Fast-OFDM Transmission with Duobinary 3-PSK Modulation

(Invited Paper)

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***Abstract*—This paper investigates duobinary signals and their applications in non-orthogonal multi-carrier systems to enhance spectral efficiency. In duobinary transmission schemes, the signal spectrum is reshaped by introducing controlled correlation, which can be eliminated at the duobinary decoder. For the first time, we propose the idea of combining duobinary transmission technique and the fast orthogonal frequency division multiplexing (Fast-OFDM) system with three sub-carriers, with experimental results presented. The proposed system is capable of achieving three times the data rate of single-carrier ASK scheme with the same bandwidth. Results show that bit error rate (BER) performance of the proposed duobinary-based Fast-OFDM system is slightly worse than the ASK system. In addition, we also tested various 3-PSK constellation patterns designed for the duobinary signal to achieve performance improvement.**

***Keywords*—duobinary, 3-PSK modulation, waveform, non-orthogonal, ASK modulation, Fast-OFDM, spectral efficiency.**

I. INTRODUCTION

The scarcity of available radio frequency (RF) spectrum continues to drive significant research interest in spectral efficiency improvement. Non-orthogonal systems have been proposed as potential solutions to mitigate the problem. Faster-than-Nyquist (FTN) signaling was initially proposed by Mazo to further enhance the spectral efficiency, of single carrier systems, by relaxing the limitation of Nyquist criterion. The work indicated that the signaling rate can be increased by up to 25% without causing performance degradation [1]. Consequently, various kinds of spectrally efficient multi-carrier systems were put forward. Fast orthogonal frequency division multiplexing (Fast-OFDM) [2], [3] and M-ary amplitude shift keying (MASK) [4] can both reduce the bandwidth utilization by half, in a way similar to minimum shift keying (MSK), with the limitation that only one dimensional modulation schemes are applicable in the systems. High compaction multi-carrier communications (HC-MCM) was introduced by overlapping subcarrier spectra to achieve higher transmission data rate [5]. Previous work on spectrally efficient frequency division multiplexing (SEFDM) presented the idea of breaking the subcarrier orthogonality intentionally to compress the subcarrier frequency spacing and realize bandwidth saving [6], [7]. Both of these techniques extend the application scenarios to two dimensional modulation schemes.

The duobinary modulation scheme was initially introduced, in 1963, by Lender with an idea of intentionally introducing "controlled" interference into the transmitted signals to reshape the signal spectrum and concentrate most power at the lower frequency end of the signal spectrum [8]. Due to the correlative property in duobinary scheme, it was also termed as correlative coding in some publications [9]. Subsequently, a more generalized version of correlative coding came to light with multi-level signal form to achieve higher data throughput at the cost of BER performance [10]. Based on the work in [8], precoding techniques were put forward as effective methods to mitigate error propagation in partial response signaling [11], [12]. Additionally, as for signal detection, maximum likelihood (ML) algorithm was implemented in the correlative coding schemes with obvious system performance improvement [13]. More recently, the duobinary signal has been gaining popularity as a potential signal candidate for in optical fiber communication due to its spectral efficiency and immunity against chromatic dispersion [14], [15]. In terms of multipath channels, research in [16] indicated that partial response signaling was capable of mitigating inter-symbol interference (ISI) effectively with substantial performance gain.

ASK modulation has been widely used in various application scenarios ranging from biomedical implants [17] to millimeter-wave radio-over-fiber systems [18] because of implementation simplicity and feasibility. In this paper, we apply duobinary techniques in Fast-OFDM system to achieve substantial data throughput enhancement relative to ASK modulation scheme of the same bandwidth. Here we employ three subcarriers in the duobinary-based Fast-OFDM system and compare to a single-carrier ASK system in terms of spectral efficiency and BER performance. Furthermore, we show implementation of the proposed system practical software defined radio (SDR) testbed for verification.

