# Pilot Aided Channel Estimation for a 2×2 MIMO DVB-T2 system in High Speed Mobile Environment

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***Abstract*—The combination between a two dimensional (2D) filter with a non-rectangular spectrum and the 3-points diagonal averaging method is proposed in this paper as a channel estimation method for a 2×2 MIMO DVB-T2 system. The 3-points diagonal averaging method can shorten the distance between reference pilot along frequency direction before interpolation; consequently, it will optimize the performance of an interpolation filter. The two stages implementation of a 2D nonrectangular filter is also proposed in this paper to reduce the complexity of the channel estimation method. Simulation results show the robustness of the proposed method in very high speed mobile environment.**

## I. Introduction

The DVB-T2 system [1] is the second generation of a digital terrestrial television standard based on the orthogonal frequency division multiplexing (OFDM) system. In this system, the multi input-single output (MISO) with Alamouti scheme was included in order to increase the diversity gain that is essential for reception performance in low speed environment. However, in the future the mobile reception of digital terrestrial television in high speed environment, such as high speed train (TGV, Maglev, etc with commercial speed $\approx$ 300 [km/h]) will become an important aspect in the competition with other digital broadcasting system, such as digital satellite. There is a need to provide information and onboard entertainment services to high speed train passengers. In this case, the inclusion of MIMO scheme become necessary to increase the reception performance of high speed digital terrestrial television.

In a 2×2 MIMO system based on the Alamouti scheme, it has been acknowleged that channel estimation would hold the important role in maintaining the diversity gain that is provided by Alamouti scheme [2]. In this paper, the channel estimation for a 2×2 MIMO system in high speed mobile environment is proposed. Until now, many research works have been conducted regarding PACE for the multi antenna OFDM system. [3], [4] proposed 1D channel estimation for the multi antenna OFDM systems, which is limited only to the frequency direction, as opposed to the 2D channel estimation method proposed by [5] that can track the variation of time varying channel even at high doppler frequencies. Reference [5] however, employed the Wiener filter which has a very high complexity cost.

In this paper, to cope with the parallelogram-shaped grid pilot pattern of the DVB-T2 system, we employed the 2D filter with a non-rectangular spectrum. It was actually proposed by [6] for an image processing application and has been successfully implemented in the single-input single-output (SISO) system channel estimation [7]. A single stage implementation of the the 2D filter continues to have a high complexity cost. Thus, we divide the 2D filter into two stage of filtering in the time and frequency direction separately, resulting in lower complexity in hardware implementation. In order to optimize the performance of interpolation filter in a 2×2 MIMO system, we propose the 3-points diagonal averaging method. This method can shorten the distances between scattered pilots resulting in the improvement of channel estimation performance.

The rest of this paper has been organized as follows. In section II, we briefly introduce the DVB-T2 OFDM system with two transmit antenna. The discussion of PACE for a 2×2 MIMO sytem is provided in section III. The design of a 2D filter with non-rectangular spectrum is discussed in section IV. Finally, we discuss the result of the computer simulation in section V.

## II. A 2×2 MIMO DVB-T2 System

### *A. A 2×2 MIMO Baseband OFDM System*

The baseband model of a 2×2 MIMO OFDM system that has been developed for this research work is shown in Fig.1. The binary data are first mapped according to the modulation that is used by the signal mapper. Then, the mapped data are processed by the MIMO encoder to generate input for each transmitter antenna. The complete process of the MIMO encoder is presented in subsection II-B. After that, the reference pilots are inserted into the data. The reference pilot will be further utilized to conduct the channel estimation, especially the scattered pilots.

An OFDM baseband symbol is generated by modulating complex data using the inverse fast fourier transform (IFFT). In order to prevent inter symbol interference (ISI), guard interval (GI) which is chosen to be larger than delay spread is inserted at the beginning of each symbol. The symbol is then transmitted through multipath fading channel. The receiver consists of a complementary process of transmitter, in order to recover the transmitted information.

