A Novel Block-wise Alamouti Scheme in FBMC/OQAM Systems

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***Abstract*—In this letter, a novel block-wise Alamouti scheme is proposed in filter-bank multicarrier with offset quadrature amplifier modulation (FBMC/OQAM) systems, and the key idea is the employment of the concept of block repetition proposed in our previous work. The proposed Alamouti scheme is based on the complex-valued symbols, instead of only real-valued symbols in the conventional block-wise Alamouti scheme in FBMC/OQAM systems. It is proved that, the proposed Alamouti scheme outperforms the conventional block-wise Alamouti scheme in terms of spectral efficiency, due to the fact that one column of zero symbol as guard interval can be saved. To evaluate the performance of the proposed Alamouti scheme, simulations are carried out under multi-path channels and the simulation results show that, the proposed Alamouti scheme achieves the same bit error ratio (BER) compared with the conventional block-wise Alamouti schemes in FBMC/OQAM systems, at a significantly reduced overhead.**

***Index Terms*—FBMC/OQAM, Alamouti, imaginary interference, complex-valued symbols, block repetition.**

I. Introduction

Recently, filter-bank multicarrier with offset quadrature amplifier modulation (FBMC/OQAM) systems have attracted increasing attention and been considered a viable alternative to the famous orthogonal frequency division multiplexing (OFDM), owing to the employment of a prototype filter with low spectrum sidelobe [1]–[3]. The low spectrum sidelobe offers the abilities of asynchronous transmissions and fragmented spectrum utilization. Besides, cyclic prefix (CP), which is usually employed in the famous OFDM, is not required in FBMC/OQAM systems, improving the spectral efficiency.

However, due to the intrinsic imaginary interference, some existing techniques for OFDM cannot be directly employed in FBMC/OQAM systems. Especially, effective combination of the famous Alamouti coding [4] with FBMC/OQAM has remained a research focus in recent years, and several solutions have been proposed. In [5], a code division multiple access (CDMA) based approach was presented to maintain the orthogonality of Alamouti in FBMC/OQAM systems. In [6], the authors proposed an iterative method to suppress the imaginary interference to Alamouti. In [7], multiple discrete Fourier transform (DFT) operators are employed at the transmitter and the receiver to get rid of imaginary interference in FBMC/OQAM systems. However, considerable computation complexities are required for all the aforementioned three approaches. In [8], a CP-based Alamouti coded FBMC scheme was presented at the cost of degradation of spectrum sidelobe. In [9]–[11], a simple block-wise Alamouti scheme was proposed and discussed in FBMC/OQAM systems, however, two column of zero symbol as guard interval are required for the Alamouti scheme to restrain the imaginary interference, resulting in a reduced spectral efficiency.

In this letter, we propose a novel block-wise Alamouti scheme based on the the concept of block repetition proposed in our previous work in [12]. The proposed Alamouti scheme is based on the complex-valued symbols, instead of only real-valued symbols in the conventional block-wise Alamouti scheme in FBMC/OQAM systems. Compared with the conventional block-wise Alamouti scheme, one column of zero symbol as guard interval can be saved in the proposed Alamouti scheme, leading to a better spectral efficiency. Simulation results show that, the proposed Alamouti scheme achieves the same bit error ratio (BER) compared with the conventional block-wise Alamouti scheme in FBMC/OQAM systems, at a significantly reduced overhead.

The remainder of this paper is organized as follows. In section II, the FBMC/OQAM system and the conventional block-wise Alamouti scheme are presented briefly. In section III, the novel block-wise Alamouti scheme is proposed, which is based on the the concept of block repetition proposed in our previous work in [12]. Simulation results are given in section IV and the work are concluded in section V.

II. Conventional Block-Wise Alamouti in FBMC/OQAM Systems

A. System Model

In this letter, we consider an FBMC/OQAM system with M subcarriers. The equivalent baseband transmitting signal of FBMC/OQAM can be written as [13]

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

where $j = \sqrt{-1}$ and $g[\cdot]$ is a prototype filter with low spectrum sidelobe [1]. The transmitting symbol, $a_{m,n}$ with the frequency index m and time index n, is usually real-valued and obtained from the real part or imaginary part of a quadrature amplifier

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modulation (QAM) symbol. It is worthwhile to point out that, $a_{m,n}$ is a complex-valued symbol in the proposed block-wise Alamouti as you can see in section III, which is based on the the concept of block repetition proposed in our previous work in [12].