II. SIGNAL MODEL

A. Duobinary and Modified Duobinary Signals: preliminaries

Nyquist first criterion indicates that it is possible to realize zero ISI with proper pulse shaping filters, so that a corresponding signal $s(t)$ can be expressed as:

$$s(nT_s) = \begin{cases} 1, & n = 0 \\ 0, & otherwise \end{cases} \tag{1}$$

where T_s represents the symbol period and the integer n defines an n^{th} sample of the signal at multiples of T_s. It is possible to design appropriate pulse shaping filters based on (1). One representative signal pulse $p(t)$ that meets the condition in (1) is denoted by

$$p(t) = \frac{\sin\left(\frac{\pi t}{T_s}\right)}{\frac{\pi t}{T_s}} = \text{sinc}\left(\frac{\pi t}{T_s}\right) \tag{2}$$

Its corresponding pulse spectrum can be therefore expressed as

$$P(f) = \begin{cases} T_s, & |f| \le \omega \\ 0, & otherwise \end{cases} \quad (3)$$

As a consequence, the signal pulse $p(t)$ is a special case of raised-cosine filter family with the roll-off factor $\beta = 0$. Note that the corresponding symbol rate R_s is given by

$$R_s = \frac{1}{T_s} = 2W \quad (4)$$

where W is the channel bandwidth and the symbol rate here reaches the Nyquist rate theoretically with zero ISI. However, the signal pulse defined in (2) is non-causal and therefore cannot be practically implemented.

On the other hand, it is possible to relax the limitation of Nyquist criterion by introducing some controlled amount of ISI which, with judicious design, can be eliminated easily at the receiver. As a consequence, the achieved symbol rate is capable of reaching the Nyquist rate given in (4) feasibly. Here we explore two practically realizable examples which are known as duobinary and modified duobinary signals respectively. The signal pulse $s(t)$is generated by making the use of signal correlation which can be given by

$$s(nT_s) = \begin{cases} 1, & n = 0,1 \\ 0, & otherwise \end{cases} \quad (5)$$

One special case that meets the condition depicted in (5) is the duobinary signal pulse $p_{duo}(t)$ expressed as [19]

$$p_{duo}(t) = \text{sinc}\left(\frac{\pi t}{T_s}\right) + \text{sinc}\left[\pi\left(\frac{t}{T_s} - 1\right)\right] \quad (6)$$

Therefore, the corresponding pulse spectrum $P_{duo}(t)$ can be obtained as

$$P_{duo}(f) = \begin{cases} \frac{1}{2W}\left(1 + e^{\frac{-j\pi f}{W}}\right), & |f| \le \omega \\ 0, & otherwise \end{cases} \quad (7)$$

In addition, another similar approach of introducing controlled correlation is denoted by signal pulse $s'(t)$ [19]

$$s'(nT_s) = \begin{cases} 1, & n = -1 \\ -1, & n = 1 \\ 0\ , & otherwise \end{cases} \quad (8)$$

The corresponding modified duobinary pulse p_{mod} that meets the condition in (8) can be specified as

$$p_{mod}(t) = \text{sinc}\left(\frac{\pi(t+T_s)}{T_s}\right) - \text{sinc}\left(\frac{\pi(t-T_s)}{T_s}\right) \quad (9)$$

As a consequence, the signal pulse spectrum is given by

$$P_{duo}(f) = \begin{cases} \frac{1}{2W}\left(e^{\frac{j\pi f}{W}} - e^{\frac{-j\pi f}{W}}\right), & |f| \le \omega \\ 0, & otherwise \end{cases} \quad (10)$$

The signal pulse shapes of duobinary and modified duobinary together with their corresponding frequency spectrum are illustrated in Fig.1 (a) and (b), rexpectively. Note that we show the ideal raised-cosine pulse shape with $\beta = 0$ for comparison. As Fig.1 (b) shows, power in the duobinary spectrum reduces from a maximuum at $f = 0$ to zero at band edges while is zero power at frequency $f = 0$ in modified duobinary signals. Both duobinary schemes provide practical pulse shaping methods to achieve the symbol rate of twice the bandwidt (=$2W$).