### *B. Modified Alamouti SFBC*

The DVB-T2 system defined the transmit diversity based on the Alamouti Coding [2], but it was slightly modified to allow a backward compatibility with the SISO system. Since this scheme exploits diversity in space and frequency-domain, therefore it has been termed as space frequency block coding (SFBC). The modified Alamouti SFBC coding is shown in Table I.

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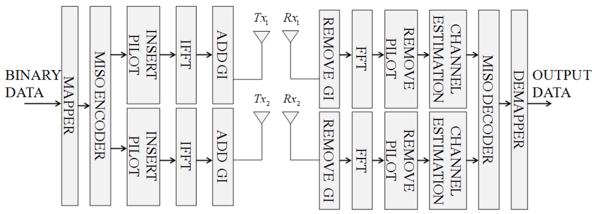


Fig. 1. Baseband Alamouti 2×2 MIMO DVB-T2 OFDM System

TABLE I
MODIFIED ALAMOUTI SCHEME

| | $k$-th subcarrier | $(k+1)$-th subcarrier |
|---|---|---|
| $\mathrm{Tx}_1$ | $S_{k,l}$ | $S_{k+1,l}$ |
| $\mathrm{Tx}_2$ | $-S^*_{k+1,l}$ | $S^*_{k,l}$ |

If $S_{k,l}$ represents the pre-coding transmitted signal of $k$-th subcarrier and $l$-th symbol, then the received signal for the first pair of MIMO cell, $Y_{j,k,l}$ and $Y_{j,k+1,l}$ can be derived as shown by (1)-(2)

$$\begin{aligned} Y_{j,k,l} &= X_{1,k,l}H_{1j,k,l}+X_{2,k,l}H_{2j,k,l}+W_{j,k,l} \\ &= S_{k,l}H_{1j,k,l}-S^*_{k+1,l}H_{2j,k,l}+W_{j,k,l} \end{aligned} \tag{1}$$

$$\begin{aligned} Y_{j,k+1,l} &= X_{1,k+1,l}H_{1j,k+1,l}+X_{2,k+1,l}H_{2j,k+1,l}+W_{j,k+1,l} \\ &= S_{k+1,l}H_{1j,k+1,l} + S^*_{k,l}H_{2j,k+1,l}+W_{j,k+1,l} \end{aligned} \tag{2}$$

where $H_{1j,k,l}, H_{1j,k,l}$ and $W_{j,k,l}$ are the channel frequency response between $\mathrm{Tx}_1$ and $\mathrm{Rx}_j$, the channel response between $\mathrm{Tx}_2$ and $\mathrm{Rx}_j$, and AWGN in $k$-th subcarrier and $l$-th symbol, respectively.

### C. Scattered Pilot Pattern of a 2×2 MIMO DVB-T2 System

The DVB-T system introduced parallelogram-shaped grid scattered pilot pattern that is especially used for channel estimation [1]. The amplitude and position of scattered pilot of $\mathrm{Tx}_1$ in $l$-th symbol and $k$-th subcarrier is given as (3)

$$\begin{aligned} &P_{1,k,l} = 2A_{sp}(0.5 - r_{k,l}) \\ &k \bmod (D_X D_Y) = D_X(l \bmod D_Y) \end{aligned} \tag{3}$$

where $r_{k,l}$ and $A_{sp}$ denote a reference sequence for generating pilot and amplitude of scattered pilot, respectively. $D_X$ and $D_Y$ are the distances of pilot bearing subcarriers forming a periodic pattern in frequency and time direction, respectively.