The orthogonality condition of FBMC/OQAM only holds in the real field, i.e.,

$$\Re\left\{\sum_{k=-\infty}^{\infty} g_{m,n}[k]] g^{*}_{m_0,n_0}[k]\right\} = \delta_{m,m_0}\delta_{n,n_0}, \tag{2}$$

where $(\cdot)^*$ denotes conjugate operator. $\delta_{m,m_0} = 1$ if $m = m_0$, and $\delta_{m,m_0} = 0$ if $m \neq m_0$. $\Re\{\cdot\}$ denotes the operation of taking real part. For simplicity, the interference factor is defined as

$$\zeta_{m,n}^{m_0,n_0} = \sum_{k=-\infty}^{\infty} g_{m,n}[k] g^{*}_{m_0,n_0}[k], \tag{3}$$

where $\zeta_{m,n}^{m_0,n_0} = 1$ if $(m,n) = (m_0,n_0)$, and $\zeta_{m,n}^{m_0,n_0}$ is an imaginary value if $(m,n) \neq (m_0,n_0)$.

At the receiver, the demodulation of the received signal can be approximately obtained as [13]

$$\hat{a}_{m,n} \approx H_m(a_{m,n} + ja^{c}_{m,n}) + \eta_{m,n}, \tag{4}$$

where H_m is the channel frequency response at m-th subcarrier. Noise $\eta_{m,n}$ satisfies the Gaussian distribution with mean zero and variance σ^2. $ja^{c}_{m,n}$ is the imaginary interference mainly from neighboring symbols of $a_{m,n}$, i.e., .

$$I_{m_0,n_0} \approx \sum\sum_{\Omega^*(1,1)} a_{m,n}\zeta_{m,n}^{m_0,n_0}, \tag{5}$$

where $\Omega^*(p,q)$ denotes the neighborhood $\{(m,n) : |m - m_0| \leq p, |n-n_0| \leq q, (m,n) \neq (m_0,n_0).\}$ [13].

Then, the transmitted symbols can be recovered by a single-tap equalizer and operation of taking real part.

B. Conventional Block-Wise Alamouti

In this subsection, the conventional block-wise Alamouti scheme [9]–[11] is briefly presented for 2×1 multiple antenna systems. Fig. 1 depicts the frame structure of conventional block-wise Alamouti scheme, in which two blocks are exhibited with block length of N and reversion technique is employed in the second block. To restrain the imaginary interference between blocks, one column of zero symbols are required as guard interval for each block. Therefore, symbols at the m-th subcarrier for the first and second transmitting antennas are written as

$$\begin{aligned}&[a_{m,0}, a_{m,1}, \cdots, a_{m,N-2}, 0, -b_{m,N-2}, \cdots, -b_{m,1}, -b_{m,0}, 0],\\ &[b_{m,0}, b_{m,1}, \cdots, b_{m,N-2},\ 0,\ \ a_{m,N-2},\ \ \cdots,\ a_{m,1},\ a_{m,0}, 0],\end{aligned} \tag{6}$$

respectively.

Then, the demodulated symbols of two blocks at the receiver are obtained as

$$\begin{aligned} y^{1}_{m,n} &= H^{1}_{m}(a_{m,n} + ja^{c1}_{m,n}) + H^{2}_{m}(b_{m,n} + jb^{c1}_{m,n}) + \eta^{1}_{m,n}\\ y^{2}_{m,N-n} &= H^{1}_{m}(-b_{m,n} - jb^{c2}_{m,n}) + H^{2}_{m}(a_{m,n} + ja^{c2}_{m,n})\\ &\quad + \eta^{2}_{m,N-n}, \end{aligned} \tag{7}$$

where $\eta^{1}_{m,n}$ and $\eta^{2}_{m,N-n}$ are the received noises at the first and second block. H^{1}_{m} is the channel frequency response at the m-th subcarrier between the first transmitting antenna and receiving antenna. H^{2}_{m} is the channel frequency response at the m-th subcarrier between the second transmitting antenna and receiving antenna. $ja^{c1}_{m,n}$, $jb^{c1}_{m,n}$, $jb^{c2}_{m,n}$ and $ja^{c2}_{m,n}$ are imaginary interference from neighboring symbols as in (5).