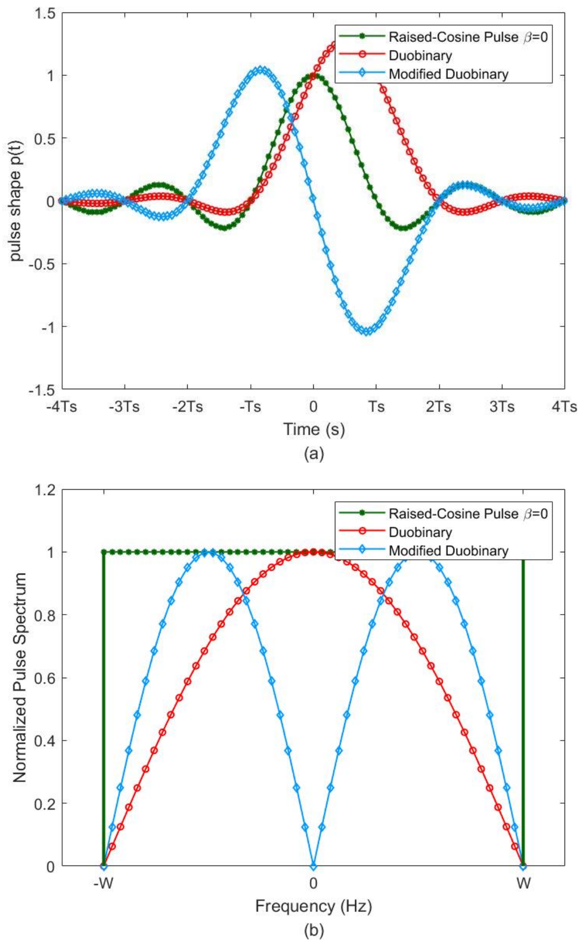


Fig. 1. Ideal raised-cosine pulse shape (β = 0), duobinary and modified duobinary signal pulses: (a) pulse shapes in time domain (b) pulse spectrum.

In order to mitigate error propagation, precoding is applied before the duobinary signal is generated from a binary sequence b_l. The precoding sequence for duobinary signal can be expressed as

$$a_l = b_l \oplus a_{l-1} \quad (11)$$

where $\oplus$ represents the XOR operation in binary. A binary sequence $p_l = 2a_l - 1$ is generated and this represents the precoding sequence with amplitudes -1 and 1. Subsequently, the duobinary sequence d_l is generated, based on the sequence p_l, as

$$d_l = p_l + p_{l-1} \quad (12)$$

For modified duobinary the equivalent precoding and signal generation can be denoted as

$$a'_l = b_l \oplus a'_{l-2} \quad (13)$$

$$d'_l = p'_l - p'_{l-2} \quad (14)$$

where a'_l is the precoding sequence for modified duobinary, and p'_l is the corresponding precoding sequence with amplitudes -1 and 1. d'_l is the obtained three-level modified duobinary signal.

At the receiver, appropriate decoding is required to remove the introduced ISI effect. The corresponding decoding rules for duobinary and modified duobinary are given as

$$\hat{b}_l = \begin{cases} 1 & |d_l| \le 1 \\ 0 & |d_l| > 1 \end{cases} \quad (15)$$

$$\hat{b}'_l = \begin{cases} 0 & |d'_l| \le 1 \\ 1 & |d'_l| > 1 \end{cases} \quad (16)$$

where $\hat{b}_l$ is the received binary sequence after duobinary decoder and $\hat{b}'_l$ is the received binary sequence for modified duobinary scheme.

B. 3-PSK Constellation Design

In this section, we investigate several mapping schemes designed for duobinary signal to seek good constellation mapping. Four constellation patterns are given in Fig. 2 below. Fig. 2 (a) and (b) are the original duobinary signal patterns. Duobinary constellation pattern in Fig. 2 (b) is generated by polarization of binary precoding sequence in (11), and the amplitudes of generated duobinary sequence are -2, 0 and 2, respectively. Based on the idea of M-ary PSK modulation, we explored two types of triangular shaped constellation patterns shown in Fig. 2 (c) and (d) separately. Corresponding spectrum and BER results are provided in Section □.

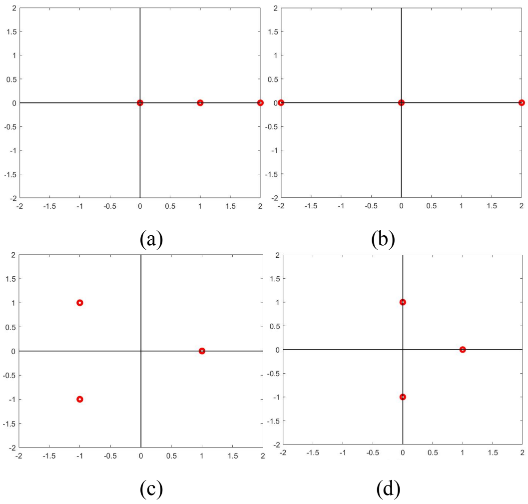


Fig. 2. 3-PSK constellation patterns designed for the duobinary signal (a) duobinary constellations [0 1 2] (b) duobinary constellations [-2 0 2] (c) 3-PSK constellations [-1-1j 1 -1+1j] (d) 3-PSK constellations [-1j 1 1j]

