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Doubly-Selective Channel Estimation in FBMC-OQAM and OFDM Systems

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ABSTRACT

Future wireless systems will be characterized by a large range of possible uses cases. This requires a flexible allocation of the available time-frequency resources, which is difficult in conventional Orthogonal Frequency Division Multiplexing (OFDM). Thus, modifications of OFDM, such as windowing or filtering, become necessary. Alternatively, we can employ a different modulation scheme, such as Filter Bank Multi-carrier (FBMC)We propose a method to estimate doubly-selective channels based on the time and frequency correlation of scattered pilots. To reduce the interference at the pilot and data positions, we apply an iterative interference cancellation scheme. Our method is applicable to arbitrary linear modulation techniques, with Orthogonal Frequency Division Multiplexing (OFDM) and Filter Bank Multicarrier Modulation (FBMC), being special cases. Simulations over doubly-selective channels show that our channel estimation method comes close to having perfect channel knowledge available.

Keywords: FBMC-OQAM, OFDM, Multipath channels, Time-varying channels, Channel Estimation.

I.INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is the dominant transmission technique of current wireless systems and is intended to remain relevant even in the next generation of wireless system (5G). However, the interest in alternative schemes, such as Filter Bank Multicarrier Modulation (FBMC) with Offset Quadrature Amplitude Modulation (OQAM), increased in recent years [1], [2]. FBMC has much better spectral properties when compared with OFDM, but also some additional disadvantages, such as a lower compatibility to Multiple-Input and Multiple-Output (MIMO) [3-5]. Moreover, all multi-carrier schemes have the drawback of a high Peak-to-Average Power Ratio (PAPR). Thus, additional processing might be necessary [6].

On the other hand, one of the biggest advantages of multi-carrier systems is that the transmission over a time-variant multi-path channel can often be modelled by one-tap channels, greatly simplifying the equalization. This works as long as the delay spread and the Doppler spread are sufficiently low [7]. Such condition, however, is not always fulfilled. In highly doubly-selective channels, symbols interfere with each other. Channel estimation and equalization then becomes more challenging. To estimate doubly-selective channels, authors in [8] and [9] utilize a Minimum Mean Squared Error (MMSE) channel estimation method, but consider only one OFDM symbol in time. This requires clustered pilots. MMSE channel

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estimation was also investigated in FBMC [10], but the authors ignore the time-varying nature of wireless channels.

Many other authors employ a basis expansion model [11], [12] to estimate doubly selective channels. Here, the time variation is modelled by a basis expansion, for example, an exponential basis [13], a polynomial basis [14], a Slepian basis [15] or an MMSE interpolation basis [16]. Some authors argue that statistical models are bulky and difficult to handle [11], which is also the main reason why they employ a basis expansion model. However, we utilize a compact matrix description, allowing to easily incorporate channel statistics, so that all elements of a doubly-selective channel can be accurately estimated with just a few pilots. The novel contributions of our paper can be summarized as follows:
1) We propose a doubly-selective channel estimation method that does not require clustered pilots or a basis expansion model.
2) We generalize our previous paper, see [17], so that our method is not only applicable to OFDM, as in [17], but to arbitrary linear modulation methods, including FBMC.
3) In contrast to [17], we employ a low-complexity interference cancellation scheme instead of a computationally demanding MMSE equalization.

II. LITURATURE SURVEY

R. Nissel, S. Schwarz, and M. Rupp,[1] proposed Future wireless systems will be characterized by a large range of possible uses cases. This requires a flexible allocation of the available time-frequency resources, which is difficult in conventional Orthogonal Frequency Division Multiplexing (OFDM). Thus, modifications of OFDM, such as windowing or filtering, become necessary. Alternatively, we can employ a different modulation scheme, such as Filter Bank MultiCarrier (FBMC). In this paper, we provide a unifying framework, discussion and performance evaluation of FBMC and compare it to OFDM based schemes. Our investigations are not only based on simulations, but are substantiated by real-world testbed measurements and trials, where we show that multiple antennas and channel estimation, two of the main challenges associated with FBMC, can be efficiently dealt with. Additionally, we derive closed-form solutions for the signal-to-interference ratio in doubly-selective channels and show that in many practical cases, one-tap equalizers are sufficient. A downloadable MATLAB code supports reproducibility of our results.

