Fast-Convolution Implementation of Linear Equalization Based Multiantenna Detection Schemes

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Abstract— **This contribution addresses the channel equalization for MIMO systems utilizing filter bank based multicarrier (FBMC) transmission. The proposed frequency-domain MIMO equalizer is integrated with the subcarrier processing of the fast-convolution filter bank (FC-FB) structure. The performance of the proposed scheme is evaluated for both the static user and the user with high mobility in highly frequency-selective propagation scenarios. It is shown that integrating the equalization functions with the FC-FB processing leads to a highly efficient overall implementation.**

I. INTRODUCTION

Wireless communications is facing new challenges as the constant growth in users and constant demand for higher data rates requires a high level of flexibility for accessing the available spectrum. In cognitive radio context, the opportunistic dynamic spectrum access and heterogeneous wireless system coexistence has turned out to be the promising techniques for increasing the efficiency in spectrum utilization. Multicarrier modulation is well suited for these new challenging radio use scenarios owing to its ability to provide the desired high level of flexibility by adjusting the spectral characteristics of the transmitted signal to available unused spectrum slots.

A relatively widely studied filter bank based waveform is FBMC/OQAM (filter bank multicarrier/offset-QAM, also known as OFDM/OQAM) [1], [2]. While reaching high spectral containment, it keeps many of the important features of OFDM. Even though FBMC/OQAM has its limitations in terms of conceptual and implementation complexity [3], it has received increasing interest in the mentioned challenging spectrum use scenarios.

Multiple-input multiple-output (MIMO) systems, employing multiple antennas at the transmitter and/or the receiver side, are capable of increasing the capacity of the wireless channel compared with the traditional single antenna systems. In so-called spatial multiplexing (SM), different data streams are assigned to each transmit antenna leading to an increase in transmission rate with the same bandwidth. In general, the increased requirements for data transmission rate and reliability point to the need of combining multicarrier modulation with the MIMO technology.

Linear minimum mean-square error (LMMSE) detection is one of the most basic approaches for detection in multiantenna systems. In SM MIMO-OFDM systems, the subchannels are flat fading and the LMMSE solution is reached basically through channel matrix inversion for each subcarrier. The subcarrier signals from different receiver antennas are combined through complex weights, i.e., single-tap subcarrier equalizers. In filter bank based multicarrier systems, the flat-fading subcarrier model is not strictly valid, and the system optimization may actually lead to significant frequency selectivity at the subcarrier level [4]. This leads to the need for multi-tap subcarrier equalizers for LMMSE detection. In the broadband professional mobile radio (B-PMR) context, the Hilly Terrain channel model [5], [6] with LTE-like FBMC/OQAM waveform parametrization is one example where the subcarriers become highly frequency-selective. The target of B-PMR development is to introduce a broadband data communication service for safety organizations, in coexistence with the TETRA family of standards in the 400 MHz frequency band [7]. Since B-PMR is expected to operate in large macrocells, the Hilly Terrain channel model is highly relevent in the development.

The European Union FP7-ICT project EMPhAtiC focuses on the B-PMR system development. One of its core ideas is to utilize the fast-convolution filter bank (FC-FB) model for implementing different filter bank based single-carrier) (SC) and multi-carrier (MC) waveforms in a unified and flexible manner, as described in the EMPhAtiC deliverable D2.1 and [8]. The embedded equalization principle was introduced for the single-input single-output (SISO) case in [9]. The idea is to combine the equalizer coefficients with the channelization filter weights in the FFT-domain processing, instead of using multitap subchannel equalizers. In this contribution we show how the frequency sampled subcarrier equalizer approach can be effectively embedded to the fast-convolution processing structure also in the single-input multiple-output (SIMO) and MIMO cases, while maintaining the multimode capabilities of the FC-FB scheme.

The paper is organized as follows. The frequency sampling based multi-tap subcarrier equalizers are shortly reviewed in Section II. Section III describes the embedded subcarrier equalizer in the context of fast-convolution processing with MIMO configuration. The performance and the computational complexity of the proposed equalizer are evaluated in Section IV and Section V, respectively. Finally, the conclusions are drawn in Section VI.