III. System Model

A. Fast-OFDM System

The Fast-OFDM system was proposed as a variant of the OFDM, which can double the data rate of the OFDM system for a given bandwidth without performance degradation. The Fast-OFDM signal can be expressed as

$$x(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N-1} S_{k,n}\, l_n(t-kT) \quad (17)$$

where N is the number of subcarriers and l_n is the n^{th} subcarrier in the Fast-OFDM system, which can be given as

$$l_n(t) = \frac{1}{\sqrt{T}} \exp(j2\pi\alpha n\Delta f t),\ t \in [0,T] \quad (18)$$

where $S_{k,n}$ is the transmitted symbol carried by n^{th} subcarrier in the k^{th} time slot. T is the corresponding symbol duration. α is the bandwidth compression factor, where $\alpha = 1$ represents the OFDM system (uncompressed) and $\alpha = 0.5$ is the corresponding Fast-OFDM system.

By assuming ideal channel conditions, which means that the received signal $r(t) = x(t)$, and the corresponding received symbol $R_{k,n}$ is obtained as

$$R_{k,n} = \int_{kT}^{(k+1)T} r(t) l_n^*(t-kT)dt \quad (19)$$

where $r(t)$ can be substituted by $x(t)$ in (17), and (19) can be rephrased as

$$R_{k,n} = \sum_{n'=0}^{N-1} S_{k,n'} \mathrm{sinc}\left(\frac{n'-n}{2}\right) \exp(j\pi(n'-n)/2) \quad (20)$$

The corresponding real part and imaginary part of the received symbol $R_{k,n}$ are therefore expressed as

$$\mathcal{Re}\{R_{k,n}\} = \sum_{n'=0}^{N-1} \mathcal{Re}\{S_{k,n'}\} \mathrm{sinc}\left(\frac{n'-n}{2}\right) \cos\left(\frac{\pi(n'-n)}{2}\right) = \mathcal{Re}\{S_{k,n}\} \quad (21)$$

$$\mathcal{Im}\{R_{k,n}\} = \sum_{n'=0}^{N-1} \mathcal{Re}\{S_{k,n'}\} \mathrm{sinc}\left(\frac{n'-n}{2}\right) \sin\left(\frac{\pi(n'-n)}{2}\right) \neq 0 \quad (22)$$

The real and imaginary values of subcarriers correlation coefficient, for different frequency spacing, are depicted in Fig. 3 (a) and (b), respectively. For orthogonal subcarrier spacing (as in OFDM systems) product $\Delta f \cdot \mathrm{T}$ is an integer. As shown in the figure, there is no interference in the real parts of two subcarriers with the subcarrier spacing specified by $\Delta f \cdot \mathrm{T} = \frac{m}{2}$, m ∈ N. As a result, the real part of transmitted symbols in Fast-OFDM system can be correctly recovered, while there will be interference in the imaginary part due to subcarrier non-orthogonality. In other words, only one-dimensional modulation schemes may be used in Fast-OFDM.

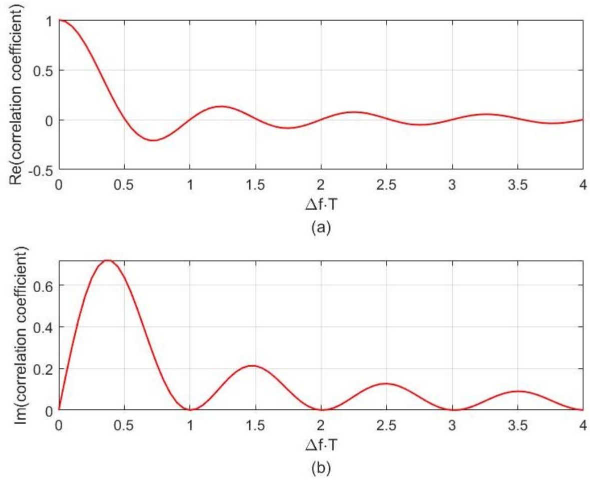


Fig. 3. Subcarrier correlation coefficient versus frequency spacing (a) real part (b) imaginary part.

