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Time and Frequency Domain Joint Channel Estimation in Multi-branch Systems

GUIXIA KANG[1], MARTIN WECKERLE[2], ELENA COSTA[2], PING ZHANG[1]
1. Wireless Tech. Innovation Institute
Beijing University of Posts and Telecommunications
No. 10, Xitucheng Road, Haidian District, Beijing, China
2. Com MN PG NT RI 4, Siemens AG, Communications
81541, Munich, Germany

Abstract: - In this paper, the relationship between time and frequency domain joint channel estimation (JCE) in multi-branch, i.e., multi-user and/or multiple antenna, systems is explained. It is proved that the design criterion of optimum pilots for frequency domain JCE can be deduced from the design criterion of optimum pilots for time domain JCE, and vice versa. This uncovers that the optimum pilots in time domain multi-branch systems, after discrete Fourier transform (DFT), will also be the optimum pilots in frequency domain multi-branch systems. Similarly, the optimum pilots in frequency domain multi-branch systems, after inverse discrete Fourier transform (IDFT), will also be the optimum pilots in time domain multi-branch systems. These properties increase the number of available optimum pilots for either time or frequency domain JCE in multi-branch systems.

Key-Words: - joint channel estimation; multiple antennas; multi-user; pilots; MIMO; OFDM; Multi-branch

1 Introduction

The future wireless communications systems should provide multimedia services at high data rates over adverse broadband fading channels characterized by highly dispersive (frequency-selective) fadings and Doppler shifts. The wireless fading channel is represented in time domain by channel impulse response. It is also interpreted in frequency domain as channel transfer function. The estimation of channel properties, either channel impulse responses or channel transfer functions, can be classified into time domain channel estimation and frequency domain channel estimation. In *time domain channel estimation*, the pilots are allocated in time domain, and the estimation of the time domain channel properties, i.e., channel impulse responses, is based on the time domain received signals. In *frequency domain channel estimation*, the pilots are allocated in frequency domain, and the estimation of the frequency domain channel properties, i.e., channel transfer functions, is based on the frequency domain received signals. Some applications are mixture of time and frequency domain channel estimation. For example, the time domain channel impulse responses are firstly estimated, although the pilots are allocated in frequency domain [1].

We introduce the term of *multiple branches* or *multi-branch* systems in this paper to refer to either multi-user and/or multi-antenna systems. We do not differentiate these two scenarios, because, from signal processing point of view, multiple antenna wireless channels and multi-user wireless channels have no intrinsical difference, if the channels are assumed to be independent from each other. This can be seen by comparing the two papers [2] and [3].

More specifically, multiple branches refer to multiple transmit branches in this paper. We do not specify the number of receive branches, or receivers. That is because, even if there are multiple receivers, each receiver can be processed independently for channel estimation, under the assumption that the signals received at different receivers are independent from each other. For easier expression, we consider only one receiver in this paper.

When all transmit branches can be assumed to arrive simultaneously at the receiver, for example, in synchronous uplink systems, the wireless channels experienced by all branches can be estimated jointly at the receiver, e.g., joint channel estimation (JCE) [1][2][4] can be applied.

In [5], the authors compare the time versus frequency domain channel estimation for orthogonal frequency division multiplexing (OFDM) systems in single branch (single user and single antenna) scenarios. In this paper we discuss further the time and frequency domain JCE in multi-branch scenarios. More specifically, we explain the relationship between the time domain JCE and the frequency domain JCE over frequency-selective fading channels in multi-branch systems. We make general interpretation without limitation to specific transmission schemes. However, the descriptions of the time and frequency domain JCEs can be applied to many multi-carrier transmission systems with multiple branches, such as OFDM based multi-carrier multi-user systems [1][4][6] or filtered multi-tone (FMT) based multi-carrier multiple antenna systems [7].

In Section II, the considered time and frequency domain multi-branch system models are described. In Section III, the relationship between time and frequency domain JCE is explained. In Section IV, the design criteria of optimum pilots for time domain JCE and frequency domain JCE are proved to be identical. In Section V, simulation results are provided. We conclude in the last section.