II. FREQUENCY SAMPLING BASED MULTI-TAP SUBCARRIER EQUALIZER APPROACH

Frequency sampling based subcarrier equalizer design was originally developed for SISO FBMC/OQAM systems [4] and SC systems [10], but it has also been extended to the SIMO and SM MIMO-FBMC/OQAM systems in [11]. Figure 1 shows the frequency sampling based equalizer structure for the $1 \times N_R$ SIMO case. Even though the equalizer adaptation is based on the frequency sampled model, the subcarrier equalizers

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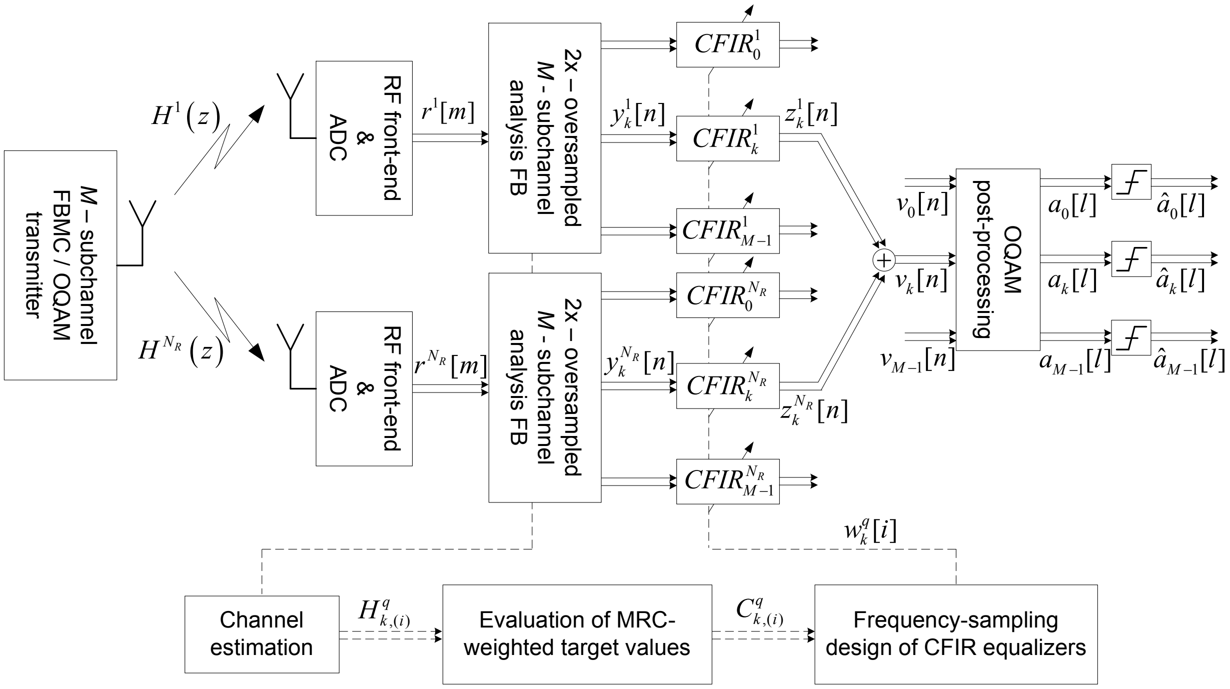


Fig. 1. SIMO system with multi-tap subcarrier equalizers based on the frequency sampling approach.

are implemented as multi-tap complex FIR filters. Frequency sampled SISO equalization has also been proposed in the context of the frequency spreading FBMC approach [12].

Actually, the frequency sampled equalization scheme is very flexible, and the same design principle and the same subcarrier equalizer structure can be used in all FBMC systems and SC systems with frequency-domain equalization in which significant frequency selectivity appears at the subcarrier/subband level. The key idea is to find the linear MMSE solution, in the same way as in MIMO-OFDM, in a number of frequency points within each subband. Then the multi-tap subcarrier equalizers are designed to reach the target frequency response at those frequencies.

III. Embedded Subcarrier Equalization in FC-FB

The idea of FC-FB is to use multirate fast-convolution processing for implementing the subchannel filters of analysis and synthesis filter banks [8]. Overlap-save processing is utilized to approximate well linear convolution by the structure that implements a cyclic convolution by nature. In this structure, the subband widths, center frequencies, and transition band shapes can be tuned independently of each others. This gives also the possibility to process different waveforms in different subbands simultaneously. In the basic scheme, the weight coefficients are designed to optimize the passband and stopband frequency response characteristics, primarily targeting at minimizing the inband interference of the transmission link and maximizing stopband attenuation to minimize out-of-band interference coupling. However, the same weights can be used also for implementing the subcarrier equalizers, as explained in [9] for the SISO case.