Note that, to maintain the orthogonality of Alamouti, it is required that $a^{c1}_{m,n} = -a^{c2}_{m,n}$ and $b^{c1}_{m,n} = -b^{c2}_{m,n}$, which is the reason that symbol reversion is employed in the second block in (6) and Fig. 1. Then, (7), in the matrix form, can be rewritten as

$$\begin{pmatrix} y^{1}_{m,n} \\ y^{2*}_{m,N-n} \end{pmatrix} = \begin{pmatrix} H^{1}_{m} & H^{2}_{m} \\ H^{2*}_{m} & -H^{1*}_{m} \end{pmatrix} \begin{pmatrix} a_{m,n} + ja^{c1}_{m,n} \\ b_{m,n} + jb^{c1}_{m,n} \end{pmatrix}$$

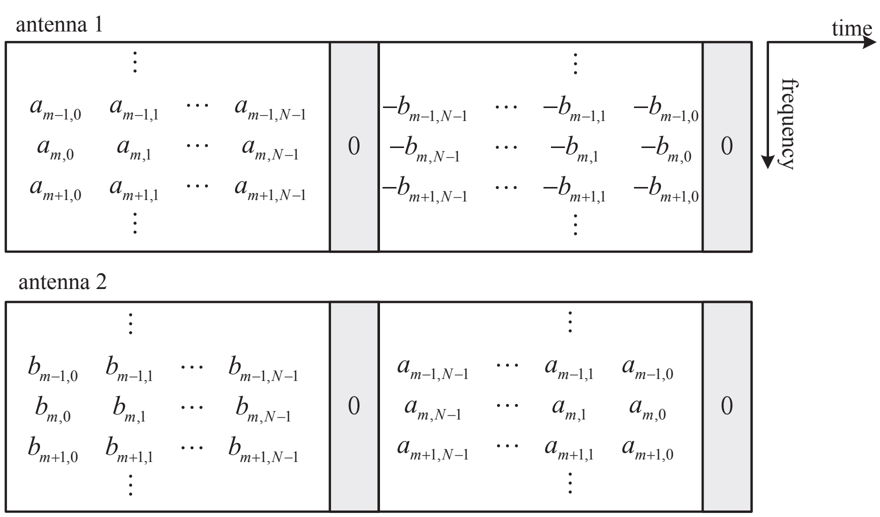

Fig. 1. Frame structure for the conventional block-wise Alamouti scheme.

$$+\begin{pmatrix} \eta^1_{m,n} \\ \eta^{2*}_{m,N-n} \end{pmatrix} \tag{8}$$

where $(\cdot)^*$ denotes conjugate operator. Then, the transmitted symbols can be recovered by

$$\begin{pmatrix} \hat{a}_{m,n} \\ \hat{b}_{m,n} \end{pmatrix} = \Re\left\{ \begin{pmatrix} H^1_m & H^2_m \\ H^{2*}_m & -H^{1*}_m \end{pmatrix}^{-1} \begin{pmatrix} y^1_{m,n} \\ y^{2*}_{m,N-n} \end{pmatrix} \right\}. \tag{9}$$

With the design of symbol reversion as shown in Fig. 1, the conventional block-wise Alamouti scheme [9]–[11] can achieve the maximum spatial diversity. However, it is worthwhile to point out that, two column of zero symbols are required as guard interval for the two blocks to restrain the imaginary interference as shown in Fig. 1, leading to a reduced spectral efficiency.

III. Proposed Block-Wise Alamouti in FBMC/OQAM Systems

In this letter, we propose a novel block-wise Alamouti scheme in FBMC/OQAM systems, based on the the concept of block repetition proposed in our previous work in [12]. Compared with the conventional block-wise Alamouti scheme in Fig. 1, one column of zero symbol as guard interval can be saved in the proposed Alamouti scheme, leading to a better spectral efficiency.

Different from the conventional block-wise Alamouti scheme, the proposed Alamouti scheme is based on the complex-valued symbols. Therefore, despite of the existence of block repetition, the spectral efficiency is maintained in the proposed block-wise Alamouti scheme, ignoring the overhead of guard interval. Fig. 2 depicts the frame structure of the proposed block-wise Alamouti scheme, in which two blocks are exhibited with an even block length of N. The second block is the repeated block and symbol reversion is employed to achieve the imaginary interference cancelation as presented in our previous work [12]. It is worthwhile to note that, compared with the conventional block-wise Alamouti as shown in Fig. 1, only one column of zero symbols are required to restrain the imaginary interference from next Alamouti coded block, and no zero symbols are required between the first and second blocks, leading a better spectral efficiency.