2 Multi-branch System Models

Throughout this paper, signals, channel impulse responses and channel transfer functions are represented by complex vectors and matrices. All complex quantities are underlined, and vectors and matrices are in bold face. Furthermore, $()^*$ and $()^{\mathrm{T}}$ designate the complex conjugate and the transpose, respectively. The complex conjugate transpose $()^{*\mathrm{T}}$ is also expressed as $()^{\mathrm{H}}$. The operator $[\cdot]_{x,y}$ yields the element in the x–th row and the y–th column, and $[\cdot]_{x_2,y_2}^{x_1,y_1}$ yields the submatrix bounded by the rows x_1 and x_2 and the columns y_1 and y_2 of a matrix in bracket. The frequency domain quantities are marked by a tilde, whereas the time domain quantities are printed without distinguishing marks.

Suppose K and W are the number of branches in the systems and the dimension of the channel impulse responses in taps in frequency-selective channels, respectively. Without loss of generality, we assume all branches transmit pilots with the same length L_{p} and the same energy E_{p}.

In Fig. 1 and Fig. 2, the multi-branch transmit structures are illustrated in time and frequency domain, respectively. As shown in Fig. 1, each branch k, $k=1\cdots K$ transmits a branch specific pilot vector

$$\underline{\mathbf{p}}^{(k)}=\left(\underline{p}^{(k,1)} \quad \cdots \quad \underline{p}^{(k,L_{\mathrm{p}})}\right)^T, \tag{1}$$

occupying L_{p} continuous time samples to form one pilot P. A cyclic prefix GA is appended to P, which is composed of the last L_{G} symbols of P. L_{G} should be not less than the number of channel taps W but less than L_{p}. The cyclic prefix aims to avoid inter symbol interference (ISI) basically. The transmit block of GA plus P is modulated to a radio frequency (RF) for transmission.

Similarly, as shown in Fig. 2, each branch k, $k=1\cdots K$, transmits a branch specific pilot vector

$$\tilde{\underline{\mathbf{p}}}^{(k)}=\left(\tilde{\underline{p}}^{(k,1)} \quad \cdots \quad \tilde{\underline{p}}^{(k,N_{\mathrm{F}})}\right)^T \tag{2}$$

occupying all N_{F} available subcarriers. After serial to parallel conversion (S/P), inverse discrete Fourier transform (IDFT) and parallel to serial conversion (P/S) a cyclic prefix is appended to the pilot in the same way as in Fig. 1. After that the signals are modulated to RF. In OFDM-based multi-carrier multi-user systems with N_{F} subcarriers, the transmit signals are normally modulated as in Fig. 2, and JCE are normally processed in frequency domain [1][4][6]. In order to derive the relationship between time and frequency domain JCEs, we assume that the time domain branch specific pilot $\underline{\mathbf{p}}^{(k)}$ of (1) in Fig. 1 has the same dimension as the frequency domain branch specific pilot $\tilde{\underline{\mathbf{p}}}^{(k)}$ of (2) in Fig. 2, i.e., $L_{\mathrm{p}}=N_{\mathrm{F}}$.

The radio channel between each transmit branch k and the receiver can be characterized by a time discrete channel impulse response represented by a vector

$$\underline{\mathbf{h}}^{(k)}=\left(\underline{h}^{(k,1)} \quad \cdots \quad \underline{h}^{(k,W)}\right)^{\mathrm{T}}, \quad k=1\cdots K \tag{3}$$

of dimension W, or by a frequency discrete channel transfer function represented by a vector

$$\tilde{\underline{\mathbf{h}}}^{(k)}=\left(\tilde{\underline{h}}^{(k,1)} \quad \cdots \quad \tilde{\underline{h}}^{(k,N_{\mathrm{F}})}\right)^{\mathrm{T}}, \quad k=1\cdots K \tag{4}$$

of dimension N_{F}. In OFDM-based multi-carrier systems, it is normally verified [8] that W is much smaller than N_{F} The relationship between $\tilde{\underline{\mathbf{h}}}^{(k)}$ and $\underline{\mathbf{h}}^{(k)}$ is given by [1]

$$\tilde{\underline{\mathbf{h}}}^{(k)}=\tilde{\underline{\mathbf{F}}}\begin{pmatrix}\underline{\mathbf{h}}^{(k)}\\ 0\\ \vdots\\ 0\end{pmatrix}, \quad k=1\cdots K, \tag{5}$$

where $\tilde{\underline{\mathbf{F}}}$ is a Fourier matrix of dimension $N_{\mathrm{F}}\times N_{\mathrm{F}}$.

