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Preamble-Based LMMSE Channel Estimation in OFDM/OQAM Modulation

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Abstract—This paper presents a preamble-based linear minimum mean square error (LMMSE) estimation technique for filter bank multicarrier (FBMC) modulations. Orthogonal frequency division multiplex (OFDM) systems have been extensively used in digital communication systems, for they are extremely efficient in terms of channel estimation and equalization. Estimation being a crucial part of digital communication systems, techniques have been developed to reduce the impact of noise on the channel estimation process, the optimal one being the LMMSE one. Until recently, non-orthogonal multicarrier modulations such as FBMC, were unable to use OFDM-like estimation techniques due to the non-orthogonality. The interference approximation method (IAM) is one of the most popular method among preamble-based estimation techniques with a limited complexity. This paper presents a combination of IAM and a LMMSE-based algorithm that makes possible to achieve a LMMSE estimation in FBMC.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has proven to be very effective when it comes to estimate a multipath propagation channel and to equalize the signal accordingly. The features of OFDM have been extensively studied (see [1], [2]) and are well documented in the literature. However, OFDM suffers from its out-of-band leakage that has become problematic with the spectrum saturation we are observing nowadays. Indeed, the use of a rectangular pulse shape with the fast Fourier transform and its inverse (FFT and IFFT) results in the emission of a non-negligible energy out of the allocated bandwidth. As a consequence, filter bank multicarrier (FBMC) systems as OFDM/offsetQAM (OFDM/OQAM) have regained a lot of interest, for they use optimized pulse shapes that reduce the out-of-band leakage. Yet, this is made at the cost of the loss of the orthogonality properties, resulting in more difficult estimation and equalization processes. Such systems are well described in the literature ([3], [4], [5]).

A very large number of estimation techniques have been developed for OFDM systems. For example, the Least Square (LS) estimation is trivial, but it remains very sensitive to noise, as detailed in [6]. In the opposite, the optimal estimator is the linear minimum mean square error (LMMSE) method [7]. It is very effective to cancel the interferences and noise since it acts like a smoothing step but has a very high computational complexity that makes it difficult to implement. In addition, it requires prior knowledge of the channel covariance matrix to achieve noise mitigation. Recently, a preamble-based OFDM channel estimation algorithm has been proposed in [8], achieving quasi-optimal LMMSE estimation without the aforementioned drawback of the classical LMMSE method.

Preamble-based estimation techniques in OFDM/OQAM systems have been recently presented to the community, asserting the non-orthogonality issue. The main techniques are described in [9], [10]. The non-orthogonality of OFDM/OQAM systems results in interferences that these methods can take into account, such as the interference approximation method (IAM, proposed in [9]). They make it possible to carry out an OFDM-like estimation and equalization, but remain quite sensitive to noise and, in practical situation, can not totally remove the intrinsic interference due to the non-orthogonality of OFDM/OQAM waveforms.

This paper deals with the combination of the OFDM quasi-optimal estimation algorithm in [8] with an IAM estimation process to achieve nearly optimal preamble-based channel estimation in OFDM/OQAM. Observing that current OFDM/OQAM estimations are sensitive to both noise and intrinsic interference, using a LMMSE algorithm that smooths the estimated channel frequency response by mitigating the noise and interferences appears to be relevant. In addition, to our knowledge, no LMMSE-based estimator has been proposed for OFDM/OQAM in the literature yet.

The remaining of the paper is organized as follows: in Section II, we will present the OFDM/OQAM transmission model and the channel used in this study, then we will detail in Section III the principle of the combination of IAM and channel/noise joint estimation. Section IV is devoted to the simulations results, and a discussion of the observed results is provided as well. Eventually, Section V will conclude on the validity of this estimation and present additional elements that will be studied in the near future.