R. Nissel, [2] proposes a method to estimate doubly-selective channels based on the time and frequency correlation of scattered pilots. To reduce the interference at the pilot and data positions, we apply an iterative interference cancellation scheme. Our method is applicable to arbitrary linear modulation techniques, with Orthogonal Frequency Division Multiplexing (OFDM) and Filter Bank Multicarrier Modulation (FBMC), being special cases. Simulations over doubly-selective channels show that our channel estimation method comes close to having perfect channel knowledge available. A downloadable Matlab code supports reproducibility.

R. Nissel and M. Rupp, [3] introduced Filter Bank Multi-Carrier (FBMC) offers superior spectral properties compared to Orthogonal Frequency Division Multiplexing (OFDM), at the cost of imaginary interference, which makes the application of Multiple-Input and Multiple- Output (MIMO) more challenging. By spreading symbols in time (or frequency), we can completely eliminate the imaginary interference, so that all MIMO techniques known in OFDM can be straightforwardly applied in FBMC. The spreading process itself has low complexity because it is based on Hadamard matrices. Although spreading allows to restore complex orthog- onality in FBMC within one transmission block, we observe interference from neighboring blocks.

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By including a guard time- slot, the signal-to-interference ratio can be further improved. Furthermore, we investigate the effect of a time-variant channel on such spreading approach. Finally, testbed measurements show the applicability of our FBMC based MIMO transmission scheme in real world environments.

R. Nissel and M. Rupp[6] proposes a novel modulation scheme which combines the advantages of filter bank multi-carrier (FBMC)-offset quadrature amplitude modulation and single-carrier frequency-division multiple access (SC-FDMA). On the top of a conventional FBMC system, we develop a novel precoding method based on a pruned discrete Fourier transform (DFT) in combination with one-tap scaling. The proposed technique has the same peak-to-average power ratio as SC-FDMA but does not require a cyclic prefix and has much lower out-of-band emissions. Furthermore, our method restores complex orthogonality, and the ramp-up and ramp-down period of FBMC is dramatically decreased, allowing low latency transmissions. Compared to pure SC-FDMA, the computational complexity of our scheme is only two times higher. Simulations over doubly selective channels validate our claims, further supported by a downloadable MATLAB code. Note that pruned DFT-spread FBMC can equivalently be interpreted as a modified SC-FDMA transmission scheme. In particular, the requirements on the prototype filter are less strict than in conventional FBMC systems.

III. PROPOSED SYSTEM

DOUBLY SELECTIVE CHANNEL ESTIMATION

In case of a doubly-selective channel, many papers [16], [26], try to estimate the channel impulse response, that is, Hˆ . However, estimating the impulse response is quite problematic because in practical systems the number of active subcarriers is always lower than the Fast Fourier Transform (FFT) size, that is, L < NFFT. This implies that the channel transfer function at the zero subcarriers cannot be accurately estimated, preventing also an accurate estimation of the impulse response. By applying an inverse Fourier transform onto the channel transfer function of the L active subcarriers, one only obtains a pseudo impulse response, implicitly assuming a rectangular filter. In particular, the delay taps of the pseudo impulse response are no longer limited in time (within the symbol duration), even though the true impulse response might be.

This is caused by the discontinuity of the channel transfer function at the edge subcarriers and becomes problematic for estimation methods which rely on the assumption that the delay taps are limited in time. Another aspect is the computational complexity. Even if one is able to accurately estimate the impulse response, the matrix multiplication in (5) still needs to be evaluated, implying a huge computational burden. All those drawbacks can be avoided by directly estimating transmission matrix D. To some extent, this is already happening in practical systems, as the one-tap channel is usually estimated through interpolation. Those one-tap channel coefficients correspond to the diagonal elements of Dˆ.

The main idea of our channel estimation method is illustrated in Fig 6.1. The “sampled” time-variant transfer function (at the pilot positions) is interpolated, delivering an estimate of the full time-variant transfer function. This is possible because of a high correlation in time and frequency.