B. Duobinary-based Fast-OFDM System

By assuming that rectangular NRZ pulse is used, the corresponding power spectral density of binary $G_1(f)$ and duobinary $G_2(f)$ schemes can be expressed as [6]

$$G_1(f) = \frac{T}{4}\left(\frac{\sin(\pi f T)}{\pi f T}\right)^2 \tag{23}$$

$$G_2(f) = \frac{T}{4}\left(\frac{\sin(2\pi f T)}{2\pi f T}\right)^2 \tag{24}$$

where T is the time duration for the NRZ pulse and the bandwidth is exactly compressed by half from binary to duobianry. As a result, the spectrum property of the proposed duobinary-based Fast-OFDM system is given in Fig. 4, where blue dotted line represents the single-carrier ASK scheme and red lines are the three subcarriers in Fast-OFDM system with corresponding carrier frequency f_0, f_1, and f_2 respectively. The bandwidth of two object systems is the same, while the proposed duobinary multi-carrier system provide three times the data rate of its ASK counterpart.

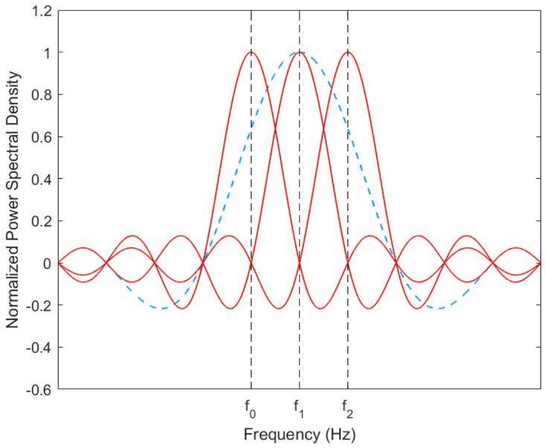


Fig. 4. Theoretical Spectral density of single-carrier ASK and 3-subcarrier duobinary-based Fast-OFDM system.

IV. Practical Implementation

Fig. 5 below provides details about practical testing of the proposed system. A sequence of binary bits b_i is initially generated randomly which then acts as input to the duobinary encoder to generate the corresponding duobinary sequence d_i. The Fast-OFDM subcarrier matrix $\boldsymbol{F}$ and its conjugate matrix $\boldsymbol{F}^*$ are created based on (18). Subsequently, The duobinary sequence stream is converted into three parallel substreams $\boldsymbol{S}$ which are then carried by individual Fast-OFDM subcarriers. The generated statistics $\boldsymbol{X}$ are downloaded and processed by the Analogue Devices' Software Defined Radio (SDR) ADALM-Pluto, which then generates and transmits the modulated analogue signal $x(t)$. After transmitting over the wireless channel, the received signal $y(t)$ is captured by an antenna and then converted into discrete statistics $\boldsymbol{Y}$ which is followed by the signal demodulation to restore the parallel substreams $\widehat{\boldsymbol{S}}$. Due to Fast-OFDM system property, we take the real part of received symbols to generate an estimate of the duobinary sequence $\widehat{d_i}$. Consequently, corresponding duobinary decoding is performed and the estimated binary stream is generated for BER calculation.

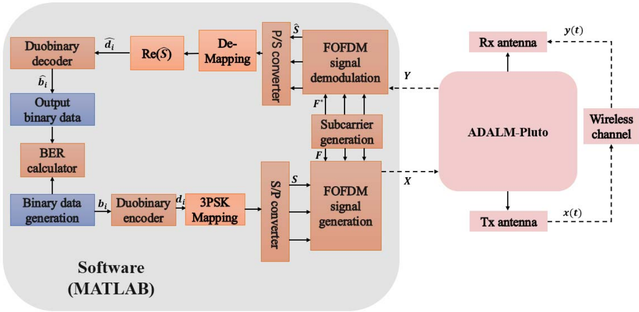


Fig. 5. Experiment setup for the pratical testing on ADAML-Pluto.

