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***Abstract*—In Multi-Carrier (MC) systems, all equalization and detection procedures are classically performed at the sub-carrier level after the received signal is projected into the frequency domain. Besides, in the presence of rapid channel variation, conventional receivers suffer from critical performance degradation caused by interference. To address this specific problem, we propose to add a low-complexity time domain preprocessing prior to the frequency domain equalization process. We specifically study Orthogonal Frequency Division Multiplexing (OFDM) and Filter-Bank Multi-Carrier (FBMC) over single-path fast-varying Rayleigh channels when using the proposed scheme. Two time domain preprocessing techniques are considered. Their impact on equalization performance is evaluated in perfect and imperfect Channel State Information (CSI) scenarios, showing robustness to reasonable channel estimation errors. For both systems, a reduction in Bit Error Rate (BER) is obtained thanks to the preprocessing. Furthermore, the proposed scheme allows for capturing time diversity leading to improvement in performance for faster channel variation, rather than inducing performance degradation, showing the relevance of our approach. For OFDM, this preprocessing allows reaching the best performance compared to the existing equalizers at significant lower complexity. For FBMC, it permits to obtain a performance gain of 10 dB at $\mathbf{F_d T_S = 0.25}$, while avoiding the BER floor effect. This gain is observed at BER$= 2 \times 10^{-2}$ for scenarios accepting Inter-Symbol Interference (ISI), and at BER$= 10^{-3}$ when assuming perfect ISI cancellation. For the latter scenario, we obtain performance very close to the (computationally intractable) optimum Maximum-Likelihood equalizer.**

***Index Terms*—OFDM, FBMC, Doppler, Rayleigh, QR, Equalizer**

I. Introduction

Multicarrier systems have been studied in research literature and used in practice for decades now. Their various benefits made them state-of-the-art systems for most communication scenarios used in several standards. Orthogonal Frequency Division Multiplexing (OFDM) [1] constitutes the most famous and widely adopted scheme among the Multi-Carrier (MC) technologies. Another very interesting variant of MC systems is Filter-Bank Multi-Carrier (FBMC) [2]. We have previously studied the severe interference such systems suffer from in single path [3] and multipath [4] channels when using conventional correlator-based receivers while having rapid variation in the channel following the Rayleigh Jakes's model [5]. To counter the Bit Error Rate (BER) degradation caused by this interference, we propose in this paper to perform front-end time domain processing at the receiver in addition to the common frequency domain equalizers. We limit the analysis to single path channels to focus on the impact of Doppler spread solely. However, this work can be extended to multipath scenarios. The proposed scheme is shown to efficiently capture time diversity in the presence of channel variation, leading to an important performance gain, in contrary to the classical techniques that suffer from performance degradation. It is important to note that some time domain preprocessing already exists in the literature for OFDM, but in the context of shortening the channel's impulse response to be less than the Cyclic-Prefix (CP) duration [6]. Up to the authors' knowledge, our preprocessing scheme designed in the perspective of countering degradation caused by fast channel variation does not exist in the literature, especially for FBMC. To sum up, the contribution of this paper can be listed as follows:

- a new concept of countering the degradation caused by fast channel variation through assisting frequency domain equalizers by time domain preprocessing is proposed,
- two techniques that aid in this context in single path channels are proposed,
- BER-based assessments for the robustness of the proposed scheme and techniques for different noise levels are provided,
- BER-based assessments for the robustness of the proposed scheme and techniques for different Doppler spread levels are also provided,
- and finally a sensitivity analysis for the case of imperfect Channel State Information (CSI) is addressed.

The rest of this paper is organized as follows: the MC system model is presented in section II; then in section III, the equalization techniques are discussed; section III-A discusses classical and state-of-the-art equalizers, and section III-B presents the time domain processing; later, in section IV, simulation and comparative discussion are presented. Finally, the paper is concluded in section V.