As already mentioned before, it is computationally more efficient to directly estimate Dˆ without the detour of the channel transfer function, whereby the underlying correlation is preserved. One element of

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transmission matrix at row position $l1_{k1} = l_1 + L_{k1}$ and column position $l2k2 = l_2 + L_{k2}$, can then be estimated by

$$[\hat{\mathbf{D}}]_{\overline{l_1 k_1}, \overline{l_2 k_2}} = \tilde{\mathbf{w}}^{\mathsf{H}}_{l_1,k_1,l_2,k_2} \, \hat{\mathbf{h}}^{\mathrm{LS}}_{\mathcal{P}}$$

Where $\tilde{\mathbf{w}}_{l_1,k_1,l_2,k_2} \in \mathbb{C}^{|\mathcal{P}| \times 1}$ represents a weighting vector and $\hat{\mathbf{h}}^{\mathrm{LS}}_{\mathcal{P}} \in \mathbb{C}^{|\mathcal{P}| \times 1}$ ×1 the LS channel estimates at the pilot positions, see (6). The weighting vector has a major influence on the channel estimation accuracy. We consider an MMSE weighting vector, the best possible channel estimation method in terms of MSE. By utilizing the orthogonal projection theorem,

$$\mathbb{E}\left\{\left([\mathbf{D}]_{\overline{l_1 k_1}, \overline{l_2 k_2}} - [\hat{\mathbf{D}}]_{\overline{l_1 k_1}, \overline{l_2 k_2}}\right) [\hat{\mathbf{D}}]^{\mathsf{H}}_{\overline{l_1 k_1}, \overline{l_2 k_2}}\right\} = 0$$

which states that the error of the estimator must be orthogonal to the estimator, the MMSE weighting vector in (9) can be calculated by

$$\tilde{\mathbf{w}}_{l_1,k_1,l_2,k_2} = \mathbf{R}^{-1}_{\hat{\mathbf{h}}^{\mathrm{LS}}_{\mathcal{P}}} \, \mathbf{r}_{\hat{\mathbf{h}}^{\mathrm{LS}}_{\mathcal{P}}, [\mathbf{D}]_{\overline{l_1 k_1}, \overline{l_2 k_2}}}$$

With denoting the correlation matrix of the LS channel estimates at the pilot positions and $\mathbf{r}_{\hat{\mathbf{h}}^{\mathrm{LS}}_{\mathcal{P}}, [\mathbf{D}]_{\overline{l_1 k_1}, \overline{l_2 k_2}}} \in \mathbb{C}^{|\mathcal{P}| \times 1}$ the correlation vector between the LS channel estimates at the pilot positions and one element of transmission matrix D. Very often, the biggest challenge is to find the required correlation matrices. Thanks to our matrix notation, however, finding those matrices is relatively easy. Let us first consider the correlation between the i^{th} LS channel estimate and the

$$\mathbf{R}_{\hat{h}^{\mathrm{LS}}_{\mathcal{P}_i}} = \frac{\mathrm{tr}\left\{\left(\mathbf{C}^{\mathsf{T}}\mathbf{G}^{\mathsf{T}} \otimes \mathbf{q}^{\mathsf{H}}_{\mathcal{P}_i}\right) \mathbf{R}_{\mathrm{vec}\{\mathbf{H}\}} \left(\mathbf{C}^{\mathsf{T}}\mathbf{G}^{\mathsf{T}} \otimes \mathbf{q}^{\mathsf{H}}_{\mathcal{P}_i}\right)^{\mathsf{H}}\right\} + P_{\mathrm{n}} \mathbf{q}^{\mathsf{H}}_{\mathcal{P}_i} \mathbf{q}_{\mathcal{P}_i}}{P_{\mathcal{P}}}$$

The cross-correlation in (12) and the auto-correlation in (13) build up the overall correlation matrix $R_{h\tilde{}LS\,P} \in C^{|P|\times|P|}$, and depend on the correlation matrix of the vectorized channel, $R_{vec\{H\}} = E\{vec\{H\}vec\{H\}^H\}$. The elements of this correlation matrix can easily be calculated because they are just the correlation of the time-variant impulse response, that is, $E\{h_{conv.}[n_1, m_1]\, h^*_{conv.}[n_2, m_2]\}$, assumed to be perfectly known. Only the mapping of this correlation to the correct position in Rvec{H} is a bit challenging because of the vectorized structure. Similar as in (12), the correlation between the LS channel estimate at the i-th pilot position and one element of transmission matrix D can be calculated by,
and builds up correlation vector.