II. TRANSMISSION MODEL

OFDM and OFDM/OQAM systems are both based on the following background: binary data are converted into complex symbols through a mapping based on a symbol constellation. These complex values are organized into vectors containing M subcarriers corresponding to the FFT size. We denote the complex symbol by \( C_{m,n} \) with \( m, n \in \{0, 1, ..., M-1\} \) the subcarrier index and \( n \) the time index corresponding to the current vector. Fig. 1 illustrates in a simple way the organization of the
symbols pointed out by a dot in the time-frequency lattice. This general scheme is common to both OFDM and OFDM/OQAM modulations. Vectors of pilot symbols are then multiplexed in the useful data stream. These pilots are samples whose position, gain and phase are known by both the transmitter and the receiver, and are used to estimate the effect of the channel on the signal, in order to invert it. The modulation step is then processed by a simple FFT in OFDM and a synthesis filter bank (SFB) in OFDM/OQAM (see [5] for details concerning the SFB). In the case of an OFDM system, a cyclic prefix (CP) composed of the last samples of the symbol is added at the beginning of the same OFDM symbol. The resulting signal is then transmitted through the channel. On the receiver side, the signal follows a symmetric processing, in addition to the estimation and equalization steps, that are used to estimate the channel perturbation, and to correct the altered signal.

In multicarrier systems, after the demodulation process, one can write the following general expression of the received signal $R$ as

$$ R = GC + W + I, \quad (1) $$

with $G$ the channel frequency response, $C$ the transmitted signal, $W$ the additive noise and $I$ the intrinsic interference. Note that in OFDM systems, due to the CP and the rectangular pulse shape there is no intrinsic and inter-symbol interference so (1) is simplified to

$$ R = GC + W. \quad (2) $$

In OFDM/OQAM systems, the waveforms are not orthogonal anymore so that the symbols interfere with each other, as shown in Fig. 1. Thus, at the frequency-time position $(m, n)$, the received symbol is:

$$ \hat{C}_{m,n} = G_{m,n} \bar{C}_{m,n} + W_{m,n} + \sum_{m',n' \in \Omega_{m,n}} G_{m',n'} \bar{C}_{m',n'} \langle h_{m,n}, h_{m',n'} \rangle, \quad \hat{C}_{m,n} = \hat{C}_{m,n}, \quad (3) $$

where the pulse shapes $h_{m,n}$ belong to a Gabor family (see [11]) and $jI_{m,n}$ is the intrinsic interference at the position $(m, n)$. We will call $\Omega_{m,n}$ the set of frequency-time positions $(m', n')$ corresponding to the area around $(m, n)$ in which symbols will significantly interfere with the current position. Practically, $\Omega_{m,n}$ contains only a few subcarriers and time positions. Note that with common pulse shapes, the interference is in quadrature with the transmitted symbol, as denoted by the $j$ (see [5]). We assume that the modulation and demodulation prototype filters $h$ are the same, and that the transmitter and the receiver are perfectly synchronized. In both OFDM and OFDM/OQAM modulation schemes, the $G_{m,n}$ coefficients need to be known in order to correct the received symbols. This is the task of the estimation step, that will now be presented.

III. CHANNEL ESTIMATION IN OFDM/OQAM AND OFDM SYSTEMS

Channel estimation is a crucial part of communication receivers. As a consequence, numerous estimation techniques have been developed for OFDM, and more recently for FBMC. Among them, we will now present the two ones we will focus on.

A. Channel estimation in OFDM/OQAM

Channel estimation in OFDM/OQAM systems has been a difficult task due to the lack of CP, and to the important interference caused by the non-orthogonality of the system. In this paper, we will focus on the IAM estimators originally proposed in [9], asserting the non-orthogonality issue. For further reading on additional estimation processes, we suggest [12] and [13]. The IAM estimation is based on the following idea: in a situation without channel nor noise, it is possible to predict the value of received symbols, if we know which ones have been transmitted. This ideal received is written

$$ \hat{C}_{m,n} = C_{m,n} + jU_{m,n}, \quad (4) $$

with $U$ the intrinsic interference assuming an ideal channel ($G = 1$). As explained in [9], we can consider that only the symbols near to the current position will interfere in a significant manner. In those conditions and under the hypothesis of a flat channel over $\Omega_{m,n}$, from (3) one can approximate that the received symbol by:

$$ \hat{C}_{m,n} \approx G_{m,n} \left( \bar{C}_{m,n} \right) + W_{m,n}. \quad (5) $$