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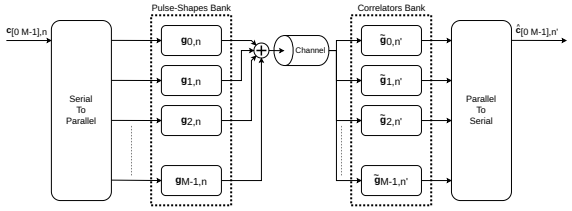

Fig. 1. Multi-Carrier System Schematic with Correlator-based Receiver.

II. Preliminary System Model

The MC system used in this paper reflects the schematic shown in fig. 1 (which can be implemented efficiently using Fast Fourier Transform (FFT) [7]), and extended later in section III to include changes of fig. 2. The pulses $g_{m,n}$ and $\tilde{g}_{m',n'}$ are designed with the aim of minimizing the cross-talk between sub-carriers and consecutive symbols by trying to satisfy the relation:

$$\langle \boldsymbol{g}_{m,n}, \tilde{\boldsymbol{g}}_{m',n'} \rangle \approx \begin{cases} \text{Const}, & \text{if } m = m' \text{ and } n = n' \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where:

- $\langle \boldsymbol{x}, \boldsymbol{y} \rangle$ is the inner product between $\boldsymbol{x}$ and $\boldsymbol{y}$ such that $\langle \boldsymbol{x}, \boldsymbol{y} \rangle = \sum_q x[q] y^*[q]$.
- $\boldsymbol{g}_{m,n}$ is the transmit pulse shape of the m^{th} sub-carrier of the n^{th} transmitted MC symbol.
- $\tilde{\boldsymbol{g}}_{m',n'}$ is the receiver pulse shape used to recover (by correlation) the m'^{th} sub-carrier of the n'^{th} received MC symbol.

In the case of a conventional matched filter receiver, $\tilde{\boldsymbol{g}}_{m',n'} = \boldsymbol{g}_{m',n'}$. This type of receiver is used for the system model derivation and extended in a later section to include equalization and preprocessing, while having Root Raised Cosine (RRC) pulse shape for FBMC and Rectangular (Rect) pulse for OFDM with additional CP implementation for OFDM. Let M be the number of sub-carriers, N be the interval – in samples – between two consecutive MC symbols such that for a sample duration T_{Sa} (the duration/interval of the MC symbol is then $T_S = NT_{Sa}$), K be the time span of a pulse shape in terms of MC symbols (number of pulse shape samples$/N$) such that KN is an integer, and (equivalently) $K-1$ be the overlapping factor. As pulse shapes have a defined length of KN, the prototype transmitting pulse shape $g[k]$ and the prototype receiving pulse shape $\tilde{g}[k]$ are supported for $k \in [0; KN-1]$, and $g[k] = \tilde{g}[k] = 0$ otherwise. The q^{th} sample transmitted due to an input symbol $c_{m,n}$ on the m^{th} sub-carrier of the n^{th} MC symbol is written as:

$$s_{m,n}[q] = c_{m,n} g_{m,n}[q], \tag{2}$$

such that the q^{th} sample of the transmitting pulse $\boldsymbol{g}_{m,n}$ is:

$$g_{m,n}[q] = g[q - nN] \, e^{j2\pi \frac{m(q-nN)}{M}}. \tag{3}$$

$c_{m,n}$ are considered to be Quadrature Amplitude Modulation (QAM) symbols in this work. Using eq. (2) and eq. (3), the sample stream of all transmitted symbols summed over n and m will be:

$$s[q] = \sum_m \sum_n c_{m,n} g[q - nN] \, e^{j2\pi \frac{m(q-nN)}{M}}. \tag{4}$$

Assuming a single path channel, the signal at the input of the receiver (complex base-band representation) will be expressed as:

$$r[q] = h[q] \, s[q] + \omega[q], \tag{5}$$

such that:

- $r[q]$ is the q^{th} sample of received MC symbol stream $\boldsymbol{r}$,
- $h[q]$ is the q^{th} sample of discrete time-varying channel,
- and $\omega[q]$ is the q^{th} realization of the additive white complex circular Gaussian noise $\boldsymbol{\omega}$.