$$\mathbf{r}_{\hat{h}^{\mathrm{LS}}_{\mathcal{P}_i}, [\mathbf{D}]_{\overline{l_1 k_1}, \overline{l_2 k_2}}} = \left(\mathbf{g}^{\mathsf{T}}_{\mathcal{P}_i} \otimes \mathbf{q}^{\mathsf{H}}_{\mathcal{P}_i}\right) \mathbf{R}_{\mathrm{vec}\{\mathbf{H}\}} \left(\mathbf{g}^{\mathsf{T}}_{l_2,k_2} \otimes \mathbf{q}^{\mathsf{H}}_{l_1,k_1}\right)^{\mathsf{H}}$$

$$\mathbf{r}_{\hat{\mathbf{h}}^{\mathrm{LS}}_{\mathcal{P}}, [\mathbf{D}]_{\overline{l_1 k_1}, \overline{l_2 k_2}}} \in \mathbb{C}^{|\mathcal{P}| \times 1}$$

With (12)-(14) we have all the necessary tools to calculate the MMSE weighting vector in (11), that is, ˜wl1,k1,l2,k2 . One might think that our channel estimation method is unrealistic because the correlation matrices are not perfectly known in practical systems. While it is indeed hard to find the true correlation matrices, a rough approximation can easily be found and is often sufficient.
For example, in the context of OFDM, testbed measurements at 400 km/h have already validated that our MMSE channel estimation works in real world testbed scenarios [17]. To measure at such high velocities, we augmented the Vienna Wireless Testbed by a rotation wheel unit [27], [28]. The measurement results in

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[17] indicate that our channel estimation method, see (9) and (11), performs close to perfect channel knowledge. In [17] we considered MMSE equalization instead of a low-complexity interference cancellation scheme. Still, in contrast to many other works related to time-variant channel estimation, our MMSE channel estimation method was already proven to work in real world testbed scenarios, at least in the context of OFDM.

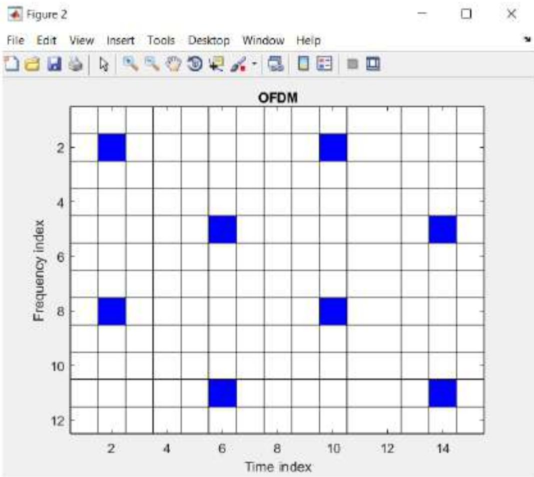

Figure 1: Shows OFDM Time Index vs Frequency Index

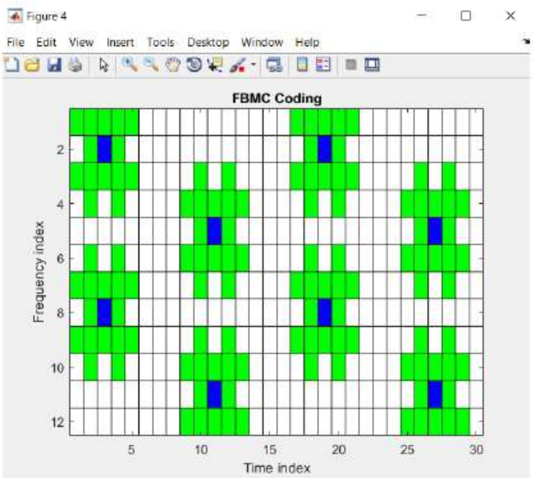

Figure 2: Shows FBMC Coding

V. RESULTS AND DISCUSSION

NUMERICAL RESULTS

For our numerical evaluations, we consider a Long term Evolution (LTE) like OFDM signal. We assume a diamond shaped pilot pattern, same as in LTE, that is, |P| = 32 pilots are distributed over a time-frequency resource of KT = 2 ms and LF = 360 kHz, representing the transmission of two subframes with eight resource blocks in total. The overhead in OFDM, including pilot symbols and the CP, is LF TCPK+|P| KT LF = 11.1%. Figure 7.2 shows the Bit Error Ratio (BER) over the Signal-to-Noise Ratio (SNR) for OFDM. Note that the BER is relatively high because of a 256-Quadrature Amplitude Modulation (QAM) signal constellation. To improve the channel estimation accuracy, we consider a pilot to-data power offset of PP /PD = 2. A one-tap equalizer performs poorly once interference starts to dominate the noise. By employing