The DVB-T2 standard proposed eight different scattered pilot patterns which are dependent on the size of FFT and GI. In the case of a 2K FFT and 1/8 of GI that has been selected for this paper, the pattern of scattered pilot for a 2×2 MIMO is that of a PP1 pattern [1] as shown by Fig.2. Since the received signal contains the mixture of channel from $\mathrm{Tx}_1$ and $\mathrm{Tx}_2$, a DVB-T2 system introduced a few modifications on the pilot from a $\mathrm{Tx}_2$ in order to estimate the channel from both transmitters antenna. In one subset (symbol 0, 2, 4,.., 2N), pilots are transmitted in the same phase from both transmitters, allowing the sum of two channel responses to be estimated. In another subset (symbol 1, 3, 5,.., 2N+1), the pilots from the second transmitter are inverted from the one in the first transmitter, allowing the difference of channel responses to be estimated. The inverted phase of scattered pilot of $\mathrm{Tx}_2$ is given by (4)

$$P_{2,k,l} = (-1)^{k/Dx} P_{1,k,l} \tag{4}$$

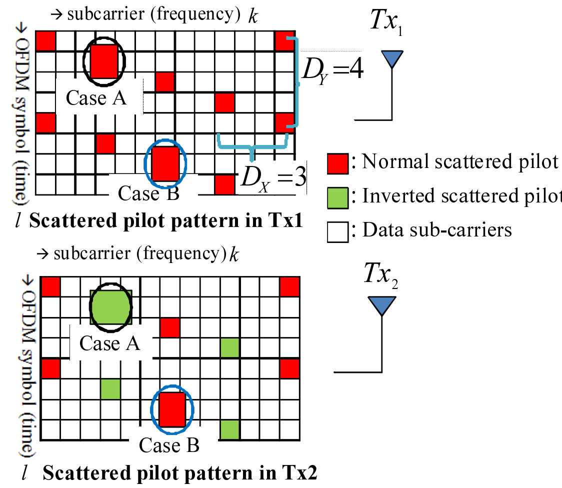


Fig. 2. Scattered Pilot Pattern for $Tx_1$ and $\mathrm{Tx}_2$

## III. PACE FOR A 2×2 MIMO DVB-T2 SYSTEM

In this section, we present the PACE for a 2×2 MIMO DVB-T2 system. This method supports the interpolation filter that is discussed in section IV.

If $X_{1,k,l}$ and $X_{2,k,l}$ represent transmitted signal from $\mathrm{Tx}_1$ and $\mathrm{Tx}_2$, then the received signal at $j$-th antenna is expressed by (5)

$$Y_{j,k,l} = X_{1,k,l}H_{1j,k,l}+X_{2,k}H_{2j,k,l}+W_{j,k,l} \tag{5}$$

where $H_{1j,k,l}, H_{2j,k,l}$, and, $W_{j,k,l}$ are the channel response between $\mathrm{Tx}_1$ and $\mathrm{Rx}_j$, channel response between $\mathrm{Tx}_2$ and $Rx_j$, and AWGN of $Rx_j$, respectively.

There are two cases to be considered to estimate the channel as shown by Fig.2. In the first case, the transmitted pilots from the $\mathrm{Tx}_2$ are the invert of the pilot from $\mathrm{Tx}_1$, $X_{1,k,l} = -X_{2,k,l} = X^a_{k,l}$. The received signal for case A is given by (6)

$$Y^a_{j,k,l} = X^a_{k,l}(H_{1j,k,l} - H_{2j,k,l})+W_{j,k,l} \tag{6}$$

In another case, the transmitted pilots from $\mathrm{Tx}_2$ are completely similar to the pilots from $\mathrm{Tx}_1$ in given subcarriers, $X_{1,k,l} = X_{2,k,l} = X^b_{k,l}$. The received signal for case B is given by (7)

$$Y^b_{j,k,l} = X^b_{k,l}(H_{1j,k,l} + H_{2j,k,l})+W_{j,k,l} \tag{7}$$

Based on this condition, the conventional method [8] and the proposed 3-points averaging method is discussed in subsection III-A and III-B.

### A. The Conventional Method

The conventional method of PACE for a 2×2 MIMO DVB-T2 system is described briefly in [8]. This method consists of several steps, i.e:

**Step 1** Estimate the sum and difference of channel using the LS method as given by (8)-(9)

$$\hat{H}^a_{j,k,l} = Y^a_{j,k,l}/X^a_{k,l} \approx H_{1j,k,l} - H_{2j,k,l} \tag{8}$$

$$\hat{H}^b_{j,k,l} = Y^b_{j,k,l}/X^b_{k,l} \approx H_{1j,k,l} + H_{2j,k,l} \tag{9}$$

**Step 2** Interpolate the estimated sum and difference of channel responses in time and frequency direction to obtain the estimation at all data subcarriers position.

