On Delay Diversity in OQAM/FBMC Based Transmission Schemes

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***Abstract*—Offset quadrature amplitude modulation based filter bank multicarrier (OQAM/FBMC) is a spectrally efficient alternative to the conventional orthogonal frequency division multiplexing (OFDM) due to its feature of time-frequency localization. However, in presence of the intrinsic interference, it is not as straightforward as OFDM for OQAM/FBMC to benefit from the gains of incorporating multiple-input multiple-output processing, especially for the spatial diversity technique. In this paper, we propose a low-complexity delay diversity (DD) scheme for OQAM/FBMC systems, which is formed by transmitting delayed versions of the same signal on multiple transmit antennas. The associated channel estimation and equalization are also developed for OQAM/FBMC systems with DD. Simulation results verify the effectiveness of the proposed channel estimation method and demonstrate that the proposed DD scheme obtains significant improvements in bit error ratio performance.**

***Index Terms*—OQAM/FBMC, MIMO, delay diversity, channel estimation**

I. Introduction

Offset quadrature amplitude modulation based filter bank multicarrier (OQAM/FBMC) is a promising alternative to the conventional orthogonal frequency division multiplexing (OFDM) [1], [2]. Compared to an OFDM technique, OQAM/FBMC provides lower sidelobes through the use of well-shaped prototype filters and a higher useful data rate due to the fact that OQAM/FBMC does not require a CP. Furthermore, OQAM/FBMC brings advantages such as robustness to narrow-band interference and carrier frequency offset. Due to the above superiorities over OFDM, OQAM/FBMC is being considered as a promising technique for several communications systems [3], [4].

It is well known that multiple-input multiple-output (MIMO) is expected to play a primary role in fulfilling future communication requirements. As one of the main form of MIMO, the diversity technique refers to a method for improving the transmission reliability by utilizing two or more communication channels with uncorrelated multipath fading. For many communication environments, the diversity technique is an effective way to improve the error performance of the transmission systems. Therefore, the design of diversity technique for OQAM/FBMC systems is attracting increasing attention, which is envisioned to provide further wireless link improvements at relatively low cost.

Differently to OFDM, the use of typical diversity schemes such as orthogonal space-time block coding (STBC) or space-frequency block coding (SFBC) in OQAM/FBMC systems is not straightforward, because of the intrinsic interference terms which accompany the data. Some research works have been proposed to enable the combination with STBC and SFBC [5]–[7]. The authors in [5] and [6] proposed a block-wise STBC and SFBC in OQAM/FBMC systems, respectively. In [7], OQAM/FBMC was combined with code division multiple access to match the orthogonality condition of STBC. These schemes, although being capable of achieving diversity gains, result in additional guard intervals or complexity.

In this paper, we propose a low-complexity diversity scheme in OQAM/FBMC systems, namely delay diversity (DD). Compared with the previously mentioned diversity schemes, the implementation of the DD scheme is simple and there is no need to change the structure of the receiver. Specifically, delayed versions of the same signal are transmitted from different antennas in the proposed DD-OQAM/FBMC system, and the diversity gain is obtained by using the forward error correction (FEC) coding. Note that, this idea has been introduced in [8] for MIMO-OFDM systems. However, applying the DD scheme to OQAM/FBMC systems needs further consideration due to the intrinsic interference effect. To obtain the diversity gain, we investigate the structure of the OQAM/FBMC system with DD and develop its associated channel estimation and equalization methods. We also compare the bit error ratio (BER) and channel estimation mean square error (MSE) performances of different methods through computer simulations. The simulation results verify the effectiveness of the proposed channel estimation method and show that the proposed DD scheme can greatly improve the BER performance.

The remainder of the paper is organized as follows. In Section II, the DD-OQAM/FBMC system model is presented. The channel estimation and equalization methods of the DD-OQAM/FBMC system are proposed in Section III. Then, we present BER performance results under different antenna configurations and a comparison of the MSE performance between different channel estimation methods by computer simulations in Section IV, followed by the conclusions in Section V.

II. System model

In this section, we address the design of the DD scheme for OQAM/FBMC systems. Delayed versions of the original OQAM/FBMC signal are transmitted on different antennas. Thus, the frequency selectivity of the equivalent single-input single-output (SISO) channel is increased, which can be exploited by FEC coding to improve the performance. Note that, the diversity processing in OQAM/FBMC systems is more complicate than that in OFDM systems due to the presence of the intrinsic interference term.

A. Transmitter

We consider a DD-OQAM/FBMC system with N_t transmit antennas and a single receive antenna. Note that, it is straightforward to extend the delay diversity technique to multiple receive antenna scenarios. Fig. 1 presents a block diagram of the DD-OQAM/FBMC transceiver.