Related experiment parameter setting is provided as follows. The bit rate R_b for the duobinary system is set to be $R_{Duo} =$ 30kbits/s and the baseband sampling frequency $f_s =$ 1 MHz. The transmitted center frequency $f_c$in ADALM-Pluto is specified as 2.4 GHz. In addition, corresponding transmitter receiver gains are -10 dB and 10 dB, respectively.

V. Results and Discussion

In this section, we provide spectrum and BER simulation results of 3-PSK mapping schemes depicted in Fig. 2. In addition, this part investigates the proposed system property and evaluates system performance based on the simulation and practical testing results. Additive White Gaussian Noise (AWGN) channel is applied in the system simulation to measure corresponding BER performance. Note that the proposed system data rate is set to be three times the data rate of single-carrier ASK system.

A. Simulation Results

Corresponding BER results of the explored 3-PSK schemes are provided in Fig. 6. It may be observed (in Fig. 6) that the duobinary signal, after polarization, provides more immunity against AWGN noise in comparison to duobinary signal with amplitudes of 0, 1 and 2. In addition, the proposed triangular shaped 3-PSK scheme (c) achieves substantial BER performance enhancement, which provides approximately2 dB extra gain in $Eb/N0$ when compared with duobinary signal with amplitudes of -2, 0 and 2, while constellation pattern (d) is only slightly better than that of the duobinary scheme.

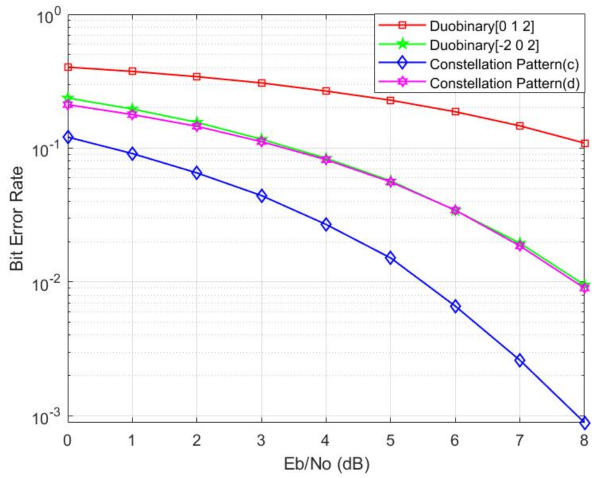


Fig. 6. Corresponding BER results of constellation patterns in Fig. 2.

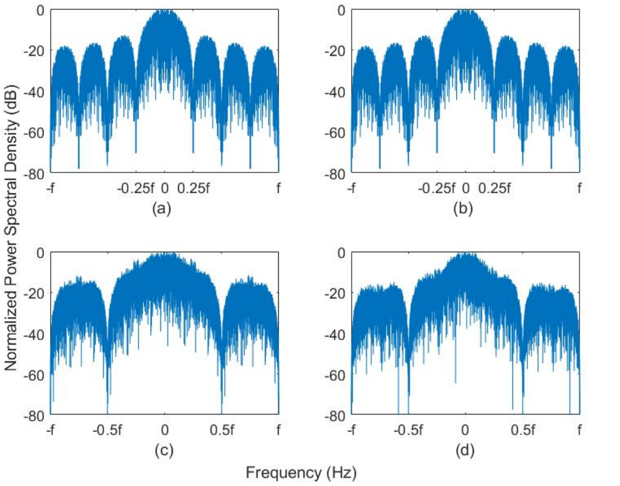


Fig. 7. Corresponding spectrum results of constellation patterns in Fig. 2 (a) duobinary constellations [0 1 2] (b) duobinary constellations [-2 0 2] (c) 3-PSK constellations [-1-1j 1 -1+1j] (d) 3-PSK constellations [-1j 1 1j]

Fig. 7 illustrates the spectra of duobinary signal and proposed 3-PSK schemes. As a result, it turns out that 3-PSK constellation patterns in Fig. 7 (c) and (d) will "lose" the duobinary spectrum property and the initially introduced signal correlation is violated. On the other hand, Fig. 7 (a) and (b) correspond to the aligned constellation patterns and maintain the duobinary spectrum property. As a result, we adopted duobinary signal format (b) in Fig. 2 in the following simulation for its duobinary spectrum property and better performance.