With (3) and (4), the total vector of the channel impulse response of dimension KW and the total vector of the channel transfer function of dimension KN_{F} of all K branches are represented as

$$\underline{\mathbf{h}}=\left(\underline{\mathbf{h}}^{(1)\mathrm{T}} \quad \cdots \quad \underline{\mathbf{h}}^{(K)\mathrm{T}}\right)^{\mathrm{T}} \tag{6}$$

and

$$\tilde{\underline{\mathbf{h}}}=\left(\tilde{\underline{\mathbf{h}}}^{(1)\mathrm{T}} \quad \cdots \quad \tilde{\underline{\mathbf{h}}}^{(K)\mathrm{T}}\right)^{\mathrm{T}} \tag{7}$$

respectively. By introducing a matrix

$$\tilde{\underline{\mathbf{F}}}_{\mathrm{W}}=\left[\tilde{\underline{\mathbf{F}}}\right]_{N_{\mathrm{F}},W}^{1,1} \tag{8}$$

of dimension $N_{\mathrm{F}}\times W$ containing the first W columns of the Fourier matrix $\tilde{\underline{\mathbf{F}}}$ of dimension $N_{\mathrm{F}}\times N_{\mathrm{F}}$, we can define a blockdiagonal matrix

$$\underline{\tilde{\mathbf{F}}}_{\text{W,tot}} = \begin{pmatrix} \left[\underline{\tilde{\mathbf{F}}}\right]^{1,1}_{N_\text{F},W} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \left[\underline{\tilde{\mathbf{F}}}\right]^{1,1}_{N_\text{F},W} \end{pmatrix} \quad (9)$$

of dimension $KN_\text{F} \times KW$, so that the relationship between $\underline{\tilde{\mathbf{h}}}$ and $\underline{\mathbf{h}}$ is given by [1]

$$\underline{\tilde{\mathbf{h}}} = \underline{\tilde{\mathbf{F}}}_{\text{W,tot}}\,\underline{\mathbf{h}} \ . \quad (10)$$

3 Relationship between Time and Frequency Domain JCEs

The relationship between $\underline{\mathbf{p}}^{(k)}$ of (1) and $\underline{\tilde{\mathbf{p}}}^{(k)}$ of (2) is given by

$$\underline{\tilde{\mathbf{p}}}^{(k)} = \underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{p}}^{(k)}\ ,\ k = 1\cdots K \ . \quad (11)$$

The noise vector at the receiver is expressed in time domain as a vector

$$\underline{\mathbf{n}} = \left(\underline{n}^{(1)} \ \cdots \ \underline{n}^{(L_\text{P})}\right)^T \quad (12)$$

of dimension L_P and in frequency domain as a vector

$$\underline{\tilde{\mathbf{n}}} = \left(\underline{\tilde{n}}^{(1)} \ \cdots \ \underline{\tilde{n}}^{(N_\text{F})}\right)^T \quad (13)$$

of dimension N_F. The relationship of (12) and (13) is obtained as

$$\underline{\tilde{\mathbf{n}}} = \underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{n}} \quad (14)$$

With the branch specific pilot matrix [2]

$$\underline{\mathbf{P}}^{(k)} = \begin{pmatrix} \underline{p}^{(k,1)} & \underline{p}^{(k,L_\text{P})} & \cdots & \underline{p}^{(k,L_\text{P}-W+2)} \\ \underline{p}^{(k,2)} & \underline{p}^{(k,1)} & \cdots & \underline{p}^{(k,L_\text{P}-W+3)} \\ \vdots & \vdots & \ddots & \vdots \\ \underline{p}^{(k,L_\text{P})} & \underline{p}^{(k,L_\text{P}-1)} & \cdots & \underline{p}^{(k,L_\text{P}-W+1)} \end{pmatrix}, k = 1\cdots K \quad (15)$$

of dimension $L_\text{P} \times W$, based on which a total pilot matrix in time domain

$$\underline{\mathbf{P}} = \left(\underline{\mathbf{P}}^{(1)} \ \cdots \ \underline{\mathbf{P}}^{(K)}\right) \quad (16)$$