Using operations matched to those at the transmitter, the received constellation symbol at the m'^{th} sub-carrier and the n'^{th} MC symbol $c_{m',n'}$ for a specific transmitting sub-carrier and symbol indices m and n can be expressed as:

$$\begin{aligned} \hat{c}_{m',n'}|_{m,n} = & \sum_q \tilde{g}^*[q - n'N] \\ & \times (h[q] \, g[q - nN] \, c_{m,n} + \omega[q]) \\ & \times e^{-j2\pi \frac{(q-nN)(m'-m) - m'N(n'-n)}{M}}, \end{aligned} \tag{6}$$

having the q^{th} sample of the receiving pulse (or Hermitian symmetric of the receiving filter's impulse response) $\tilde{\boldsymbol{g}}_{m',n'}$ as:

$$\tilde{g}_{m',n'}[q] = \tilde{g}[q - n'N] \, e^{j2\pi \frac{m'(q-n'N)}{M}}. \tag{7}$$

Summing eq. (6) over all m and n will give the total contribution of the symbols such that:

$$\begin{aligned} \hat{c}_{m',n'} &= \sum_m \sum_n \hat{c}_{m',n'}|_{m,n} \\ &= \langle \boldsymbol{r}, \tilde{\boldsymbol{g}}_{m',n'} \rangle. \end{aligned} \tag{8}$$

Generalizing eq. (8) into an end-to-end matrix form:

$$\hat{\boldsymbol{c}}_{n'} = \sum_n \boldsymbol{H}^{(n',n)} \boldsymbol{c}_n + \boldsymbol{\omega}_{n'}, \tag{9}$$

such that $\hat{\boldsymbol{c}}_{n'} = [\hat{c}_{0,n'}, \hat{c}_{1,n'}, ..., \hat{c}_{M-1,n'}]^T$, $\boldsymbol{c}_n = [c_{0,n}, c_{1,n}, ..., c_{M-1,n}]^T$, $\boldsymbol{\omega}_{n'} = [\omega_{0,n'}, \omega_{1,n'}, ..., \omega_{M-1,n'}]^T$, $\omega_{m',n'} = \langle \boldsymbol{\omega}, \tilde{\boldsymbol{g}}_{m',n'} \rangle$, and:

$$\begin{aligned} H^{(n',n)}_{m',m} = & \sum_q \tilde{g}^*[q - n'N] \, h[q] \, g[q - nN] \\ & \times e^{-j2\pi \frac{(q-nN)(m'-m) - m'N(n'-n)}{M}}, \end{aligned} \tag{10}$$

where $\boldsymbol{H}^{(n',n)} = \boldsymbol{0}$ for $|n - n'| \geq K$. As the design of $\boldsymbol{g}$ and $\tilde{\boldsymbol{g}}$ in OFDM and FBMC achieves the relation in eq. (1), it can be easily shown that this propagates to $\hat{c}_{m,n} \approx H^{(n)}_{m,m} c_{m,n} + \omega_{m,n}$ if $h[q_1] \approx h[q_2]$ when $|q_1 - q_2| \leq N$. This relates to what is commonly known as a slow-varying channel scenario, where the normalized Doppler spread $f_d T_S \to 0$. Such slow-varying scenarios are approximately interference-free and simple to deal with when eq. (1) is satisfied. However, as it is known and was discussed in our previous work [3], high values of $f_d T_S$

would lead to severe Inter-Carrier Interference (ICI) and Inter-Symbol Interference (ISI) in MC systems what might lead to unusable communication channels. This severe impact of fast-varying channels on MC transmission needs to be mitigated at the level of interference and possibly benefitted from at the level of diversity. In the next section, we discuss the commonly used equalizers and the enhancement proposed in this paper to be used later in the simulation and discussion.

III. Equalization Techniques

In this work, we introduce the concept of enhancing the frequency domain equalizers robustness to rapid channel variation by exploiting time domain preprocessing. To perform this, we revisit some frequency domain equalizers to first be used in this scheme, and second to compare with their performance without preprocessing. Some equalizers are considered for being classically used, and others are considered for being proved to be suboptimal following the framework they are designed in. Later, we present the two techniques we will consider for preprocessing.