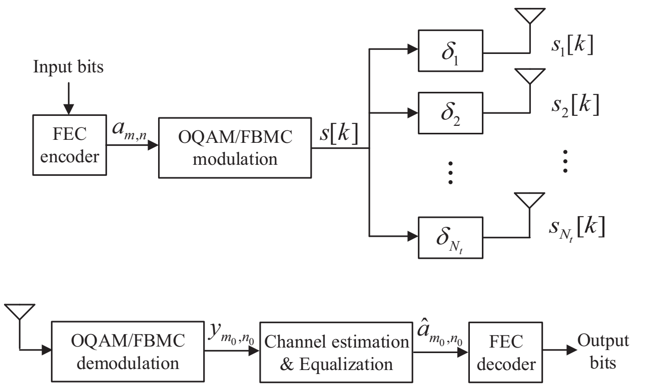

Fig. 1. Block diagram of the OQAM/FBMC transceiver with delay diversity.

Following Fig. 1, the baseband discrete-time signal at the output of an OQAM/FBMC synthesis filter bank (SFB) may be expressed as [9]

$$s[k] = \sum_{m=0}^{M-1} \sum_{n\in\mathbb{Z}} a_{m,n} \underbrace{g\left[k - n\frac{M}{2}\right] e^{j2\pi mk/M} e^{j\frac{\pi(m+n)}{2}}}_{g_{m,n}[k]}, \quad (1)$$

where M is the number of subcarriers and $a_{m,n}$ denotes the real-valued symbol conveyed by the subcarrier of index m during the symbol time of index n. $g[k]$ is a symmetrical real-valued prototype filter and and spans over the time interval $0 \le k \le KM-1$, where K is a positive integer, referred to as overlapping factor.

After the OQAM/FBMC modulation, each antenna introduces a different delay parameter $\delta_t \in \mathbb{N}, t = 1, 2, \ldots, N_t$ to the original signal $s[k]$, where $\mathbb{N}$ is the set of natural numbers. For the t-th transmit antenna, the time-domain k-th transmitted signal $s_t[k]$ is given by

$$s_t[k] = s[k-\delta_t] = \sum_{m=0}^{M-1} \sum_{n\in\mathbb{Z}} a_{m,n} g_{m,n}[k-\delta_t]. \quad (2)$$

It is assumed that the delay parameter is significantly shorter than the symbol interval. Then, the prototype function has relatively low variations in time over the delay parameter, that is $g\left[k - n\frac{M}{2} - \delta_t\right] \approx g\left[k - n\frac{M}{2}\right]$ for $t = 1, 2, \ldots, N_t$. As a consequence, the transmitted signal becomes

$$s_t[k] = \sum_{m=0}^{M-1} \sum_{n\in\mathbb{Z}} \underbrace{a_{m,n} e^{-j2\pi m\delta_t/M}}_{a_{m,n,t}} g_{m,n}[k], \quad (3)$$

where $a_{m,n,t}$ is a phase shifted version of $a_{m,n}$ due to the delay operation. It is of interest to observe that delays of the time-domain transmitted signal are translated to phase shifts of the original data symbols.

B. Receiver

At the receiver side, the link of each transmit and receive antenna pair is degraded by multipath fading and contaminated with additive white Gaussian noise (AWGN). Under the assumption that the channel is almost flat at the subcarrier level and varies slowly with time, the channel frequency response (CFR) between the t-th transmit antenna and the receive antenna is defined as $H_{m,n,t}$ for each given frequency-time (FT) point (m, n), which satisfies

$$H_{m,n,t} = \sum_{k=0}^{L-1} h[k,t] e^{-j2\pi km/M}, \quad (4)$$

where $h[k,t]$ is the channel impulse response (CIR) of the t-th transmit antenna and L is the maximum channel delay spread. With the slow varying assumption, we omit subscript n from $H_{m,n,t}$ for the sake of brevity. Then, the demodulated symbol at the receive antenna, noise taken apart, can be obtained as [10]

$$\begin{aligned} y_{m_0,n_0} &= \sum_{t=1}^{N_t} \sum_{m=0}^{M-1} \sum_{n\in\mathbb{Z}} H_{m,t} a_{m,n,t} \zeta_{m,n}^{m_0,n_0} \\ &= \sum_{m=0}^{M-1} \sum_{n\in\mathbb{Z}} \underbrace{\left[\sum_{t=1}^{N_t} H_{m,t} e^{-j2\pi m\delta_t/M} \right]}_{H_m^{eqv}} a_{m,n} \zeta_{m,n}^{m_0,n_0}, \quad (5) \end{aligned}$$