**Step 3** Conduct the sum and difference operations to obtain the estimation of channel frequency responses from both transmitters.

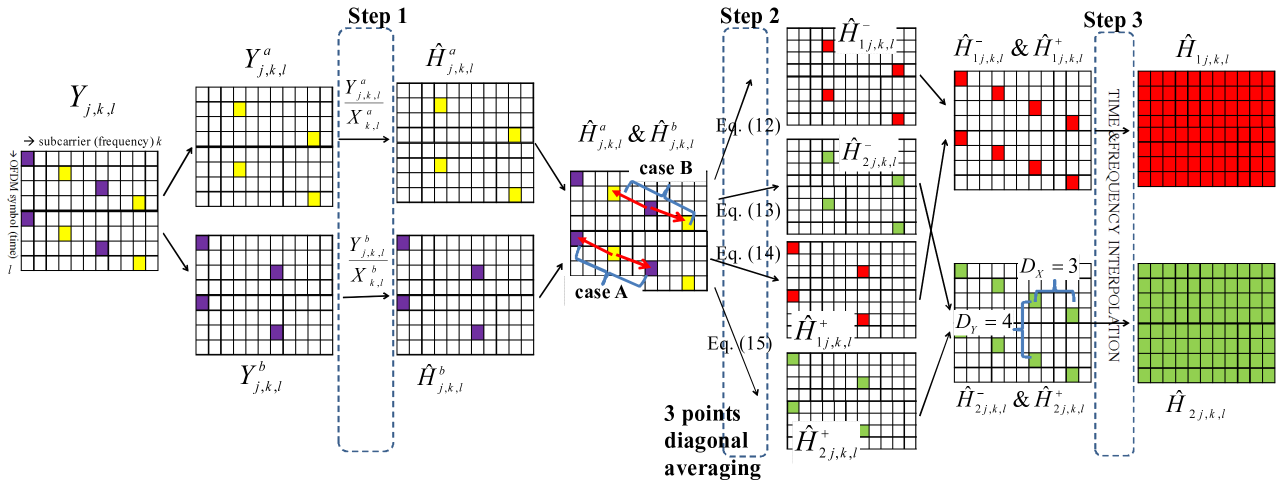

Fig. 3. The illustration of the proposed 3-points diagonal PACE for a 2×2 MIMO OFDM system

$$\hat{H}_{1j,k,l} = 0.5(\hat{H}^a_{j,k,l} + \hat{H}^b_{j,k,l}) \tag{10}$$

$$\hat{H}_{2j,k,l} = -0.5(\hat{H}^a_{j,k,l} - \hat{H}^b_{j,k,l}) \tag{11}$$

The weakness of the conventional method is the larger distance among scattered pilots in frequency direction before interpolation, i.e. $D_X = 6$ which means less density of reference pilot that may decrease the performance of interpolation filter along frequency direction.

### B. The Proposed 3-Points Averaging Method

In this paper, we propose the channel estimation method that can optimize the performance of the interpolation filter by shortening the distance between reference pilots in frequency direction before interpolation and also increase the number of points included in averaging process, The channel estimation that we propose in this paper consists of several steps, i.e:

**Step 1** Estimate the sum and difference of channel using the LS method as given by (8)-(9)

**Step 2** Estimate the channel frequency responses, $\hat{H}_{1j,k,l}$ and $\hat{H}_{2j,k,l}$ by conducting 3-points averaging operation operations. Based on the scattered pilot pattern, we divide the sum and difference operations in two cases, i.e case A and B. In case A, the estimation of channel frequency responses from both transmitters at j-th transmitter are given by (12)-(13)

$$\hat{H}^-_{1j,k,l} = 0.25(2\hat{H}^a_{j,k,l} + \hat{H}^b_{j,k-3,l-1} + \hat{H}^b_{j,k+3,l+1}) \tag{12}$$

$$\hat{H}^-_{2j,k,l} = -0.25(2\hat{H}^a_{j,k,l} - \hat{H}^b_{j,k-3,l-1} - \hat{H}^b_{j,k+3,l+1}) \tag{13}$$

