right)\log(\frac{N}{2})$	$N\log(N)$(BETTER)
Receiver	$2N\log(N)$	$N\log(N)$(BETTER THAN ACO-OFDM)

Table 2: Comparison between various parameters of FLIP-OFDM and ACO-OFDM

Parameters	**ACO-OFDM**	**FLIP-OFDM**
Spectral Efficiency	Same	Same
Symbol Energy	Same	Twice
Noise Power	σ_z^2(Less)	$2\sigma_z^2$(More)
SNR	$SNR = \frac{\sigma_x^2}{2\sigma_z^2}$(Same)	$SNR = \frac{\sigma_x^2}{2\sigma_z^2}$(Same)
Bit Error Rates	$P_b \simeq \frac{2}{\log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) erfc\left(\sqrt{\frac{3}{2(M-1)}}SNR\right)$ (Same)	$P_b \simeq \frac{2}{\log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) erfc(\sqrt{\frac{3}{2(M-1)}}SNR)$ (Same)

Thus, Flip-OFDM is an alternative and efficient unipolar OFDM technique which has potential applications in unipolar communication. Future work will focus on the potentials of FLIP-OFDM for non-coherent RF wireless communications.

Acknowledgments

The author would like to thank the anonymous reviewers for their helpful comments and suggestions.

References

[1] J. Armstrong, "OFDM for optical communications," *J. Lightwave Technol.*,vol. 27, no. 3, pp. 189–204, Feb. 2009.

[2] J. Armstrong and B. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-Biased optical OFDM in AWGN," *IEEE Commun. Lett.*, vol. 12, no. 5, pp. 343–345, May 2008.

[3] J. Armstrong and A. Lowery, "Power efficient optical OFDM," *Electron. Lett.*, vol. 42, no. 6, pp. 370–372, Mar. 2006.

[4] J. Armstrong, B. Schmidt, D. Kalra, H. Suraweera, and A. Lowery, "Performance of asymmetrically clipped optical OFDM in AWGN for an intensity modulated direct detection system," in *Proc. 2006 IEEE Global Telecommun. Conf.*, pp. 1–5.

[5] X. Li, R. Mardling, and J. Armstrong, "Channel capacity of IM/DD optical communication systems and of ACO-OFDM," in *Proc. 2007 IEEE International Conf. Commun.*, pp. 2128–2133.

[6] S. Wilson and J. Armstrong, "Digital modulation techniques for optical Asymmetrically-Clipped OFDM," in *Proc. 2008 IEEE Wireless Commun. Netw. Conf.*, pp. 538–542.

[7] S. Wilson and J. Armstrong, "Transmitter and receiver methods for improving asymmetrically-clipped optical OFDM," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4561–4567, Sep. 2009.

[8] L. Chen, B. Krongold, and J. Evans, "Diversity combining for asymmetrically clipped optical OFDM in IM/DD channels," in *Proc. 2009 IEEE Global Telecommun. Conf.*, pp. 1–6.

[9] D. J. F. Barros and J. M. Kahn, "Comparison of orthogonal frequencydivision multiplexing and ONOFF keying in direct-detection multimode fiber links," *J. Lightwave Technol.*, vol. 29, no. 15, pp. 2299–2309, Aug. 2011.

[10] J. Yong, "Modulation and demodulation apparatuses and methods for wired / wireless communication," Korea Patent WO2007/064 165 A, 07, 2007.

[11] *Fernando, Nirmal, Yi Hong, and Emanuele Viterbo*., "Flip-OFDM for unipolar communication system", pp. 1-8, 2011.

[12] *N. Fernando, Y. Hong, and E. Viterbo*, "Flip-OFDM for optical wireless communications", in IEEE Information Theory Workshop, Paraty, Brazil, September 2011.

[13] *V. Jungnickel, V. Pohl, S. Nonnig, and C. von Helmolt*, "A physical model of the wireless infrared communication channel", IEEE J. on Selected Areas in Communications, vol. 20, no. 3, pp. 631–640, April 2002.

[14] *J. G. Proakis*, **"**Digital Communications", 4th ed. McGraw-Hill, 2001.