where $\zeta_{m,n}^{m_0,n_0}$ is known as *intrinsic* imaginary interference and H_m^{eqv} denotes the SISO-equivalent CFR at the m-th subcarrier. Correspondingly, the SISO-equivalent CIR can be defined as

$$\begin{aligned} h[k]^{eqv} &= \sum_{m=0}^{M-1} H_m^{eqv} e^{j2\pi mk/M} \\ &= \sum_{t=1}^{N_t} \sum_{m=0}^{M-1} H_{m,t} e^{j2\pi m(k-\delta_t)/M} \\ &= \sum_{t=1}^{N_t} h[k-\delta_t, t], \; \delta_t \le k \le \delta_t + L - 1. \quad (6) \end{aligned}$$

It is clear from (6) that there is an increase of the channel delay spread, resulting in more severe channel frequency selectivity and yielding an increased coding gain in a coded OQAM/FBMC system.

III. Channel estimation and equalization in the DD-OQAM/FBMC system

For a well-designed prototype filter $g[k]$, the intrinsic imaginary interference $\zeta_{m,n}^{m_0,n_0}$ mostly originates from the first-order neighboring FT points [11]. In this case, consider a neighborhood of size 1×1 around a given FT point (m_0, n_0), denoted $\Omega_1 = \{(m,n)| \, |m-m_0| \le 1, |n-n_0| \le 1, \text{ and } (m,n) \neq (m_0,n_0)\}$. Note that, $\zeta_{m,n}^{m_0,n_0} = 1$ when $(m,n) = (m_0,n_0)$, otherwise it is a pure imaginary number or is equal to zero. Then, with the assumption that the channel frequency responses remain the same across adjacent subcarriers, the demodulated symbol in (5) can be rewritten as

$$\begin{aligned} y_{m_0,n_0} &= H_{m_0}^{eqv} a_{m_0,n_0} + \sum_{(m,n)\in\Omega_1} H_m^{eqv} a_{m,n} \zeta_{m,n}^{m_0,n_0} \\ &= H_{m_0}^{eqv} \left[a_{m_0,n_0} + \sum_{(m,n)\in\Omega_1} a_{m,n} \zeta_{m,n}^{m_0,n_0} \right]. \end{aligned} \tag{7}$$

Considering a preamble structure for OQAM/FBMC systems, we assume that the preamble symbols have a time index of 0, preceded and followed by enough zero guard symbols to protect the preamble from the intrinsic interference due to the data section of the frame. Then, the demodulated preamble symbol on the m_0-th subcarrier is obtained as

$$y_{m_0,0} = H_{m_0}^{eqv} \left[a_{m_0,0} + \sum_{(m,n)\in\Omega_1} a_{m,0} \zeta_{m,0}^{m_0,0} \right]. \tag{8}$$

With the above frequency domain model, the least squares estimate of the SISO-equivalent CFR at the m_0-th subcarrier is given as

$$\hat{H}_{m_0}^{eqv} = \frac{y_{m_0,0}}{a_{m_0,0} + \sum\limits_{(m,n)\in\Omega_1} a_{m,0} \zeta_{m,0}^{m_0,0}}. \tag{9}$$

Correspondingly, since $\zeta_{m,n}^{m_0,n_0}$ is a purely imaginary term for $(m,n) \in \Omega_1$, the estimate of the transmitted symbol is obtained as

$$\hat{a}_{m_0,n_0} = \Re \left\{ \frac{y_{m_0,n_0}}{\hat{H}_{m_0}^{eqv}} \right\}. \tag{10}$$

Apparently, under the channel flatness assumption and in line with symbol model (7), the associated channel estimation and equalization of the DD-OQAM/FBMC system are similar to that of the original OQAM/FBMC system. Thus, the traditional methods in OQAM/FBMC can be directly applied into the DD-OQAM/FBMC system. At the same time, it is worth noting that for the scattered pilot-based channel estimation approaches, the increased frequency selectivity of the SISO-equivalent channel will undoubtedly increase the error of channel interpolation between pilot locations. Thus, more accurate channel estimation approaches based on the original multiple-input single-output channel model need further investigation.

IV. Simulation Results

In this section, we evaluate the performance of the DD-OQAM/FBMC system that was presented in this paper, through computer simulations. The presented results reveal excellent BER performance of the proposed delay diversity scheme, when used along with the channel coding. Besides, a satisfactory MSE performance is obtained by extending the typical channel estimation methods in the OQAM/FBMC system to the DD-OQAM/FBMC system.

