Maximum Likelihood Alamouti Receiver for Filter Bank Based Multicarrier Transmissions

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***Abstract*—Filter-bank based multicarrier (FBMC) transmission is an alternative to orthogonal frequency division multiplexing (OFDM) transmission, more spectrally efficient and more robust to asynchronisms than the latter. For these reasons, FBMC waveform is a promising candidate for 5G mobile networks. However, the non-orthogonal character of the FBMC waveform generates intrinsic inter-carrier interference (ICI) at reception. The presence of this ICI makes difficult the combination of FBMC waveforms with some multiple-input multiple-output (MIMO) schemes such as the Alamouti scheme in particular. In this context, the purpose of this paper is to present and to analyze the performance of a new Alamouti receiver for the per-subcarrier detection of the OQAM symbols transmitted by FBMC waveforms. This receiver is based on the maximum likelihood (ML) joint detection of the symbols transmitted by the sub-carrier of interest and its two adjacent sub-carriers.**

I. Introduction

FBMC waveform is an alternative to OFDM waveform, much better localized in the frequency domain and offering a much better spectral efficiency than the latter. Moreover, FBMC waveform does not require any cylic prefix (CP) and is more robut to asynchronisms than OFDM waveforms [1]. For these reasons, FBMC waveform is a promising candidate for 5G mobile networks [2]. However, the non-orthogonal character of the FBMC waveform generates intrinsic ICI at reception. Despite this fact, it has been shown in [3] that by using OQAM constellations, it is possible to achieve a baud-rate spacing between adjacent sub-carriers and still recover the information symbol, free of both inter-symbol interference (ISI) and ICI, for ideal propagation channels. This gives rise to FBMC-OQAM waveforms whose efficient implementations based on the discrete Fourier transform (DFT) are given in [4], [5].

In recent years, FBMC waveforms have attracted a lot of interest and many equalization and synchronization methods have been proposed, for single-input single-output (SISO) systems corrupted by frequency selective propagation channels [6]. However, if multiple antennas are incorporated at both ends of the link, MIMO communications can be designed to boost the performance, in terms of reliability or bit rate, as shown in [7], [8]. Nevertheless, due to the presence of both ICI and inter-antenna interference (IAI) at reception, the way to reach the full potential of MIMO schemes for FBMC waveforms remains an open topic.

Recently, some transmitter-receiver designs using channel state information (CSI) at transmission have been proposed for MIMO FBMC-OQAM systems for both mono-user [9], [10] and multi-user transmissions [11–14]. Several receiver designs have also been developed for MIMO FBMC-OQAM systems exploiting no CSI at transmission and using spatial multiplexing [15–20].

The works related to MIMO FBMC-OQAM systems using space-time coding mainly concern the Alamouti scheme [21]. The conventional Alamouti scheme, which can be implemented easily for OFDM transmissions, cannot be directly applied to FBMC-OQAM waveforms due to the presence of ICI at reception [22]. For this reason, several transmitter-receiver designs have been proposed recently to couple the Alamouti scheme with FBMC-OQAM waveforms. Unfortunately, all these solutions have serious drawbacks. In particular, a pseudo-Alamouti transceiver is proposed in [22] for FBMC-OQAM systems, whereas a new FBMC scheme, called FFT-FBMC scheme, allowing to easily couple the Alamouti scheme with FBMC-OQAM waveforms is proposed in [19], but both solutions require the insertion of a CP. A block-wise version of the Alamouti scheme for FBMC-OQAM systems is proposed in [23] but it requires the insertion of guardbands and guard periods between the blocks, which decreases the spectral efficiency. In [24] it is shown that the Alamouti scheme can be coupled with FBMC-OQAM waveforms but provided that it is combined with code division multiple access (CDMA). In [25] a modification of the Alamouti scheme is proposed for FBMC-OQAM waveforms, jointly with an iterative processing at reception to cancel ICI. However, this iterative processing may generate errors propagation for moderate signal to noise ratio.

In this context, the purpose of this paper is to present and to analyze the performance of a new Alamouti receiver for FBMC-OQAM waveforms. This receiver is based on a per-subcarrier detection of the OQAM symbols. It implements a ML joint detection of the sub-carrier of interest and its two adjacent subcarriers, assuming that the latter are the only ones which contribute to the ICI. This proposed receiver has not the drawbacks of existing solutions but requires the ML joint detection of three subcarriers per subcarrier, which may be a bit costly.