In case B, the estimation of channel frequency responses from both transmitters are given by (14)-(15)

$$\hat{H}^+_{1j,k,l} = 0.25(2\hat{H}^b_{j,k,l} + \hat{H}^a_{j,k-3,l-1} + \hat{H}^a_{j,k+3,l+1}) \tag{14}$$

$$\hat{H}^+_{2j,k,l} = 0.25(2\hat{H}^b_{j,k,l} - \hat{H}^a_{j,k-3,l-1} - \hat{H}^a_{j,k+3,l+1}) \tag{15}$$

Equation (12)-(15) are derived from 3 stage averaging processes. In the first stage, we average the reference pilot with reference pilot in the left side. In the second stage, we average the reference pilot with the reference pilot in the right side. Finally, we average the result of the first stage and the second stage.

**Step 3** Combine $\hat{H}^-_{ij,k,l}$ and $\hat{H}^+_{ij,k,l}$, then conduct the interpolation in time and frequency direction to obtain the estimation of $\hat{H}_{ij,k,l}$ in all subcarrier data position. The complete processes of the proposed method are illustrated in Fig. 3

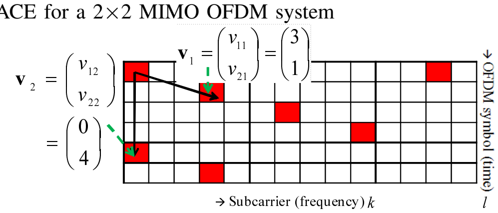

Fig. 4. Lattice expression according to the DVB-T system pilot pattern

The advantage of this method compared to the conventional method [8] is the shorter distance in frequency direction before interpolation, i.e. $D_X = 3$, which means higher density of reference pilot that may increase the performance of interpolation filter along frequency direction compared to the conventional method.

This method has also some advantages compared to the 2-points averaging proposed by [9]. Firstly, it does the averaging not only with the neighbour reference pilot in one side, but with the neighbours reference pilots at the both side. Utilizing more number of averaging points will definitely increase the accuracy of the channel estimation. Secondly, the averaging is not performed after time direction interpolation, thus the performance is not dependent of the time direction interpolation performance as the pointed weakness of 2-points averaging [9]. Therefore, it will be more robust in lower SNR.

## IV. A 2D Filter with Non-rectangular Spectrum as Interpolation Filter

In this paper, we propose the utilization of a 2D Filter with non rectangular spectrum as the interpolation filter for a 2×2 MIMO DVB-T2 channel estimation. Multidimensional multirate filters for non-rectangular lattices were proposed by [6] for multidimensional multirate signal processing with parallelogram-shaped passbands. In this paper, we modified the 2D filter based on the multidimensional multirate filter concept [6] to obtain the estimation of channel frequency responses. Since the DVB-T2 system utilizes the pilot pattern with parallelogram-shaped grid, the idea of 2D filter with a non-rectangular spectrum has become important in achieving a better performance for channel estimation.