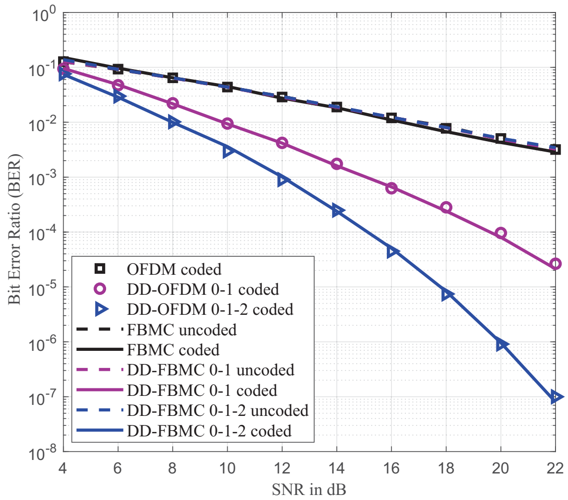

Fig. 2. BER comparison for the conventional and proposed DD-OQAM/FBMC systems, with the PHYDYAS filter.

The simulation parameters for both the OQAM/FBMC and DD-OQAM/FBMC systems are as follows. There are $M = 256$ subcarriers modulated by 4-QAM constellations and the subcarrier spacing is 10.94 kHz. Each data frame consists of 20 complex OQAM/FBMC symbols. The rate-1/2 feedforward convolutional code with a constraint length of 7, code generator polynomials of 171 and 133 (in octal numbers) is utilized. The coded bits are block interleaved and mapped into the QPSK symbols. Besides, results are given for the two most popular choices of the prototype filter, i.e., the PHYDYAS filter and the isotropic orthogonal transform algorithm (IOTA) filter. The overlapping factor is $K = 4$ in all cases. In the following we will compare the BER and MSE performances with different antenna configurations and channel estimation methods, respectively.

The BER performances are considered firstly. In order to investigate the influence of the antenna delay parameter on the BER performances, we conduct simulations under 2×1 and 3×1 antenna configurations, respectively. The delay of antenna one is constant zero, i.e., $\delta_1 = 0$. In the case of two transmit antennas, the delay parameter on the second transmit antenna is empirically selected to be 1. In the case of three transmit antennas, the delay parameters on the first two transmit antennas are unchanged and that on the third transmit antenna is empirically selected to be 2, i.e., $\delta_2 = 1, \delta_3 = 2$.

Fig. 2 and Fig. 3 show the BER versus signal-to-noise ratio (SNR) performance with ideal channel state information for the PHYDYAS filter and IOTA filter, respectively. The channel has typical flat fading characteristics. Besides, BER

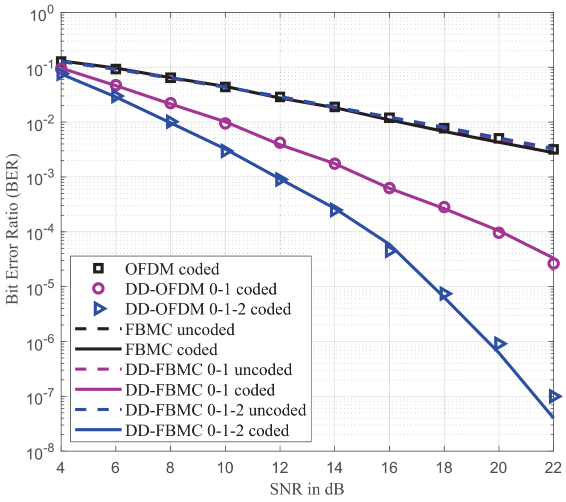

Fig. 3. BER comparison for the conventional and proposed DD-OQAM/FBMC systems, with the IOTA filter.

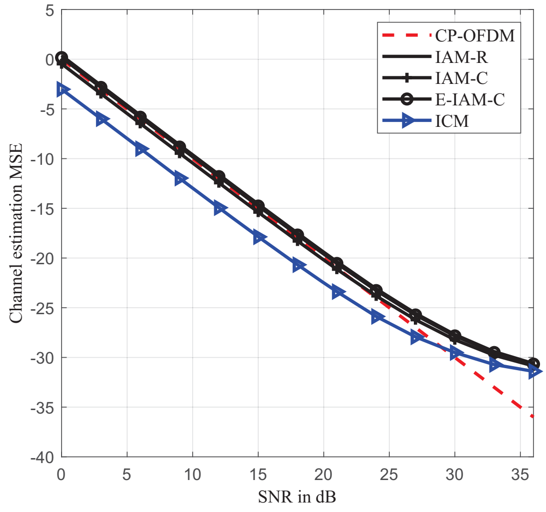

Fig. 4. MSE comparison between different channel estimation methods, with the PHYDYAS filter.