The reception model associated with the Alamouti scheme for a FBMC-OQAM waveform is presented in section II jointly with the problem formulation. The proposed ML Alamouti receiver is presented in section III, jointly with its main properties. (Section IV presents and discusses the simulations results. Section V concludes the paper.)[1]

II. Reception model

A. Transmitted Alamouti FBMC-OQAM signals

We consider a radio communications system that employs the Alamouti scheme, with $M = 2$ transmit antennas [21], on each subcarrier of an FBMC-OQAM waveform, as depicted at Fig. 1. Under this assumption, the baseband signals, $s_1(t)$ and $s_2(t)$, transmitted by antennas 1 and 2 respectively, can be written as

$$s_1(t)=\sum_{l=0}^{L-1}\sum_{k}\left[a_{l,2k-1}v(t-(2k-1)T)-a^*_{l,2k}v(t-2kT)\right]j^l e^{j\pi\frac{lt}{T}} \tag{1}$$

$$s_2(t)=\sum_{l=0}^{L-1}\sum_{k}\left[a_{l,2k}v(t-(2k-1)T)+a^*_{l,2k-1}v(t-2kT)\right]j^l e^{j\pi\frac{lt}{T}} \tag{2}$$

Here, $(.)^*$ means complex conjugate, L is the number of subcarriers, $1/2T$ is the subcarrier spacing and $v(t)$ is the pulse shaping filter. As the constellation is assumed to be OQAM with a symbol duration of $2T$, the symbol $a_{l,k}$ is such that $a_{l,k} = j^k b_{l,k}$, where $b_{l,k}$ is the real-valued symbol transmitted at time kT on the subcarrier l.

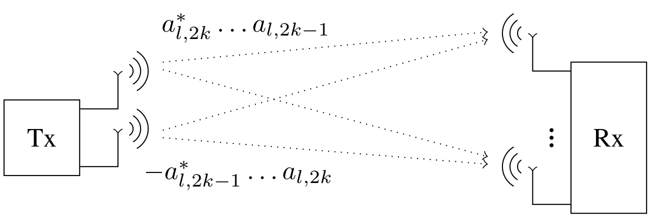

Fig. 1. MIMO $2 \times N$ system using Alamouti space-time coding

B. Received Alamouti FBMC-OQAM signals

Assuming a reception with N antennas, and denoting by $\mathbf{h}_i(t)$ $(i = 1, 2)$ the impulse response vector of the propagation channel between the transmit antenna i and the reception array, the observation vector at time t at the output of the receive antennas is given by

$$\mathbf{x}(t) = \sum_{i=1}^{2} s_i(t) * \mathbf{h}_i(t) + \mathbf{n}(t) \tag{3}$$

Here, $*$ is the convolution operation, $\mathbf{n}(t)$ is the background noise vector assumed to be zero-mean, Gaussian, circular, stationary, spatially and temporally white.

C. Observation model after pass-band filtering

Considering that l_0 is the subcarrier of interest for the per subcarrier processing we propose, the vector $\mathbf{x}(t)$ is first frequency shifted by $e^{-j\pi l_0 t/T}$ to put this subcarrier in baseband. Then a pass-band filter, $p(t)$, is applied to the shifted observation vector to isolate the baseband contribution of the subcarrier l_0. The bandwidth B of the filter $p(t)$ is the one of a subcarrier, i.e. $B = 1/T$. Under these assumptions, we deduce from (3) that the observation vector after frequency shifting and pass-band filtering takes the form

$$\begin{aligned}\mathbf{x}_p(t) &\triangleq p(t) * \left[e^{-j\pi\frac{l_0 t}{T}}\mathbf{x}(t)\right]\\ &= \sum_{i=1}^{2} p(t) * \left[e^{-j\pi\frac{l_0 t}{T}} s_i(t) * \mathbf{h}_i(t)\right] + \mathbf{n}_p(t)\\ &\triangleq \sum_{i=1}^{2}\mathbf{s}_{p,i}(t) + \mathbf{n}_p(t)\end{aligned} \tag{4}$$

Here, $\mathbf{n}_p(t) \triangleq p(t) * [e^{-j\pi l_0 t/T}\mathbf{n}(t)]$ and $\mathbf{s}_{p,i}(t) \triangleq p(t) * [e^{-j\pi l_0 t/T} s_i(t) * \mathbf{h}_i(t)]$.

III. Maximum Likelihood receiver

A. Presentation

The proposed approach consists in demodulating the subcarrier of interest jointly with the subcarriers which overlap with the former, from a maximum likelihood criterion based approach, and then to retain only the symbols belonging to the subcarrier of interest. Under the assumptions of section II-B, we deduce from (4) that the maximum likelihood joint detection of the symbols belonging to the subcarrier of interest l_0 and to the $2M$ subcarriers which overlap with the latter, consists to generate the sequences $b_{l,k}$, for $(l_0 - M \leq l \leq l_0 + M)$, which maximize the following criterion [26], [27][2]

$$\mathrm{C}(\mathbf{b}) = \int_B \left[\mathbf{x}_p(f) - \sum_{i=1}^{2}\mathbf{s}_{p,i}(f)\right]^H \mathbf{R}^{-1}_{n,p}(f)\left[\mathbf{x}_p(f) - \sum_{i=1}^{2}\mathbf{s}_{p,i}(f)\right] df \tag{5}$$

where $(.)^H$ means transpose and conjugate whereas $\mathbf{R}_{n,p}(f)$ is the power spectral density matrix of $\mathbf{n}_p(t)$, defined by