This way, it becomes possible to estimate the channel coefficients, under the hypothesis of a locally flat channel as

$$ \hat{G}_{m,n} = \hat{C}_{m,n}. \quad (6) $$

This observation is the base of the IAM estimation techniques. Different IAM implementations corresponding to several pilot preamble organizations have been described in the literature as in [9], [10], in order to keep the peak-to-average power ratio (PAPR) reasonably low. The IAM processes allow...
to realize a simple zero forcing equalization, but remain quite sensitive to noise, and are limited by the hypothesis of a locally flat channel. The less this hypothesis is verified during the transmission, the more residual interference from neighboring transmitted values will remain. In such conditions, using a LMMSE algorithm seems to be an extremely interesting option, for it allows to significantly reduce the interferences. But, as said before, LMMSE requires the knowledge of the channel covariance matrix, that is a priori unknown at the receiver. Consequently, it is difficult to implement.

In an OFDM context, a joint channel/noise estimation algorithm has been recently developed in [8] for preamble-based estimation in order to overcome this drawback. Hereafter, we present the latter and propose to adapt it to OFDM/OQAM modulation scheme.

B. LMMSE-based estimation algorithm

Classical LMMSE estimation relies on the following expression:

\[
\hat{G} = R_G (R_G + \sigma^2 I_d)^{-1} \hat{G}^{LS},
\]

(7)

with \(R_G\) the channel covariance matrix, \(I_d\) the identity matrix and \(\hat{G}^{LS}\) the LS channel estimation that is quite similar to (6) and covered in detail in [6]. As we can see, it relies on the knowledge of the channel covariance matrix, that is a priori unknown in our situation. The algorithm presented here asserts these issues, following the scheme illustrated in Fig. 2, and is described as follows:

1) Initialization: an LS estimation \(\hat{G}^{LS}\) is performed, leading to the covariance matrix \(\hat{G}_L^{LS}\):

\[
\hat{G}_L^{LS} = \hat{G}^{LS}(\hat{G}^{LS})^H,
\]

(8)

with \((.)^H\) the Hermitian matrix transposition.

2) At the first step \((i = 1)\), a LMMSE channel estimation is performed, based on \(\hat{G}_L^{LS}\):

\[
\hat{G}^{LMMSE}_{(i=1)} = \hat{G}_L^{LS} (\hat{G}_L^{LS} + \hat{\sigma}^2_{(i=0)} I_d)^{-1} \hat{G}^{LS},
\]

(9)

with \(\hat{\sigma}^2_{(i=0)}\) the noise variance initialization, strictly positive value.

3) Estimation of the noise variance:

\[
\hat{\sigma}^2_{(i=1)} = \frac{1}{N} E \left\{ \|\hat{G}^{LS} - \hat{G}^{LMMSE}_{(i=1)}\|^2 \right\},
\]

(10)

4) Estimation of a more accurate covariance matrix:

\[
\hat{G}_L^{LMMSE} = \hat{G}^{LMMSE}_{(i=1)} (\hat{G}^{LMMSE}_{(i=1)})^H,
\]

(11)

5) For \(i \geq 2\), we estimate the channel iteratively:

\[
\hat{G}^{LMMSE}_{(i)} = \hat{G}_L^{LMMSE} (\hat{G}_L^{LMMSE} + \hat{\sigma}^2_{(i-1)} I_d)^{-1} \hat{G}^{LS},
\]

\[
\hat{\sigma}^2_{(i)} = \frac{1}{N} E \left\{ \|\hat{G}^{LS} - \hat{G}^{LMMSE}_{(i)}\|^2 \right\},
\]

(12)

with \(E \{ \} \) the mathematical expectation.