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our interference cancellation scheme, on the other hand, the performance can be significantly improved. Overall, our doubly-selective channel estimation technique performs close to perfect channel knowledge (only a small SNR shift of approximately 1 dB for the "no edges" curve). For the "no edges" MMSE channel estimation curve in Figure 7.2, we exclude time-frequency positions close to the edge, that is, we consider only points which are in the center of the frame. One can imagine a sliding block with an inner and an outer block where only the inner block is evaluated for the BER, while the outer block only contributes to the channel estimation.

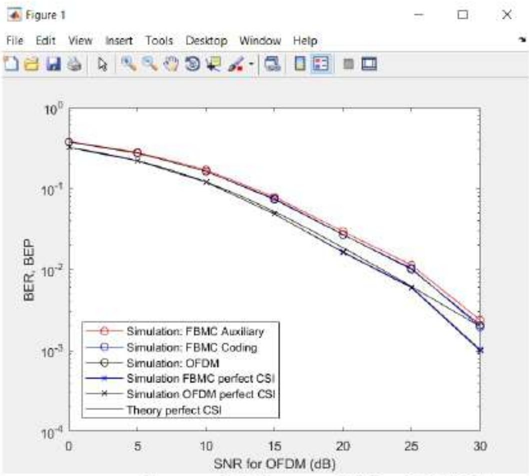

Figure 3: Shows SNR of OFDM

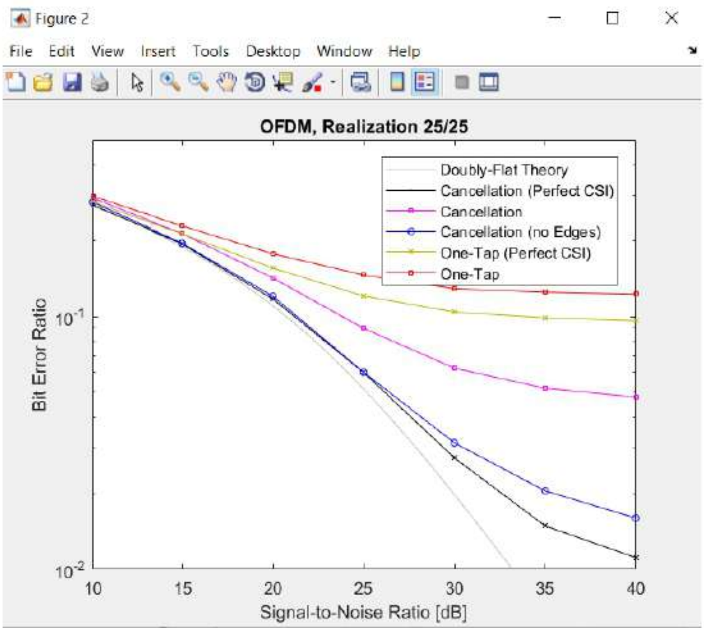

Figure 4: Our proposed doubly-selective channel estimation method performs close to perfect channel knowledge

Many challenges associated with FBMC, such as channel estimation and MIMO, can be efficiently dealt with, as validated by our real-world testbed measurements. Additionally, one-tap equalizers are in many practical cases sufficient once we match the subcarrier spacing (pulse shape) to the channel statistics. In highly doubly selective channels, we can switch from an FBMC-OQAM transmission to an FBMC-QAM transmission, thus deliberately sacrificing spectral efficiency but gaining robustness. We have proposed a doubly-selective channel estimation and interference cancellation scheme. Our method is applicable to any linear modulation scheme, such as, OFDM and FBMC. FBMC based on the auxiliary symbol method outperforms OFDM in terms of BER. FBMC based on that data spreading method performs slightly worse than FBMC based on the auxiliary symbol method, but has the additional advantage of a higher data rate.

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