$$\mathbf{R}_{n,p}(f) = N_0\,|p(f)|^2\,\mathbf{I} \tag{6}$$

where N_0 is the power spectral density of $\mathbf{n}(t)$ and $\mathbf{I}$ is the identity matrix. We assume in the following that the propagation channels are known and approximately flat over the bandwidth B. Under this assumption, we deduce from (4) that $\mathbf{s}_{p,i}(f)$ can be written as

$$\mathbf{s}_{p,i}(f) = p(f)s_i\left(f + \frac{l_0}{2T}\right)\mathbf{h}_i = p(f)s_{R,i}\left(f + \frac{l_0}{2T}\right)\mathbf{h}_i \tag{7}$$

where $\mathbf{h}_i \triangleq \mathbf{h}_i(f + l_0/2T) = \mathbf{h}_i(l_0/2T)$ and $s_{R,i}(f + l_0/2T) \triangleq s_i(f + l_0/2T)\Pi_B(f)$, $(i = 1, 2)$, such that $\Pi_B(f) = 1$ for $-B/2 \leq f \leq B/2$ and $\Pi_B(f) = 0$ otherwise. Moreover, we assume that $M = 1$, i.e. that only the two adjacent subcarriers, $l_0 - 1$ and $l_0 + 1$, overlap with the subcarrier l_0. Besides, to simplify the notations, we now denote by $b_{m,k}$ the real-valued symbol transmitted at time kT on the subcarrier

[1]These sections are to be added in the final paper.

[2]All Fourier transforms of vectors $\mathbf{x}$ and matrices $\mathbf{X}$ use the same notation where t is simply replaced by f.

$l_0 + m$ $(-1 \leq m \leq 1)$, such that $a_{m,k} = j^k b_{m,k}$. Under these assumptions, we deduce from (1) that

$$s_{R,1}\Big(f + \frac{l_0}{2T}\Big) = \Pi_B(f) \sum_{m=-1}^{1} \sum_k \big[a_{m,2k-1} e^{j2\pi Tf} (-1)^m - a^*_{m,2k}\big] e^{-j4\pi kTf} v\Big(f - \frac{m}{2T}\Big) j^{l_0+m} \quad (8)$$

$$s_{R,2}\Big(f + \frac{l_0}{2T}\Big) = \Pi_B(f) \sum_{m=-1}^{1} \sum_k \big[a_{m,2k} e^{j2\pi Tf} (-1)^m + a^*_{m,2k-1}\big] e^{-j4\pi kTf} v\Big(f - \frac{m}{2T}\Big) j^{l_0+m} \quad (9)$$

Using (6) and (7) into (5), we obtain an alternative expression of (5) given by

$$\mathrm{C}(\mathbf{b}) = \int \left\| \mathbf{x}_R(f) - \sum_{i=1}^{2} s_{R,i}\Big(f + \frac{l_0}{2T}\Big)\mathbf{h}_i \right\|^2 df \quad (10)$$

where $\mathbf{x}_R(f) \triangleq \Pi_B(f)\mathbf{x}(f)$. Criterion (10) shows that the joint ML receiver does not depend on the form of the pass-band filter $p(t)$, provided that $p(f) \neq 0$ for $-B/2 \leq f \leq B/2$. Inserting (8) and (9) into (10), we obtain, after straightforward manipulations

$$\mathrm{C}(\mathbf{b}) = \int \Bigg\| \mathbf{x}_R(f) - \Pi_B(f) \sum_{m=-1}^{1} \sum_k e^{-j4\pi kTf} v\Big(f - \frac{m}{2T}\Big) \times j^{l_0+m} (-1)^k \Big\{ j b_{m,2k-1} \big[e^{j2\pi Tf}(-1)^{m+1}\mathbf{h}_1 + \mathbf{h}_2\big] + b_{m,2k} \big[e^{j2\pi Tf}(-1)^m \mathbf{h}_2 - \mathbf{h}_1\big] \Big\} \Bigg\|^2 df \quad (11)$$

B. Work to be bone

In the final paper, expression (11) will be developed to express $\mathrm{C}(\mathbf{b})$ as a function of the symbol vectors $\mathbf{b}_k \triangleq [b_{-1,k}, b_{0,k}, b_{1,k}]$ and the samples of the quantities $r_m(t) \triangleq v(-t)^* * [e^{j\pi mt/T} v(t)]$, $(-1 \leq m \leq 1)$. We will then analyze the conditions under which the vectorial sequences b_{2k} and b_{2k-1} may be demodulated separately or not, which will control the complexity of the system. A physical interpretation of (11) will then be given, generating a functional scheme of the system, in terms of set of matched filters and multi-dimensional Viterbi algorithm. A performance analysis of the system, in terms of output symbol error rate, will be presented by simulations for Rayleigh fading propagation channels and pulse shaped filters borrowed from the Phydias project [28]. Finally, implementations issues will be considered jointly with sub-optimal structures easier to implement.

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