In the proposed block-wise Alamouti scheme, the coded symbols at the m-th subcarrier for the first and second transmitting antennas are written as

$$\begin{aligned} \text{antenna 1:}\quad & [a_{m,0}, -a^*_{m,1}, \cdots, a_{m,N-2}, -a^*_{m,N-1}, \\ & -a^*_{m,N-1}, a_{m,N-2}, \cdots, -a^*_{m,1}, a_{m,0}, 0], \\ \text{antenna 2:}\quad & [a_{m,1}, -a^*_{m,0}, \cdots, a_{m,N-1}, a^*_{m,N-2}, \\ & -a^*_{m,N-2}, a_{m,N-1}, \cdots, a^*_{m,0}, a_{m,1}, 0], \end{aligned} \tag{10}$$

respectively.

For an Alamouti symbol pair, $a_{m,n}, a_{m,n+1}$, the corresponding received symbols in the original block can be obtained as

$$\begin{aligned} y^1_{m,n} = {} & H^1_m(a_{m,n} + ja^{d1}_{m,n}) + H^2_m(a_{m,n+1} + ja^{d2}_{m,n+1}) \\ & + \eta^1_{m,n}, \end{aligned} \tag{11}$$

and

$$\begin{aligned} y^1_{m,n+1} = {} & H^1_m(-a^*_{m,n+1} + ja^{d3}_{m,n+1}) + H^2_m(a^*_{m,n} + ja^{d4}_{m,n}) \\ & + \eta^1_{m,n+1}. \end{aligned} \tag{12}$$

And the corresponding received symbols in the repeated block can be obtained as

$$\begin{aligned} y^2_{m,N-n} = {} & H^1_m(a_{m,n} + ja^{d5}_{m,n}) + H^2_m(a_{m,n+1} + ja^{d6}_{m,n+1}) \\ & + \eta^2_{m,N-n}, \end{aligned} \tag{13}$$

and

$$\begin{aligned} y^2_{m,N-n-1} = {} & H^1_m(-a^*_{m,n+1} + ja^{d7}_{m,n+1}) \\ & + H^2_m(a^*_{m,n} + ja^{d8}_{m,n}) + \eta^2_{m,N-n-1}. \end{aligned} \tag{14}$$

where $a^{d1}_{m,n}$, $a^{d4}_{m,n}$, $a^{d5}_{m,n}$, $a^{d8}_{m,n}$, $a^{d2}_{m,n+1}$, $a^{d3}_{m,n+1}$, $a^{d6}_{m,n+1}$, $a^{d7}_{m,n+1}$ are the imaginary interferences of FBMC/OQAM and

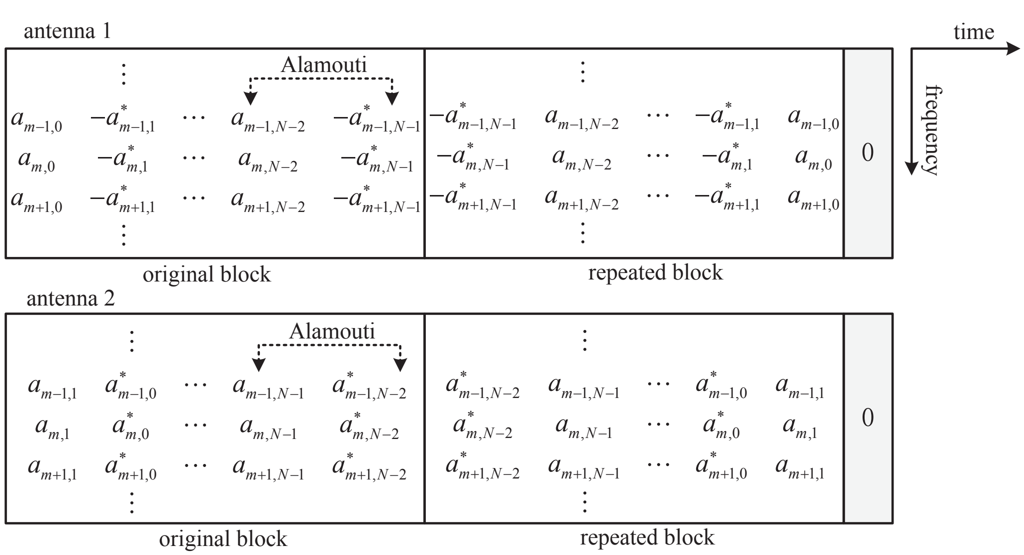

Fig. 2. Frame structure for the proposed block-wise Alamouti scheme.