A. Existing MC Frequency Domain Equalizers

For MC systems, equalization is traditionally performed at the sub-carrier level ($i.e.$ in the frequency domain after Inverse Fast Fourier Transform (iFFT) for OFDM). We consider the following equalizers in this paper:

1) Linear Minimum Mean Square Error (MMSE): A classical and considerable optimization criterion when designing any kind of estimator is the minimization of the mean square error. As equalization is an estimation problem, MMSE equalizers are commonly used. However, the classical MMSE equalizer is a one-tap equalizer (also called a diagonal equalizer) following the MMSE minimization criteria [8]. Such equalization neglects the fact that significant errors are introduced due to the ICI and just consider (per sub-carrier) Signal to Noise Ratio (SNR). We then have the equalized symbol $\check{c}_{m',n'}$ as:

$$\check{c}_{m',n'} = \frac{\hat{c}_{m',n'} \times \left(H_{m',m'}^{(n',n')}\right)^*}{\left|H_{m',m'}^{(n',n')}\right|^2 + \text{SNR}^{-1}}. \tag{11}$$

This makes use of the information available only on the diagonal of the channel matrix, which is not efficient for high values of normalized Doppler spread.

2) Linear Least Square (LS): Linear single-step Least Square equalizer follows the MMSE minimization criteria for the multitap equalization, and is implemented through matrix operations [9] such that:

$$\check{\boldsymbol{c}}_{n'} = \left(\boldsymbol{H}^{(n',n')}\right)^H \left(\boldsymbol{H}^{(n',n')}\left(\boldsymbol{H}^{(n',n')}\right)^H + \text{SNR}^{-1}\boldsymbol{I}\right)^{-1} \hat{\boldsymbol{c}}_{n'}, \tag{12}$$

where $()^H$ is the conjugate transpose operator. Although this matrix implementation considers more information than the MMSE, it does not consider the knowledge of the set of possible symbols to be transmitted, which if used may improve the performance if symbol detection is performed while suppressing the interference.

3) SIS: Successive Interference Suppression (SIS) considers the knowledge of the channel matrix and the symbols that can be transmitted (the constellation). The equalization is performed recursively as described in [10]:

- Ordering: selecting the diagonal element of the channel matrix that was not selected before and has the highest magnitude,
- Detection: detecting the corresponding symbol by performing a one-tap equalization (Zero-Forcing (ZF) or MMSE) then quantization,
- and Suppression: regenerate the interference due to the detected symbol using the channel matrix and remove it from the signal.

This technique is not considered directly in the comparison since the QR decomposition technique, described in the next section, represents its extension.

4) QR Decomposition: QR decomposition-based equalizer is built using the same concept as SIS. However, it applies QR decomposition to the channel matrix such that $\boldsymbol{H} = \boldsymbol{QR}$ where $\boldsymbol{Q}$ is a unitary matrix and $\boldsymbol{R}$ is a triangular matrix. The vector of received symbols $\hat{\boldsymbol{c}}_{n'}$ is then multiplied by the conjugate of $\boldsymbol{Q}$ making the equivalent channel matrix triangular ($\boldsymbol{Q}^*\boldsymbol{H} = \boldsymbol{Q}^*\boldsymbol{QR} = \boldsymbol{R}$). This permits to have a simpler and more performant SIS [11]. However, as it is possible that we benefit from the channel variation in the time domain as some kind of diversity gain, especially for FBMC where a symbol includes more samples in time domain, we look into some possible time domain processing to be done on the receiver in the next section.

B. Time Domain Preprocessing

In this section, we present two one-tap time domain preprocessing techniques that are proposed to replace/complete conventional (frequency domain) MC equalizers. They will be used in the comparative discussion provided later in this paper.