of K branches is constructed, and together with (6), the time domain receive signal vector

$$\underline{\mathbf{r}} = \underline{\mathbf{P}}\underline{\mathbf{h}} + \underline{\mathbf{n}} = \left(\underline{\mathbf{P}}^{(1)} \ \cdots \ \underline{\mathbf{P}}^{(K)}\right)\begin{pmatrix} \underline{\mathbf{h}}^{(1)} \\ \underline{\mathbf{h}}^{(2)} \\ \vdots \\ \underline{\mathbf{h}}^{(K)} \end{pmatrix} + \underline{\mathbf{n}} \quad (17)$$

of dimension L_P is derived over frequency-selective fading channels. (17) has been used in [2][3][7]. In (17), there are KW uncertain channel taps and L_P known received signals. In the case of $KW \le L_\text{P}$, we have a determined system in which the solutions of the uncertain channel taps can be derived.

With the total pilot matrix $\underline{\mathbf{P}}$ of (16) and the receive signal vector $\underline{\mathbf{r}}$ of (17) the least square (LS) JCE of the total channel impulse response vector $\underline{\mathbf{h}}$ of (6) is derived by [2]

$$\hat{\underline{\mathbf{h}}}_\text{LS} = (\underline{\mathbf{P}}^H\underline{\mathbf{P}})^{-1}\underline{\mathbf{P}}^H\underline{\mathbf{r}} \ . \quad (18)$$

Let us suppose a frequency domain receive signal vector

$$\underline{\tilde{\mathbf{r}}} = \underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{r}} \quad (19)$$

of dimension N_F, which is the Fourier transformation of the time domain receive signal vector $\underline{\mathbf{r}}$ of (17). From (19), and together with (14), (16) and (17), we derive

$$\underline{\tilde{\mathbf{r}}} = \left(\underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{P}}^{(1)} \ \cdots \ \underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{P}}^{(K)}\right)\begin{pmatrix} \underline{\mathbf{h}}^{(1)} \\ \underline{\mathbf{h}}^{(2)} \\ \vdots \\ \underline{\mathbf{h}}^{(K)} \end{pmatrix} + \underline{\tilde{\mathbf{n}}}. \quad (20)$$

Using the shift property of the discrete Fourier transform (DFT), we are able to prove that

$$\begin{aligned}&\left(\underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{P}}^{(1)} \ \cdots \ \underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{P}}^{(K)}\right) \\ &= \left(diag\left(\underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{p}}^{(1)}\right) \ \cdots \ diag\left(\underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{p}}^{(1)}\right)\right)\underline{\tilde{\mathbf{F}}}_{\text{W,tot}}\end{aligned}, \quad (21)$$

in which a total pilot matrix in frequency domain

$$\begin{aligned}\underline{\tilde{\mathbf{P}}} &= \left(diag\left(\underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{p}}^{(1)}\right) \ \cdots \ diag\left(\underline{\tilde{\mathbf{F}}}\,\underline{\mathbf{p}}^{(1)}\right)\right) \\ &= \begin{pmatrix} \underline{\tilde{p}}^{(1,1)} & \cdots & 0 & \cdots & \underline{\tilde{p}}^{(K,1)} & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \underline{\tilde{p}}^{(1,N_\text{F})} & \cdots & 0 & \cdots & \underline{\tilde{p}}^{(K,N_\text{F})} \end{pmatrix}\end{aligned} \quad (22)$$

of dimension $N_\text{F} \times K\,N_\text{F}$ is exploited.

From (20) through (22), and together with (7) and (9), we derive the receive signal vector

$$\underline{\tilde{\mathbf{r}}} = \underline{\tilde{\mathbf{P}}}\,\underline{\tilde{\mathbf{h}}} + \underline{\tilde{\mathbf{n}}} \quad (23)$$

of dimension N_F in frequency domain, which has been used for JCE in [1][4][6]. In (23), there are KN_F uncertain channel frequency samples and N_F known receive signals. So this system of N_F equations of (23) is underdetermined. Therefore, a unique solution cannot be obtained without reducing the number of unknowns. To solve this problem, using (10), (23) is represented as [4]

$$\underline{\tilde{\mathbf{r}}} = \underline{\tilde{\mathbf{P}}}\,\underline{\tilde{\mathbf{F}}}_{\text{W,tot}}\,\underline{\mathbf{h}} + \underline{\tilde{\mathbf{n}}} \ . \quad (24)$$

In (24), there are KW uncertain channel taps and N_F known signals. So in the case of $KW \le N_\text{F}$, there are solutions of the uncertain channel taps.