Figure 2 shows the FC-FB structure with embedded subcarrier equalizers in the 2×2 MIMO case, with two transmitted data streams. Each FC-FB data path from a receiver antenna to an output data stream implements subchannel filtering using the multirate fast-convolution processing principle: long (N-point) FFT, selection of the L FFT bins corresponding to the subchannel frequency band, weighting of the FFT bins, and short (L-point) IFFT to obtain a filtered and decimated block of samples. Overlap-save processing by the factor of $1 - N_S/N = 1 - L_S/L$ is used in the process to implement linear convolution through a cyclic convolution process. Here N_S and L_S are the non-overlapped (useful) data block lengths on the high-rate and low-rate sides, respectively.

In the embedded equalizer, the frequency sampling based equalizer coefficients are directly combined with the weights of the basic FC-FB design. The weights are implemented separately for each signal path from one of the receiver antennas to an output stream, and IFFT processing is implemented after combining the antenna signals. This embedded equalizer structure is independent of the transmitted waveform, subcarrier bandwidth and center frequency. The frequency domain weights are computed from the channel frequency responses and the pre-designed basic weight mask of each subcarrier. The weight for each frequency bin is obtained as the product of the weight coming from the basic weight mask and the linear equalizer weights computed from the channel frequency responses:

$$w_{q,p,k,i} = w_{k,i}^{(FB)} w_{q,p,k,i}^{(eq)}. \tag{1}$$

Here q is the index of the receiver antenna, p is the index of the data stream, k is is the subcarrier/subband index and i is the IFFT bin index. We can see that the frequency sampling based subcarrier equalizer can be embedded in a natural way to the FC analysis filter bank. With zero-forcing criterion, the equalizer weights would be obtained for each frequency bin from the pseudo-inverse of the channel matrix $H_{k,i}$ at the corresponding bin,

$$\mathbf{W}_{k,i}^{(ZF)} = (\mathbf{H}_{k,i}^H \mathbf{H}_{k,i})^{-1} \mathbf{H}_{k,i}^H, \tag{2}$$

where the superscript H stands for Hermitian (complex conjugate transpose). With MSE criterion, the corresponding expression is

$$\mathbf{W}_{k,i}^{(MSE)} = (\mathbf{H}_{k,i}^H \mathbf{H}_{k,i} + \rho \mathbf{I}_{N_T})^{-1} \mathbf{H}_{k,i}^H, \tag{3}$$

where ρ is the noise-to-signal power ratio and I_{N_T} is an identity matrix of dimension N_T, the number of transmit antennas.

It can be noted that the zero-forcing solution would completely cancel the interference from other data streams and also from adjacent subcarriers in case of FBMC/OQAM waveform. However, the MSE solution results in lower MSE in the equalized signal, by balancing the effects of imperfect equalization and noise enhancement.

Some clarification concerning the linear receiver structure used in different antenna configurations is appropriate in this context. In SISO and SIMO configurations, it is possible to utilize the frequency-domain equalizer to closely approximate the classical, optimal receiver structure where the fractionally-spaced equalizer implements the matched filter, matched both to the transmitted pulse shape and the channel response, along with linear channel equalizer [10]. However in the SM MIMO configuration, each antenna chain receives multiple data streams affected by different channel responses and it is not possible to match the receiver processing for multiple channel responses at the same time. Therefore, our receiver structure consists of the pulse shape matched filter, implemented by the basic weight mask of the FC-FB structure, and the MSE-criterion based weights obtained from Eq. (3).

IV. SIMULATION BASED PERFORMANCE EVALUATION

We consider the 5 MHz LTE-like scenario with FBMC/OQAM waveform, 512 subcarriers out of which 300 are active, and subcarrier spacing of 15 kHz [13]. Results are shown for the 2×2 spatial multiplexing MIMO configuration using QPSK modulation, Vehicular A (VehA) and Hilly Terrain (HT) channel models with 0 km/h and 200 km/h mobilities and the carrier frequency of 450 MHz, corresponding to the target PMR frequency band. In the simulations, independent instances of the corresponding channel model are used for the four propagation paths of the 2×2 MIMO configuration. In addition to the embedded equalizer, also the single-tap subcarrier equalization model (using the same equalizer weights in FC-FB implementation for all bins of a subcarrier) is included in the comparisons. Figures 3 and 4 show the results assuming perfect channel knowledge in the receiver. While the single-tap equalizer model works quite well with the Vehicular A channel (with about 2.5 μs delay spread), its performance with Hilly Terrain channel (with about 18 μs delay spread) is significantly degraded. The embedded equalizer is able to handle very well also the highly frequency-selective subchannel case of the HT channel.