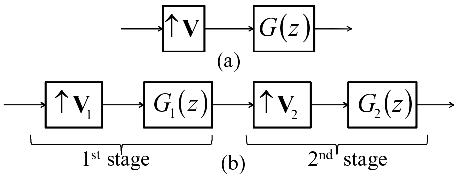


Fig. 5. (a).A single stage implementation (b).Two stage implementation

TABLE II
TYPICAL URBAN POWER AND DELAY PROFILE (TU6) [10]

| Tap number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Delay ($\mu s$) | 0.0 | 0.2 | 0.5 | 1.6 | 2.3 | 5.0 |
| Power (dB) | -3 | 0 | -2 | -6 | -8 | -10 |

### A. General Lattice Expression of a 2D Sampling

In this section, we discuss about the general lattice expression of a 2D sampling that is used in 2D filter discussion. Given $\mathbf{n} = [n_1, n_2]^T$ and $\mathbf{t} = [t_1, t_2]^T$ are the rectangular coordinate before and after upsampling, respectively. The relation between $\mathbf{t}$ and $\mathbf{n}$ can be defined as (16)

$$\mathbf{t}\begin{pmatrix} t_1 \\ t_2 \end{pmatrix} = \mathbf{V}\begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = \begin{pmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{pmatrix}\begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \tag{16}$$

where $\mathbf{V}$ is the sampling matrix. Every sample location $\mathbf{t}$ is of the form (17)

$$\mathbf{t} = n_1\mathbf{v}_1 + n_2\mathbf{v}_2 \tag{17}$$

where $\mathbf{v}_1 = [v_{11}, v_{21}]^T$ and $\mathbf{v}_2 = [v_{12}, v_{22}]^T$. The DVB-T2 system [1] has a pilot pattern as shown in Fig.4. For this pattern, the sampling matrix $\mathbf{V}$ can be expressed as (18)

$$\mathbf{V} = \begin{pmatrix} 3 & 0 \\ 1 & 4 \end{pmatrix}, \mathbf{v_1} = \begin{pmatrix} 3 \\ 1 \end{pmatrix}, \mathbf{v_2} = \begin{pmatrix} 0 \\ 4 \end{pmatrix} \tag{18}$$

### B. A Design of Non-rectangular Spectrum 2D Interpolation Filter

In this section, we explain about the process of designing a 2D Interpolation Filter with a non-rectangular spectrum. The process itself consists of three steps:

**Step 1** Generate a 1D FIR LPF $p(n)$ which its spectrum doesn't involve aliasing when the 2D filter is later generated. The pass band region of 1D LPF is , $[-\pi/\det(\mathbf{V}), \pi/\det(\mathbf{V})]$ where the $\det(\mathbf{V})$ is a determinant of matrix $\mathbf{V}$ that is given by (18).

**Step 2** Generate a 2D separable and rectangular spectrum filter $g^{(s)}(\mathbf{n})$ as defined by (19).

$$g^{(s)}(\mathbf{n}) = p(n)^T p(n) \tag{19}$$

**Step 3** Obtain the impulse response of non-separable filter $g(\mathbf{n})$ by decimating $g^{(s)}(\mathbf{n})$ matrix with the matrix $\hat{\mathbf{V}}$ and scaling with $\det(\hat{\mathbf{V}})$

$$g(\mathbf{n}) = \det(\hat{\mathbf{V}})g^{(s)}(\hat{\mathbf{V}}\mathbf{n}) \tag{20}$$

Where matrix $\hat{\mathbf{V}}$ is the adjoint of matrix $\mathbf{V}$. From here, we obtain the non-rectangular spectrum 2D filter.

### C. Two Stages Implementation of a 2D Filter

In terms of implementation, a single stage of 2D filter could involve a high complexity in hardware design. It is represented in Fig. 5(a). The interpolation filter, i.e. $G(z)$ is performed after upsampling the reference pilots by matrix $\mathbf{V}$.

In order to achieve a design with less complexity, we propose the two stage filtering, as shown in Fig. 5(b). In this implementation, the upsampling matrix $\mathbf{V}$ is divided into two stages as shown by (21)