Suppose

$$\underline{\tilde{\mathbf{G}}} = \underline{\tilde{\mathbf{P}}}\,\underline{\tilde{\mathbf{F}}}_{\text{W,tot}} \ , \quad (25)$$

then (24) turns out to be

$$\underline{\tilde{\mathbf{r}}} = \underline{\tilde{\mathbf{G}}}\,\underline{\mathbf{h}} + \underline{\tilde{\mathbf{n}}} \ . \quad (26)$$

From (26), the LS JCE of the total channel impulse response vector $\underline{\mathbf{h}}$ of (6) is given by [1][4]

$$\hat{\underline{\mathbf{h}}}_{\mathrm{LS}} = (\tilde{\underline{\mathbf{G}}}^{H} \tilde{\underline{\mathbf{G}}})^{-1} \tilde{\underline{\mathbf{G}}}^{H} \tilde{\underline{\mathbf{r}}} . \quad (27)$$

The JCE of the total channel impulse response in (18) and (27) are different since they are processed in different domains. The channel impulse responses are estimated in time domain in (18), in that both the branch specific pilots $\underline{\mathbf{p}}^{(k)}$, $k = 1, \cdots, K$ of (1) (based on which the total pilot matrix $\underline{\mathbf{P}}$ of (16) is derived) and the received signal vector $\underline{\mathbf{r}}$ of (17) are in time domain. As a result, (18) can be classified as time domain JCE. In (27), on the other hand, both pilot sequences $\tilde{\underline{\mathbf{p}}}^{(k)}$, $k = 1, \cdots, K$ of (2) (based on which the matrix $\tilde{\underline{\mathbf{G}}}$ of (25) is derived) and the receive signal vector $\tilde{\underline{\mathbf{r}}}$ in (26) are in frequency domain. However, since the time domain total channel impulse response vector $\underline{\mathbf{h}}$ of (6) is estimated in (27), the JCE in (27) is a mixture of time and frequency domain processing. Using (10) and (27) the total channel transfer function vector $\tilde{\underline{\mathbf{h}}}$ of (7) is estimated as [1][4]

$$\hat{\tilde{\underline{\mathbf{h}}}} = \tilde{\underline{\mathbf{F}}}_{\mathrm{W,tot}} \left(\tilde{\underline{\mathbf{G}}}^{H} \tilde{\underline{\mathbf{G}}} \right)^{-1} \tilde{\underline{\mathbf{G}}}^{H} \tilde{\underline{\mathbf{r}}} , \quad (28)$$

which can be classified as frequency domain JCE.

4 Identity of the Design Criteria between Time and Frequency Domain JCE

In the previous section, the relationship between time and frequency domain JCEs in multi-branch systems has been explained mathematically. In this section, we will investigate further on the design criteria of the optimum pilots for time and frequency domain JCEs, and clarify the relationship of optimum pilots between time and frequency domain JCEs.

The performance of both time domain JCE [2] and frequency domain JCE [6] is evaluated in terms of SNR degradation in noise environments. The pilots by which 0dB SNR degradation is achieved are referred to as optimum pilots, which result in JCE in multi-branch environments without noise enhancement as compared with single-branch scenarios.

It has been proved that in the time domain the optimum pilots require [2]

$$\underline{\mathbf{P}}^{H} \underline{\mathbf{P}} = E_{\mathrm{P}} \mathbf{I}_{KW} , \quad (29)$$

where $\mathbf{I}_{KW}$ is a $KW \times KW$ identity matrix

In the meanwhile, it has been proved that in frequency domain the optimum pilots require [6]

$$\tilde{\underline{\mathbf{G}}}^{H} \tilde{\underline{\mathbf{G}}} = E_{\mathrm{P}} \mathbf{I}_{KW} . \quad (30)$$