However, the equalizer weights are constant over each FFT processing block, which introduces performance degradation with high mobility. Figures 5 and 6 give results with pilot based channel estimation. The used pilot structure is shown in Fig. 7. It is based on the auxiliary pilot model [14] to control intrinsic interference of the pilot symbols, which is due to the offset-QAM signal structure. The pilot structure is designed to have high density in the frequency direction, in order to handle well highly frequency selective subchannels. We can see that the basic scattered pilot based channel estimation scheme suffers from high frequency selectivity at the subcarrier level, through interference coupling from adjacent subcarriers. The effect was found to be clearly stronger in the 2×2 MIMO case than in the SISO case.

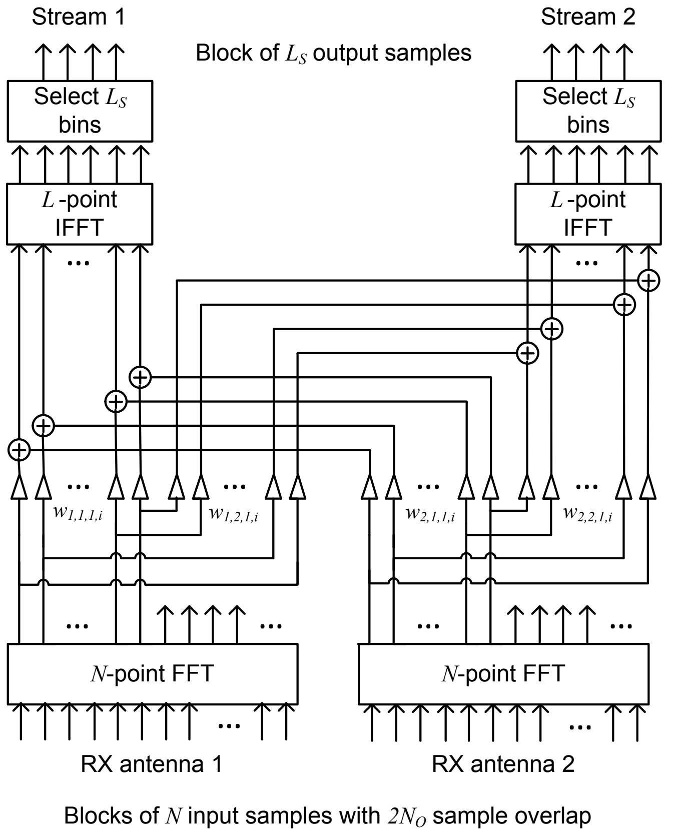


Fig. 2. 2×2 spatial multiplexing MIMO receiver utilizing the FC-FB structure with embedded equalization.

V. COMPLEXITY EVALUATION

The FC-FB structure has potential for reduced computational complexity, in terms of multiplication and addition rates, in comparison to the commonly used polyphase filter bank structure [8]. In the following, we use N_T and N_R as the number of transmitter and receiver antennas, respectively, and assume that the number of transmitted streams in a SM MIMO system is equal to N_T. We assume the LTE-like parametrization for the FC-FB receiver. The FFT length is $N = 512L/2 = 4096$, IFFT length is $L = 16$ and the overlap factor is $(L - L_S)/L = 6/16$, where $L_S = 10$ is the number of useful output samples (half-symbols) per IFFT processing block. In the structure of Fig. 2, long FFT is implemented blockwise for each receiver antenna. The short IFFTs are implemented for each output stream. The

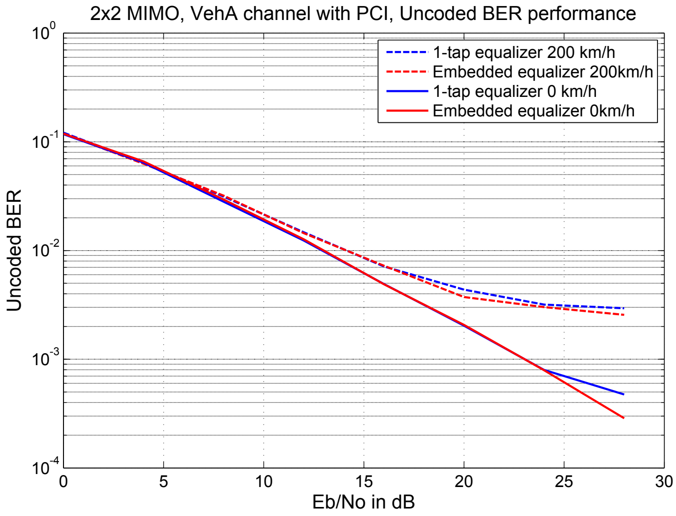


Fig. 3. LMMSE detection performance for 2×2 spatial multiplexing MIMO with QPSK modulation, Vehicular A channel and perfect channel knowledge (PCI) in the receiver.