performances of the coded OFDM and DD-OFDM systems are also presented for comparison [8]. As observed, there is little change in performance when changing filters. Whether or not to use delay diversity, the corresponding BER performance of the coded OQAM/FBMC system is almost the same as that of the coded OFDM system. For uncoded transmission the delay introduced on the antenna cannot improve the BER performance of the OQAM/FBMC system. But with channel coding there is a significant BER performance improvement compared with the original OQAM/FBMC system. Moreover, in the case of three transmit antennas, an additional gain of approximately 5 dB at a BER of 10^{-4} is achieved compared with the two transmit antennas case. The reason is that the frequency selectivity of the equivalent SISO channel is higher in the case of three transmit antennas, which helps to further improve the decoding performance of the convolutional code.

To verify the validity of the proposed least-squares estimate of CFR in Section III, the simulations are also conducted under 2×1 antenna configuration with the PHYDYAS filter and IOTA filter, respectively. The multipath channel SUI-3 proposed by the IEEE 802.16 broadband wireless access working group is adopted for our simulations [12]. The typical preamble-based *Interference Approximation Method (IAM)* and *Interference Cancellation Method (ICM)* are extended to the DD-OQAM/FBMC system, with a slight modification on the estimated channel expression according to (9). The key idea of the IAM family, which mainly include IAM-R, IAM-C, and E-IAM-C, is to approximate the intrinsic interference from neighboring symbols and construct complex-valued pseudo-pilots at all frequencies to estimate the channel [11]. This is in contrast to the ICM method, where the pilots are isolated from each other to avoid the intrinsic interference [13]. For fair comparison, the pilots of all methods are normalized to equal power at the SFB output.

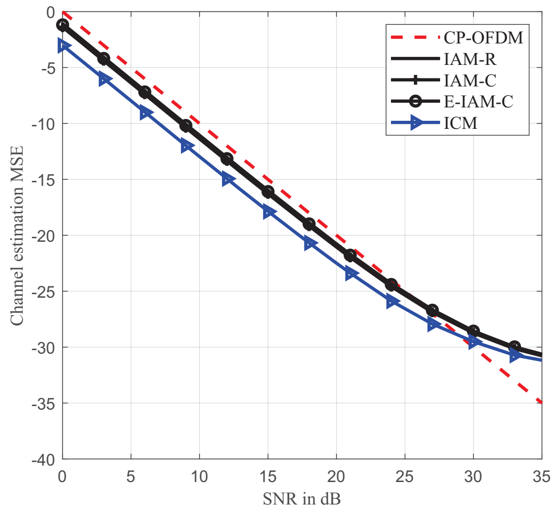

Fig. 5. MSE comparison between different channel estimation methods, with the IOTA filter.

Fig. 4 and Fig. 5 show the MSE comparison between different channel estimation methods with the PHYDYAS filter and IOTA filter, respectively. For the sake of completeness, the performance curves of the OFDM system are also presented, where the pilots are optimally chosen as one of the columns of the DFT matrix [14]. From the simulation results, the channel estimation performance of the DD-OQAM/FBMC system is better than that of the OFDM system at low to medium SNRs when IOTA filter is employed. However, in the case of relatively higher SNRs, the interference pre-cancellation errors which comes from the invalidation of model (9) prevail and DD-OQAM/FBMC is then outperformed by OFDM. One can also see that the MSE performance of the ICM method is the best at all SNR regimes compared to the other three channel estimation methods in the DD-OQAM/FBMC system. Besides, the IAM channel estimation methods with IOTA filter yield better MSE performances compared with that of the PHYDYAS filter due to a higher virtual pilot power boosting, which weakens the effect of noise.

V. Conclusions

In this paper, we investigated the performance of a simple transmission diversity scheme in OQAM/FBMC, namely delay diversity. This diversity scheme increased the frequency selectivity of the equivalent SISO channel by transmitting different delayed versions of the same OQAM/FBMC signal, which can help to improve the decoding performance of the convolutional code. Besides, we developed the associated channel estimation and equalization methods based on the proposed DD-OQAM/FBMC structure. Simulations under different antenna configurations demonstrated that the BER performance of the coded DD-OQAM/FBMC system was much better than that of the conventional OQAM/FBMC system. Moreover, the effectiveness of the channel estimation methods of the DD-OQAM/FBMC system was also verified by comparison with the MSE performance of the OFDM system.

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