Fig. 8 below compares the simulation results of 3-subcarrier duobinary and single-carrier ASK systems, where f_c represents the carrier frequency in ASK scheme, while f_1, f_2 , and f_3 are the corresponding carrier frequency of individual subcarriers in the duobinary system. As a consequence, results show that the bandwidth of two systems is practically the same, however, the proposed duobinary system is achieves *three times* the data rate of the single-carrier ASK system.

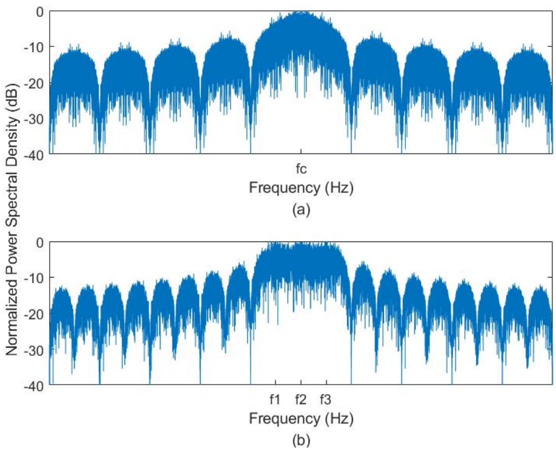


Fig. 8. Power spectral density of (a) single-carrier ASK (b) duobinary-based Fast-OFDM system (3 subcarriers).

Fig. 9 presents constellation diagrams of received duobinary signal in Fast-OFDM system, over channels with and without AWGN noise. There are three straight constellation lines clearly shown in the Fig. 9 (a) and (b), which represent three-level digits of duobinary signal, respectively. Clearly the proposed duobinary system maintains the signal property of the Fast-OFDM system and hence the real part of received symbols can be correctly recovered.

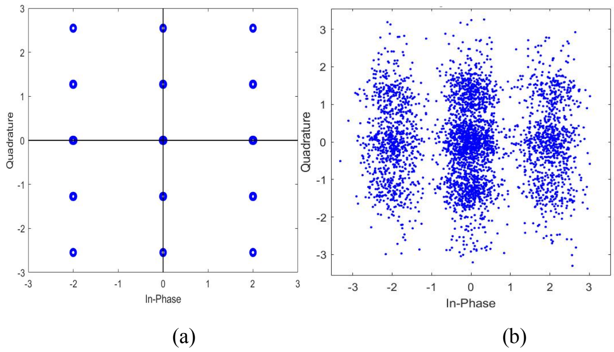


Fig. 9. Constellation diagram of received duobinary signals in the Fast-OFDM system (a) ideal channel (b) $Eb/No = 10$ dB

BER results of ASK and the duobinary-based Fast-OFDM systems are provided in Fig. 10 and clearly show the two duobinary schemes to have almost identical error performance with 1 dB error penalty relative to ASK.

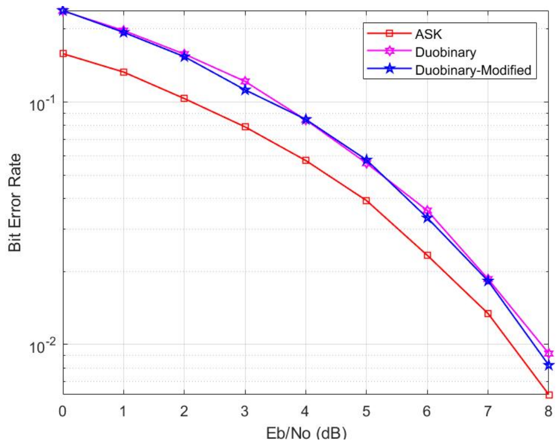
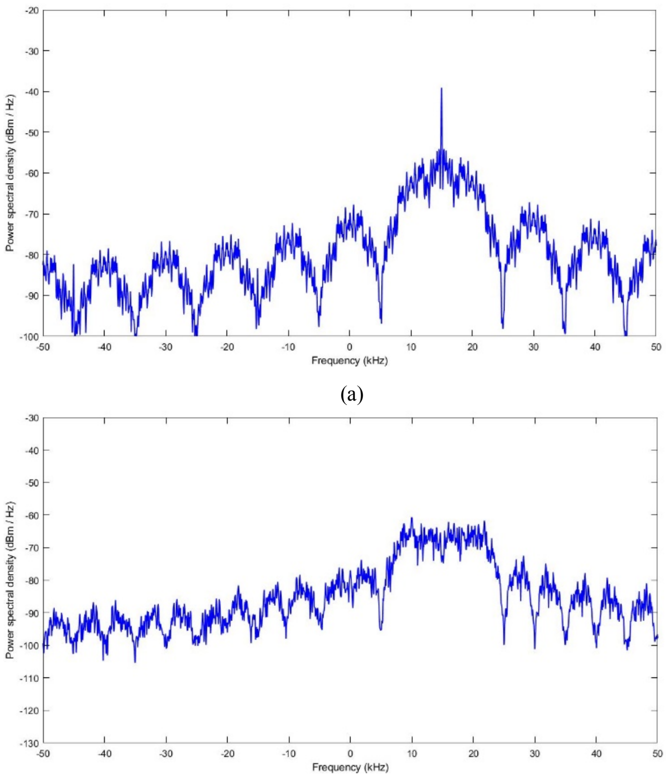