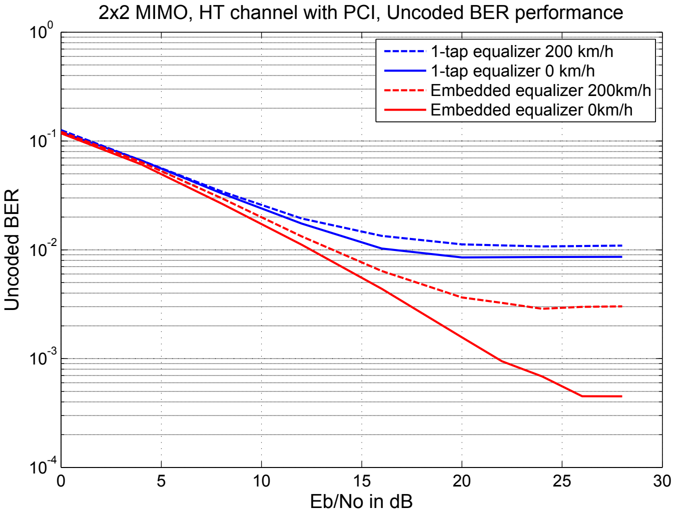


Fig. 4. LMMSE detection performance for 2×2 spatial multiplexing MIMO with QPSK modulation, Hilly Terrain channel and perfect channel knowledge (PCI) in the receiver.

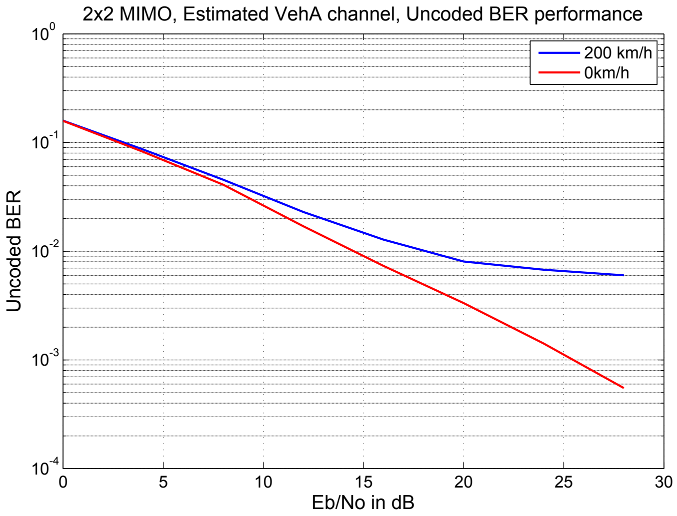


Fig. 5. LMMSE detection performance for 2×2 spatial multiplexing MIMO with QPSK modulation, Vehicular A channel and pilot based channel estimation.

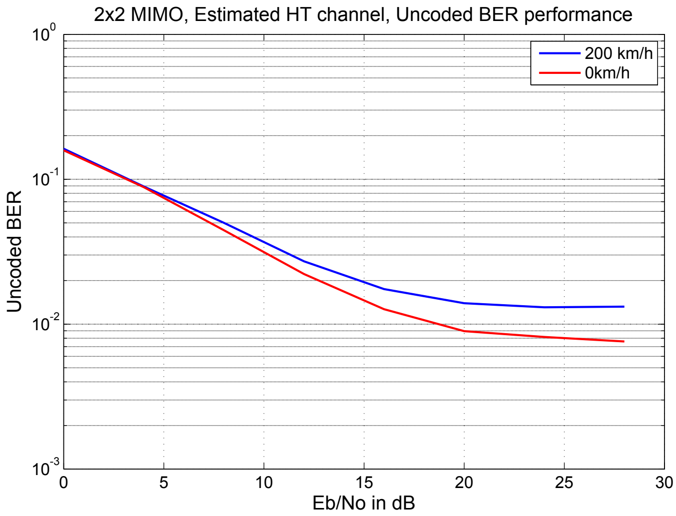
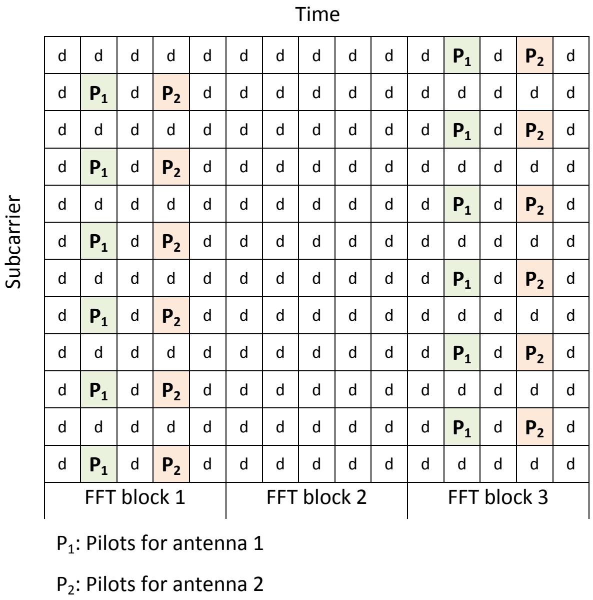