1) MMSE: We consider the MMSE technique performed in time domain, not to be confused with the frequency domain version discussed in section III-A1. This follows the same concept as in the frequency domain version of the MMSE equalizer. However, to be applied in the time domain just after receiving the signal and before feeding it to the correlator banks. Thus, the processed signal $s^\dagger$ is defined as:

$$s^\dagger[q] = \frac{r[q]\, h^*[q]}{|h[q]|^2 + \text{SNR}^{-1}}. \tag{13}$$

2) Matched Channel Multiplier (MCM): Another time domain processing technique, named Matched Channel Multiplier, is considered in this work. In this technique, we propose to perform correlation with the channel's matched filter. Since we assume a single-path channel, this is equivalent to a one-tap matched filter, i.e., multiplying by the conjugate of the channel's value:

$$s^\dagger[q] = r[q]\, h^*[q]. \tag{14}$$

This operation will permit to have a real-valued positive equivalent channel, in addition to giving more weight to the

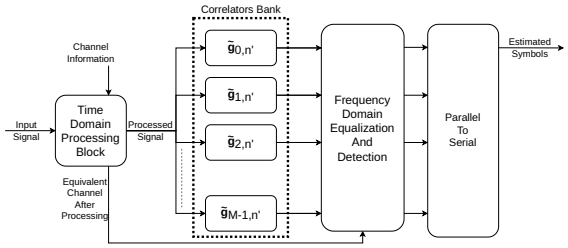

Fig. 2. MC Receiver With Time Domain Processing Block and Frequency Domain Equalization and Detection.

channel's taps with higher values (or maximizing the SNR). However, in contrast to MMSE which can be used alone as a time domain equalizer, this technique keeps (or even increases) the spread in the Doppler frequency domain. Consequently, it must be used along with a frequency domain equalization-technique like the ones mentioned in section III-A. To do so, it is required to compute that new equivalent channel $h^{\dagger}$ in the perspective to pass it to the later process. The equivalent channel is:

$$h^{\dagger}[q] = h[q]\, h^{*}[q]\,. \tag{15}$$

This combination of time domain and frequency domain processing is depicted in fig. 2. In the next section, simulation of the content and propositions of section III is provided along with relative discussions.

IV. Simulation and Discussion

In this section, simulation and BER-based performance analysis for the techniques discussed in section III are provided. Simulations are performed for $M = 4$, $N = 5$, and QAM4. A stream of 100000 MC symbols is used for every simulated value of BER assuming a single-path unitary power Jakes' model Rayleigh channel [5] with perfect CSI. All simulations provided in this section are repeated for imperfect CSI (MSE $= 10^{-2}$) compared to the literature [12] in the appendix. The results showed how the analysis provided in this work is valid and equivalent for both perfect and imperfect CSI. However, we kept the perfect CSI assumption in order to study the capabilities of the proposed techniques away from the CSI accuracy. Simulations are provided for OFDM and FBMC by setting the pulse shapes to Rect (with CP of length $N - M$) and RRC pulse (with roll-off factor $\beta = 0.25$), respectively. These pulse shapes and their interference-related properties are discussed in our previous work [3], [4]. We analyze the performance of the equalization techniques discussed in section III depending on the value of the normalized Doppler spread (F_dT_S) and the normalized SNR (E_b/N_0) for OFDM and FBMC. The legends of the plots of this section have the following format: the processing done in the time domain is subscripted with t, while that done in the frequency domain is subscripted with f. A technique split into two parts, one in time and the other in frequency, simply have their names concatenated. Additional reference '*Slow Fading Ref.*' is plotted corresponding to the theoretical BER of a Rayleigh slow-

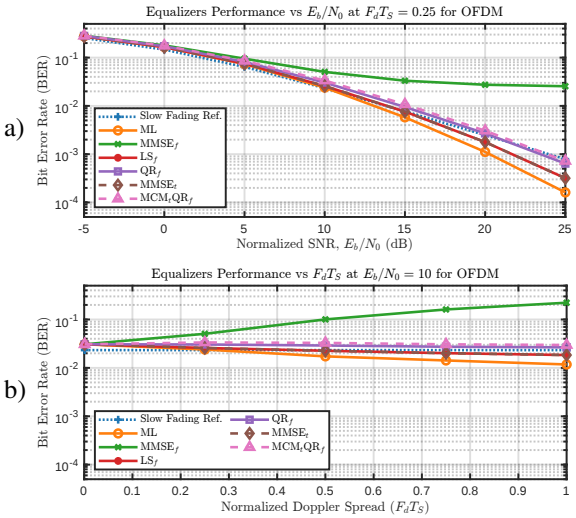

Fig. 3. Equalizers' performance for OFDM System a)versus E_b/N_0 at $F_dT_S = 0.25$ and b)versus F_dT_S at $E_b/N_0 = 10dB$.