6) While \(\hat{\sigma}^2_{(i)} - \hat{\sigma}^2_{(i-1)} > \epsilon_{\sigma}\), where \(\epsilon_{\sigma}\) is a well-chosen threshold, go back to previous step. Else, go to next step.

7) At the final step \(i = i_0\): estimation of the Signal to Noise Ratio (SNR), using the second order moment of the received pilot signal \(U\):

\[
\hat{\rho} = \frac{M(2)(U)}{\hat{\sigma}^2_{(i_0)}} - 1
\]

(14)

This algorithm has proven to be very effective, significantly reducing the noise perturbation on the channel estimation in OFDM systems. Applying it to OFDM/OQAM estimation sounds even more relevant, since its ability to remove interference might work as well for noise and intrinsic interference. However, due to the presence of these two kinds of interference, we will first focus on the channel estimation rather than the noise estimation that will be altered by the presence of ISI, and attempt to define criteria to transpose this estimation process to OFDM/OQAM systems.

C. How could we apply this algorithm to OFDM/OQAM?

To the best of our knowledge, no LMMSE estimation method has been proposed for OFDM/OQAM. In order to adapt the LMMSE joint algorithm to OFDM/OQAM systems, one needs to determine which parts have to be modified:

- The initialization is made by LS estimation. As this estimation technique is adapted to OFDM is sensitive to the noise, it cannot be satisfying in OFDM/OQAM systems due to the interference. Therefore this step must be replaced by an estimation that takes this interference into account, such as IAM as presented just before.
- The iterative part is purely mathematical and is independent from the nature of the system. It should not be modified in a first approach, except maybe for the initial noise variance estimation, as it is not anymore an LS estimation that is processed.
- This estimator can be used for Zero Forcing equalization in OFDM systems, and should be used to do Zero Forcing in OFDM/OQAM systems.

As a consequence, it seems that only the initialization needs to be modified in a first approach, first simulation results indicating that further modifications would be required, for noise variance estimation. In this paper, it seems acceptable to consider the channel estimation as a priority, noise estimation being corrected later, if needed. The process is then mostly the same as in Fig. 2, except for the initialization. For its similarity to the LS method, we decided to use the IAM2 [9] estimation method as the initialization of the algorithm, and developed a transmission chain able to perform both OFDM and OFDM/OQAM transmissions.
IV. SIMULATION RESULTS

We performed simulations of transmissions based on OFDM and OFDM/OQAM transmission schemes. The results we will present here have been computed on a system with $M = 1024$ subcarriers for more than $10^7$ binary elements, using a modulated cosine prototype filter [14] with an overlapping factor of 4. We used four-paths channels of various lengths, inspired by the US Consortium channel used in digital broadcasting simulations (see [15] for specifications). We will call $\Delta = T_{\text{channel}}/T_{\text{symbol}}$ the ratio between the maximum channel length and the symbol duration as previously defined. This value can be viewed as a good indicator of the channel frequency selectivity.

A. Observed results

Figs. 3 and 4 present the mean square error (MSE) and the bit error rate (BER) results versus $E_b/N_0$ for three estimation techniques: IAM2 and the adapted joint estimation for OFDM/OQAM, and the OFDM joint estimation as a reference.

We can observe that the performance indicators of presented estimators in OFDM/OQAM reach a lower bound. Besides, the adapted joint estimation follows the same behavior as the IAM2 estimation. This phenomenon had been already observed in the literature as in [16] for IAM. However, numerical results showed BER values up to twice lower for the joint estimation, compared to the IAM2 estimation scheme at the same $E_b/N_0$ value. In the same time, the MSE on the estimation is significantly reduced in the OFDM/OQAM joint estimation, compared to the IAM2 one.