Fig. 10. BER performance of ASK scheme, duobinary-based and modified duobinary-based Fast-OFDM system.

B. Practical Testing

The proposed system was further applied in the practical ADALM-Pluto testbed for verification. Fig. 11 (a) and (b) illustrate the received signal spectrum of ASK scheme and the duobinary system separately. Note that the bit rate of ASK scheme is set to be $R_{ASK} = 1e^4$ bits/s and the parameter setting is $R_{Duo} = 3e^4$ bits/s for the proposed duobinary system. The spectrum shown in the figure corresponds to the baseband signal after signal processing in the Pluto device where the bandwidth of two systems are nearly the same. Consequently, the testing results match the previously obtained simulation results very well and experimentally demonstrate the proposed idea in Fig. 4.

Fig. 12 compares the BER performance of single-carrier ASK, single-carrier duobinary and the proposed duobinary multi-carrier systems. These preliminary proof of concept results were taken by varying the received signal power through fixing receiver gain (at 10 dB) and varying the transmitter gain from -30 dB to -10 dB. The performance of proposed system is very close to that of the single-carrier duobinary scheme, but both are worse than ASK.



(a)

(b)

Fig. 11. Practical testing of (a) ASK signal spectrum (b) duobinary-based Fast-OFDM signal spectrum.

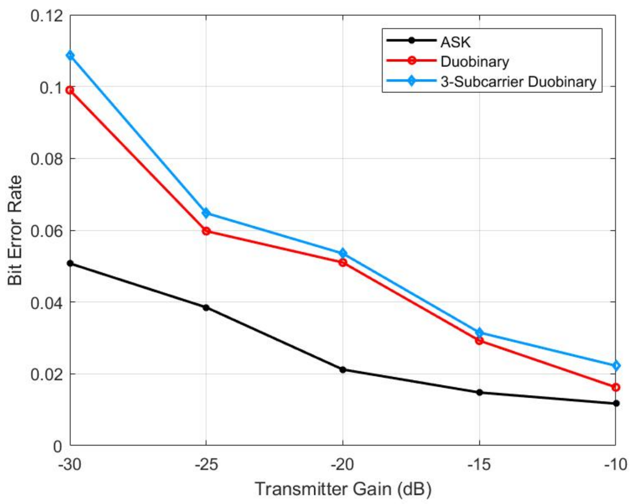


Fig. 12. Practical testing of system BER performance.

VI. Conclusion

This work experimentally tested and verified the idea of applying duobinary signal in the Fast-OFDM system to achieve substantial spectral efficiency improvement. Simulation and testing results show that the proposed duobinary system can provide three times the data throughput of single-carrier ASK scheme with the same bandwidth occupation at the cost of slight BER performance degradation. According to simulation results, the proposed duobinary system needs extra $1-2$ dB to achieve the same BER performance as ASK scheme. However, this extra gain is reduced as the increase of Eb/No. Modified duobinary scheme was also applied for testing and there is not obvious performance improvement while using the technique. On the other hand, we explored several 3-PSK constellation patterns designed for duobinary signal. Results show that only constellation patterns in line will maintain the duobinary spectrum property without violating introduced correlation.

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