TABLE III
SIMULATION PARAMETER

| | |
|---|---|
| Modulation | QAM-64 |
| Bandwidth | 8 MHz ($T_s = 7/64\mu s$) |
| FFT size | 2K |
| GI length | 1/ 8 |
| Channel model | COST207 TU6 [10] |
| Channel encoding/decoding | No |
| Maximum doppler frequency | $156Hz$(360 [km/h]) |
| Carrier frequency | 470 MHz |
| Pilot pattern | PP1 |

$$\mathbf{V} = \begin{pmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{pmatrix} = \mathbf{V_2} \times \mathbf{V_1} \tag{21}$$

where $\mathbf{V_1}$ and $\mathbf{V_2}$ are defined as shown by (22)

$$\mathbf{V_1} = \begin{pmatrix} 1 & 0 \\ 0 & 4 \end{pmatrix}, \mathbf{V_2} = \begin{pmatrix} 3 & 0 \\ 1 & 1 \end{pmatrix}, \tag{22}$$

In the first stage, the reference pilot is upsampled using matrix $\mathbf{V_1}$ and then filtered by filter $G_1(z)$ that is shown in Fig.6. The first stage filtering denotes a 1D filtering in time-domain. In the second stage. the reference pilot is upsampled using matrix $\mathbf{V_2}$ and then filtered by filter $G_2(z)$ that is shown in Fig.7. The second stage filtering denotes a 2D non-rectangular filtering in frequency-domain. If we multiply $G_1(z)$ and $G_2(z)$, the frequency response spectrum become a 2D non-rectangular filter as shown by Fig.8

## V. SIMULATION

In order to confirm the performance of the proposed channel estimation method, we conducted computer simulation to simulate mean square error (MSE) and bit error rate (BER) performance. We compared the performance of three method, i.e. the proposed 3-points diagonal averaging method, conventional method [8], and 2-points averaging method [9] in a 2×2 MIMO system. For a channel model, we used the Typical Urban 6 path channel (TU6) that was defined by COST 207 [10]. The power delay profile of this channel model is described in table II. This channel model reproduces the terrestrial propagation for an urban area. The complete parameters of simulation are shown in table III. We conducted the simulation within very high speed mobile environment $v = 360$ [km/h] in order to prove the robustness of the proposed system in high speed train environment.

Fig.9 show the MSE vs SNR performance of the channel estimation methods. The MSE is defined as the mean squared difference between the channel frequency responses of transmitter channel $H_{ij,k,l}$ and the estimated channel frequency responses $\hat{H}_{ij,k,l}$. It is given by (23)

$$\hat{H}_{ij,k,l} = [|H_{ij,k,l} - \hat{H}_{ij,k,l}|^2] \tag{23}$$

The MSE simulation results show that the proposed 3-points diagonal averaging method outperforms the conventional and the 2-points averaging. Since the conventional method shows the worst performance among three methods, we can confirm the importance of the averaging method to increase the performance of system by shortening the distance between reference pilot along frequency direction before interpolation in a 2×2 MIMO channel estimation.

Fig.10 show the BER vs SNR performance of the channel estimation methods. Based on the simulation results, The proposed 3-points diagonal averaging method is the most effective in optimizing the diversity gain provided by the Alamouti scheme