fading channel provided by [13] and adopted by Proakis [14] and Mathworks [15]. For comparison purposes, FBMC plots also included '*OFDM ML*' corresponding to the best possible performance when using OFDM obtained by the Maximum Likelihood (ML) criterion implemented by (computationally intractable in practice) exhaustive search applied directly to the time domain received signal (after removing the CP).

Figure 3.a) shows the performance of different equalizers in an OFDM system versus the normalized SNR E_b/N_0 while transmitting over a time varying channel with a normalized Doppler spread $F_dT_S = 0.25$ having transmitted symbols as QAM4 symbols. Complementary to that, fig. 3.b) shows the same plots versus the normalized Doppler Spread F_dT_S at a normalized SNR $E_b/N_0 = 10dB$. *'ML'* represents the Maximum Likelihood optimal receiver implemented through (computationally intractable in practice) exhaustive search. First, this figure shows how the classical one-tap frequency domain MMSE equalizer has very poor (and the worst) performance in such channels with BER floor 2×10^{-2} at $F_dT_S = 0.25$. The ML equalizer benchmark shows that BER can be lower than the slow varying channels benchmark. This means that in case of high Doppler, the gain driven by the time domain diversity can be possibly greater than the performance loss due to Doppler-driven interference, if a suitable receiver scheme is employed. Relevantly, it is the case of our proposed MMSE_t and MCM_tQR_f, as can be seen in the provided simulation. In contrary to that, classical frequency domain MMSE exhibits severe loss with the increase of F_dT_S. On the other hand, more advanced frequency domain equalizers like QR and LS perform significantly better than classical frequency domain MMSE, and are able to maintain or improve their performance with an increase of F_dT_S. It appears that for OFDM, MCM does not provide any improvement as it nearly matches the performance of the QR equalizer alone. On the other hand, the simple proposed equalization of time domain MMSE matches the performance of LS both having the best

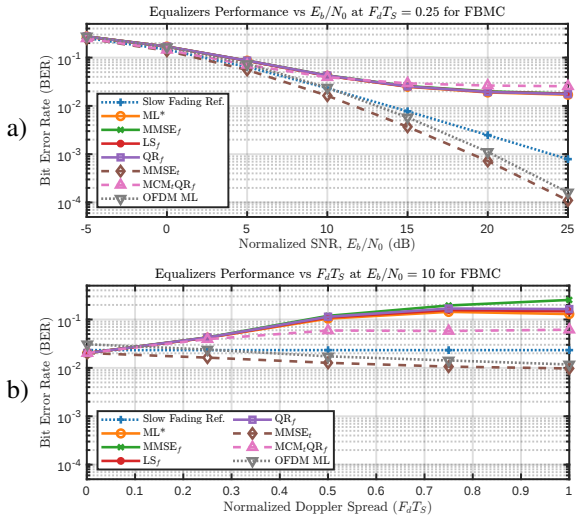

Fig. 4. Equalizers' performance for FBMC System a)versus E_b/N_0 at $F_dT_S = 0.25$ and b)versus F_dT_S at $E_b/N_0 = 10dB$.