In addition to these observations, we note that the BER reaches a floor in FBMC whatever the estimation method. The same behavior is observed for the mean square error on the estimation, as shown in Fig. 3. We conducted additional simulations on a twice longer channel, in order to determine if the floor we observed was dependent or not of the channel length. BER results of these simulations are compiled in Fig. 6, and the MSE results in Fig. 5. As one can see, both performance indicators reach a lower bound, but whose value is larger for $\Delta = 0.04$ than for $\Delta = 0.02$. We conclude that the performance of the IAM2 and the LMMSE-based algorithm is directly linked to the channel frequency selectivity, but this result must be discussed.

B. Discussion of the results

Previous results show a significantly improved performance of the OFDM/OQAM joint estimation compared to the IAM2
estimation method, for both BER and MSE measurements. However, when the noise is reduced, one can observe the presence of a floor for these two performance indicators, as shown in [16]. We now go further by analyzing the results and by providing a measurement of the error of estimation.

This floor might be due, at least for a part, to the flat channel hypothesis that was made for the IAM estimation. Indeed, ZF equalization requires a flat channel around the current symbol, so that after equalization, the interference is in quadrature with the current transmitted value and is successfully rejected by the OQAM processing. However, in a practical situation, this hypothesis may not be verified, resulting in a residual interference from the neighboring symbols on the current symbol, causing an error at the estimation level and for data symbols as well. In longer channels, the frequency response varies faster, and reality is further from the flat channel hypothesis, resulting in a higher error rate. Using the IAM estimation equations, we managed to calculate the error caused by the non verified hypothesis.

Recalling (4), let us precisely develop $J U_{m,n}$:

$$\hat{C}_{m,n} = C_{m,n} + \sum_{m',n' \in \Omega_{m,n}} C_{m',n'} \left\langle \hat{h}_{m,n}, h_{m',n'} \right\rangle.$$

After applying the IAM estimation (6) and further calculation, one determines the value of the estimated channel coefficient, involving the quantity $\delta_{m',n'} = \hat{G}_{m',n'} - G_{m,n}$:

$$\hat{G}_{m,n} = G_{m,n} + \frac{\sum_{m',n' \in \Omega_{m,n}} h_{m,n}' C_{m',n'} \left\langle h_{m,n}, h_{m',n'} \right\rangle}{C_{m,n} + \sum_{m',n' \in \Omega_{m,n}} C_{m',n'} \left\langle h_{m,n}, h_{m',n'} \right\rangle}.$$

(16)

The second term in the right side of (16) clearly shows that the selectivity of the channel, pointed out by the $\delta_{m',n'}$ value, has a crucial role in the estimation accuracy, even for negligible noise level. Though not developed in this paper, similar calculations on the ZF equalized data symbols $C_{m,n}/G_{m,n}$ also show the apparition of interference due to neighboring symbols, leading to an increased error risk. As a consequence, since IAM is used for the initialization of the LMMSE-based algorithm, the errors induced by IAM also affect the performance of proposed iterative method, leading to the error floors in Figs. 3 to 6.

However, Figs. 4 and 6 shows that the IAM approximation remains decently accurate. Thus, one solution would consists of using the previous equations to cancel the residual interference, by using the IAM as a first estimation. This could reduce the constraint of the flat channel hypothesis on the estimation process, leading to a more accurate channel estimation. Further work will be conducted in the near future to explore this possibility.

VI. CONCLUSIONS AND FUTURE WORKS

We studied a LMMSE estimation algorithm for OFDM and successfully adapted it to OFDM/OQAM systems, by combining it with an existing preamble-based OFDM/OQAM estimation process. This resulted into the development of a LMMSE preamble-based estimation for OFDM/OQAM without prior knowledge of the channel covariance matrix. To the best of our knowledge, there was no LMMSE estimation available for OFDM/OQAM, making this new algorithm the first of its kind in this modulation scheme. We identified a limitation of the performance of OFDM/OQAM estimations, and made hypotheses on its origin. Further works will be conducted in the near future to determine a way to cancel the need of the hypothesis that causes this limitation.

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