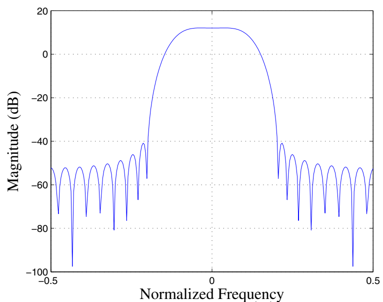


Fig. 6. $G_1(z)$

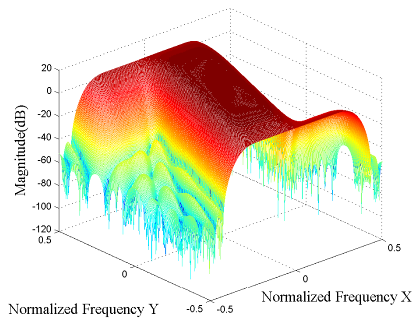


Fig. 7. $G_2(z)$

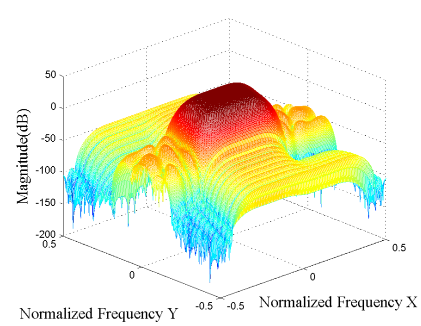


Fig. 8. $G_2(z) * G_1(z)$

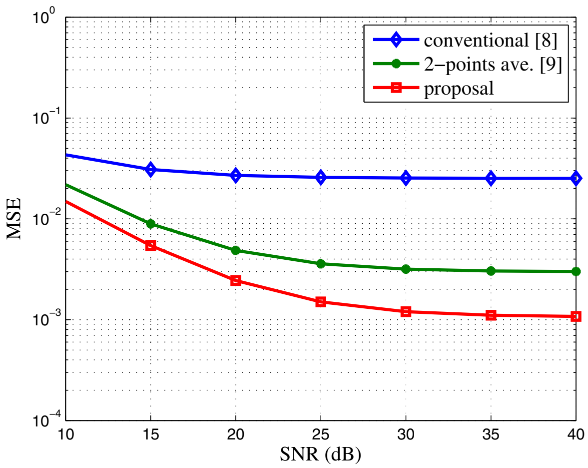


Fig. 9. MSE vs SNR for $f_d$ = 156 Hz (360 [km/h])

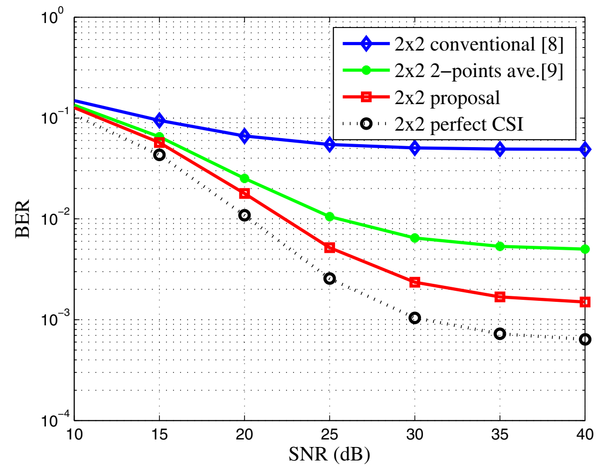


Fig. 10. BER vs SNR for $f_d$ = 156 Hz (360 [km/h])

compared to others. The proposed method can give SNR improvement around 5 dB at uncoded BER = $7 \times 10^{-3}$ compared to a 2-points averaging method [9].

## VI. Complexity Analysis

In terms of complexity, we compare the complexity between a single stage 2D non-rectangular interpolation filter with a two stage implementation as shown by Fig. 5. Based on our design, for number of taps: 20 taps for 1D FIR LPF time direction interpolation and 16 taps for 1D FIR LPF frequency direction interpolation, the number of multipliers for a single stage implementation is $27 \times 17 = 459$ multipliers, compared to a two stage implementation, i.e. $21 + 11 \times 17 = 208$ multipliers. From here, we can conclude that the two stage implementation of a 2D non-rectangular filter can reduce the number of multiplication around 50% of multiplication number that is needed by the single stage implementation.

## VII. Conclusion

In this paper, we have proposed the robust and low complexity PACE for a 2×2 MIMO DVB-T2 system. A 3-points diagonal averaging method is proposed to shorten the distance between reference pilot along frequency-domain and increase the accuracy of estimation. A two stage implementation of a 2D non-rectangular spectrum filter is utilized as an interpolation filter. We have proven that the proposed method 3-point diagonal averaging has a capability to optimize a diversity gain provided by Alamouti scheme around 5 dB at uncoded BER = $7 \times 10^{-3}$ compared to the 2-point averaging [12]. In terms of complexity, the two stages implementation of a 2D filter with non-rectangular spectrum is able to reduce the number of multipliers by approximately 50% compared to a single stage implementation of a 2D filter. For future works, we will conduct an FPGA implementation of the proposed channel estimation method.

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