can be obtained by (5). In our previous work [12], it has been proven that, when symbol reversion is employed in the repeated block as shown in Fig. 2, the imaginary interferences from the original and repeated blocks can be canceled by a simple linear combination, and the following equations hold, i.e.,

$$a_{m,n}^{d1} + a_{m,n}^{d5} = 0, \quad a_{m,n+1}^{d2} + a_{m,n+1}^{d6} = 0,$$
$$a_{m,n}^{d4} + a_{m,n}^{d8} = 0, \quad a_{m,n+1}^{d3} + a_{m,n+1}^{d7} = 0. \tag{15}$$

Then, according to equations (11) - (14), the following equation can be obtained,

$$\begin{aligned} \frac{y_{m,n}^{1} + y_{m,N-n}^{2}}{2} &= H_m^1 a_{m,n} + H_m^2 a_{m,n+1} + \xi_1, \\ \frac{y_{m,n+1}^{1} + y_{m,N-n-1}^{2}}{2} &= -H_m^1 a_{m,n+1}^{*} + H_m^2 a_{m,n}^{*} + \xi_2, \end{aligned} \tag{16}$$

where the Gaussian noises $\xi_1 = (\eta_{m,n}^1 + \eta_{m,N-n}^2)/2$ and $\xi_2 = (\eta_{m,n+1}^1 + \eta_{m,N-n-1}^2)/2$.

Then, in the matrix form, the Alamouti coded complex-valued symbols can be recovered by

$$\begin{aligned} \begin{pmatrix} \hat{a}_{m,n} \\ \hat{a}_{m,n+1} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} H_m^1 & H_m^2 \\ H_m^{2*} & -H_m^{1*} \end{pmatrix}^{-1} \\ \cdot \begin{pmatrix} y_{m,n}^{1} + y_{m,N-n}^{2} \\ y_{m,n+1}^{1*} + y_{m,N-n-1}^{2*} \end{pmatrix}. \end{aligned} \tag{17}$$

IV. Simulation Results

In this section, simulation results are given to evaluate the performance of the proposed block-wise Alamouti scheme. We consider a 2×1 multiple antenna FBMC/OQAM system with 2048 subcarriers and 4QAM modulation, and the prototype filter for FBMC/OQAM is isotropic orthogonal transform algorithm (IOTA) filter [13]. Besides, the channel model in [13] is employed for simulations in this letter.

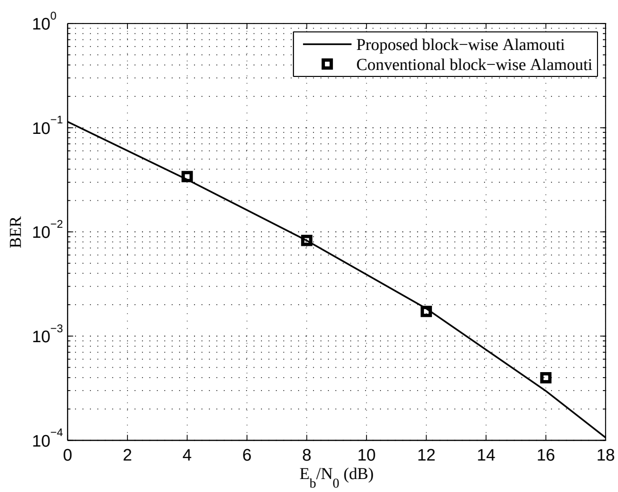

Fig. 3. BER comparison between the proposed and conventional block-wise Alamouti schemes, ideal channel estimation.

Fig. 3 shows BER comparison between the proposed and conventional block-wise Alamouti schemes, under ideal channel estimation. From the simulation results, the proposed Alamouti scheme can achieve the same BER compared with the conventional block-wise Alamouti scheme. Note that, as exhibited in Fig. 1 and Fig. 2, one column of zero symbol as guard interval can be saved in the proposed block-wise Alamouti scheme. Above all, it can be concluded that the proposed Alamouti scheme outperforms the conventional block-wise Alamouti scheme in terms of spectral efficiency.

V. Conclusion

In this letter, we proposed a novel block-wise Alamouti scheme in FBMC/OQAM systems, based on the the concept of block repetition proposed in our previous work in [12]. Compared with the conventional block-wise Alamouti scheme, better spectral efficiency can be achieved in the proposed Alamouti scheme since one column of zero symbol as guard interval can be saved. Simulation results indicated that, the proposed Alamouti scheme can achieve the same BER compared with the conventional block-wise Alamouti scheme, at a significantly reduced overhead.

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