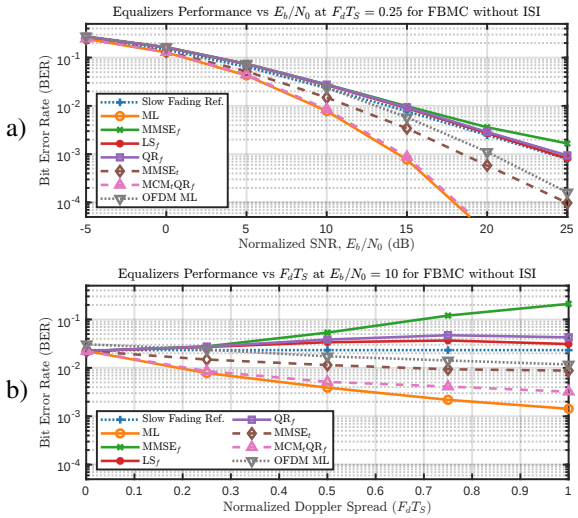

Fig. 5. Equalizers' performance for FBMC System a)versus E_b/N_0 at $F_dT_S = 0.25$ and b)versus F_dT_S at $E_b/N_0 = 10dB$. Both assuming perfect ISI cancellation.

performance. However, the proposed time domain MMSE is much simpler to implement as it requires a single tap operation at sample time while frequency domain LS requires multi-tap matrix operations in the frequency domain.

Figure 4 shows the same information as fig. 3 but for an FBMC system. The additional plot to fig. 4 is the *'OFDM ML'* plot that would allow for comparison between OFDM and FBMC in the scenario being considered. Another difference is that the ML is numerically very difficult to simulate for such scenarios of FBMC. Alternatively, we compute *'ML*'* which is simply a frequency domain exhaustive search but without accounting to the ISI. This accounts for the best performance that can be obtained for FBMC frequency domain equalizers without ISI cancellation. It can be directly seen from fig. 4 that for FBMC, while not compensating for the ISI which is not a problem for OFDM, almost all the equalizers have a bad performance with a floor of 2×10^{-2}. One exception is the proposed time domain MMSE which performs better than the ML receiver of OFDM. If we compare in fig. 4.a) the proposed time domain MMSE with the frequency domain techniques of FBMC while limiting the comparison to the point where the floor BER$\approx 2 \times 10^{-2}$ is reached at $E_b/N_0 = 20$dB, we can see that time domain MMSE achieves the same BER at $E_b/N_0 = 10$dB with a gain of 10dB.

Although these results might seem satisfying by surpassing the *'OFDM ML'* performance, yet FBMC can achieve better performance when accounting to ISI. Figure 5 corresponds to plots similar to that of fig. 4 assuming perfect cancellation of ISI. These plots show through ML the potential of FBMC to obtain much better performance. In addition to that, although the time domain MMSE maintained the same performance, it can be seen that MCM$_t$QR$_f$ achieves near ML performance. From fig. 5.a), if we focus on the 10^{-3} BER level, we can see that the frequency domain equalizers reaches this performance at $\sim E_b/N_0 = 25$dB. On the other hand, MCM$_t$QR$_f$ reaches this level at $\sim E_b/N_0 = 15$dB providing a gain of around 10dB. This shows how in all cases, FBMC can, with simple time domain equalization, reach a performance better than the best possible performance of OFDM benefiting from channel variation instead of being negatively affected even when keeping ISI. In addition to that, when an efficient ISI cancellation algorithm is employed, FBMC can reach much better performance, making it very useful in scenarios where Doppler spread is a major concern.

V. Conclusion

Classical frequency domain equalizers suffers from high BER due to high interference in fast varying environments. In this work, we have proposed to assist equalization at the receiver by additional low complexity time domain pre-processing. We provided two preprocessing techniques, and assessed their performance for OFDM and FBMC when operating in single path fast varying Rayleigh channels. The proposed scheme is shown to efficiently capture time diversity in the presence of channel variation, leading to an important performance gain, in contrary to the classical techniques that suffer from performance degradation. As a result, for OFDM, this preprocessing has aided the system to reach the best possible performance similar to the frequency domain LS equalizer which requires multi-tap matrix operations, but with significantly lower complexity requiring a single tap operation at sample time. Furthermore, for FBMC, our pre-processing permits to avoid a BER floor effect and leads to 10dB gain in performance at $F_dT_S = 0.25$. This gain is observed at BER$= 2 \times 10^{-2}$ for scenarios accepting ISI and at BER$= 10^{-3}$ when assuming perfect ISI cancellation. For the latter scenario, we obtain performance very close to the (computationally intractable) optimum ML equalizer.