Fig. 6. LMMSE detection performance for 2×2 spatial multiplexing MIMO with QPSK modulation, Hilly Terrain channel and pilot based channel estimation.

FFT and IFFT lengths are powers of two and we assume that the implementation uses the split-radix algorithm taking $B(\log_2(B) - 3) + 4$ real multiplications for length B FFT or IFFT.

Then in the FC-FB receiver implementation, the following elements are needed in the example case: (i) N_R FFTs of length $N = 4096$, (ii) $M_{\text{used}} N_T$ IFFTs of length $L = 16$ with $M_{\text{used}} = 300$, and (iii) $M_{\text{used}} N_T N_R$ sets of weight coefficients each containing $L - 1 = 15$ non-trivial coefficients. There is a need for using arbitrary complex coefficients as weights, instead of fixed basic weight coefficients which, depending on the specific parametrization and design, could also take real values [8]. From each processing block, $M_{\text{used}} N_T L_S / 2$ data symbols are detected. In the 2×2 MIMO case, the needed number of real multiplications per detected symbol is about 53. This compares favorably with the multiplication rate of the polyphase implementation with 3-tap subcarrier equalizers [11], [3], which takes about 65 real multiplications per detected symbol with the polyphase filter bank overlap factor of $K = 3$, or about 72 multiplications per detected symbol with polyphase filter bank overlap factor of $K = 4$. The arithmetic complexity of the FC-FB based implementation depends greatly on the overlap factor. As another example, if the IFFT length is 24, the FFT length is 6144, and the overlap factor is 6/24, then the multiplication rate is reduced to 39 real multiplications per detected symbol.

The above calculations include only the multiplications in the data signal paths. Additional computations are needed for channel estimation and calculation of the equalizer weight coefficients. It was assumed that the weights are recalculated for each IFFT bin for each FFT processing block, which naturally leads to relatively high complexity. To reduce the



d	d	d	d	d	d	d	d	d	d	d	P_1	d	P_2	d
d	P_1	d	P_2	d	d	d	d	d	d	d	d	d	d	d
d	d	d	d	d	d	d	d	d	d	d	P_1	d	P_2	d
d	P_1	d	P_2	d	d	d	d	d	d	d	d	d	d	d
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d	d	d	d	d	d	d	d	d	d	d	P_1	d	P_2	d
d	P_1	d	P_2	d	d	d	d	d	d	d	d	d	d	d
FFT block 1					FFT block 2					FFT block 3				

Fig. 7. Pilot structure used for 2×2 spatial multiplexing MIMO.

complexity, methods based on interpolation over each set of weight coefficients and between FFT processing blocks should be developed.

VI. CONCLUSIONS

In this contribution, we have investigated MIMO channel equalization in LTE-like FBMC systems. The frequency sampling based subcarrier equalizer has been effectively embedded into the FC analysis filter bank. The performance of the proposed equalizer has been evaluated in Vehicular A and Hilly Terrain channels models and it was shown that it is able to handle very well also the highly frequency-selective subchannel case. On the other hand, the long block structure of FC-FB leads to increased sensitivity to fast fading. It was also found out that the performance of basic scattered pilot based channel estimation is degraded in case of high frequency selectivity. The degradation is significantly stronger in 2×2 MIMO case compared to the SISO case. One of the important topics for future studies is to investigate interference cancellation methods to enhance the channel estimation quality.

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