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APPENDIX

In this appendix, we provide through figs. 6 to 8 same simulations as in the main text, but with an imperfect CSI (MSE $= 10^{-2}$) compared to the literature, which leads to equivalent conclusions of the main text simulations. However, in the main text, we kept the assumption of perfect CSI in order to study the capabilities of the proposed techniques away from the accuracy of the CSI.

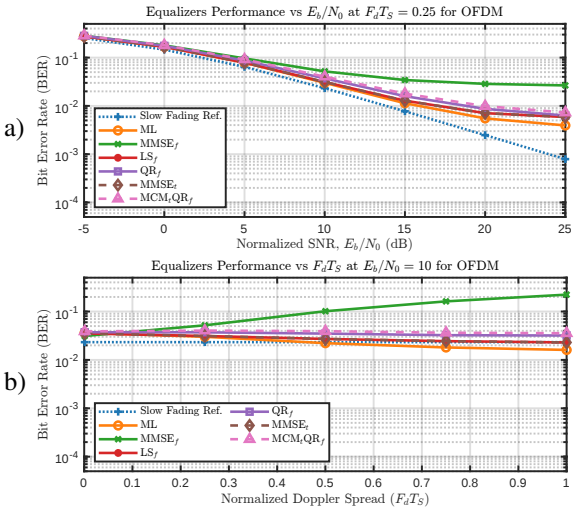

Fig. 6. Equalizers' performance for OFDM System a)versus E_b/N_0 at $F_dT_S = 0.25$ and b)versus F_dT_S at $E_b/N_0 = 10dB$.

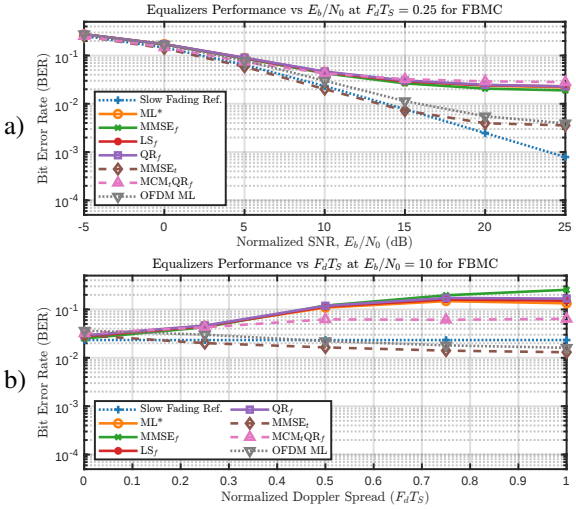

Fig. 7. Equalizers' performance for FBMC System a)versus E_b/N_0 at $F_dT_S = 0.25$ and b)versus F_dT_S at $E_b/N_0 = 10dB$.

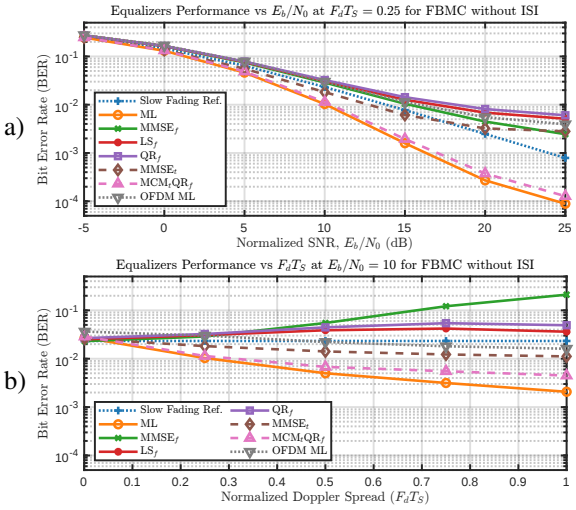

Fig. 8. Equalizers' performance for FBMC a)versus E_b/N_0 at $F_dT_S = 0.25$ and b)versus F_dT_S at $E_b/N_0 = 10dB$, assuming perfect ISI cancellation.