The relationship of the two design criteria of (29) and (30) can be seen in the following. Since (21) can be represented as

$$\tilde{\underline{\mathbf{F}}} \underline{\mathbf{P}} = \tilde{\underline{\mathbf{G}}} , \quad (31)$$

we have

$$\tilde{\underline{\mathbf{G}}}^{H} \tilde{\underline{\mathbf{G}}} = \underline{\mathbf{P}}^{H} \tilde{\underline{\mathbf{F}}}^{H} \tilde{\underline{\mathbf{F}}} \underline{\mathbf{P}} = \underline{\mathbf{P}}^{H} \underline{\mathbf{P}} , \quad (32)$$

in which the property of Fourier matrix $\tilde{\underline{\mathbf{F}}}^{H} \tilde{\underline{\mathbf{F}}} = \mathbf{I}_{N_{\mathrm{F}}}$ is exploited. As a result, applying (32), (30) can be derived from (29), and vice versa. This means that the design criteria of optimum pilots in time domain JCE are identical to that in frequency domain JCE.

The expression in (32) uncovers that we can design optimum pilots for multi-branch systems either in time domain according to (29), or in frequency domain according to (30). Considering the relationship of (11), we conclude that the optimum pilots derived from (29) in time domain multi-branch systems, after discrete Fourier transform (DFT), will also be the optimum pilots in frequency domain multi-branch systems satisfying the condition of (30). Similarly, the optimum pilots derived from (30) in frequency domain multi-branch systems, after inverse discrete Fourier transform (IDFT), will also be the optimum pilots in time domain multi-branch systems satisfying the condition (29). The properties derived in Section IV increase the number of available optimum pilots for either time or frequency domain JCE in multi-branch systems.

5 Simulation Result

In this section, some simulation results are provided to validate our theoretical analysis. As examples, some optimum pilots designed in frequency domain JCE [4][6] according to (30) are applied to time domain JCE after IDFT transformation. The performance of the resulted pilots is evaluated by mean square estimation error in Fig. 3 and SNR degradation in Fig. 4, respectively. The mean square estimation error for time domain JCE is defined by

$$MSE = E\left\{ \left\| \hat{\underline{\mathbf{h}}} - \underline{\mathbf{h}} \right\|_{2} \right\} , \quad (33)$$

and the minimum mean square estimation error is derived by [3]

$$MSE_{\min} = \frac{KW\sigma_z^2}{E_{\mathrm{P}}} , \quad (34)$$

where σ_z^2 is the variance of the additive white noise at the receiver. The time domain minimum mean square estimation error is achieved if and only if (29) is fulfilled [3]. In Fig. 3, the mean square estimation error of three classes of frequency domain optimum pilots, i.e., Walsh code based pilots, CAZAC code based pilots and disjoint pilots, are applied to time domain JCE after IDFT transformation, with the exemplary scenarios of N_F=16, K=2, W=1, 4, and 8, respectively. It is demonstrated that in each scenario the three classes of pilots, after IDFT transformation, coincide with the mean square estimation error bound when applied to time domain JCE in multi-branch systems. So the resulted pilots appear to be the optimum pilots in time domain JCE since (29) is satisfied. This can also be seen by evaluating the SNR degradation for these three classes of pilots. In Fig. 4, SNR degradation of time domain JCE [2] is evaluated for the three classes of frequency domain optimum pilots, i.e., Walsh code based pilots, CAZAC code based pilots and disjoint pilots, which are applied to time domain JCE after IDFT transformation. It is shown that all these pilots achieve 0 dB SNR degradation in time domain for the exemplary scenario of N_F=16, K=2, and W=4, which validate our theoretical analysis in Section IV.

5 Conclusion

In this paper the relation between time domain JCE and frequency domain JCE in multi-branch systems is explained. We reveal that the design criteria of optimum pilots in time domain JCE can deduce the design criteria of optimum pilots in frequency domain JCE in terms of SNR degradation, and vice versa. This uncovers that the optimum pilots in time domain multi-branch systems, after discrete Fourier transform (DFT), will also be the optimum pilots in frequency domain multi-branch systems. Similarly, the optimum pilots in frequency domain multi-branch systems, after inverse discrete Fourier transform (IDFT), will also be the optimum pilots in time domain multi-branch systems. These properties increase the number of available optimum pilots for both time and frequency domain JCEs in multi-branch systems

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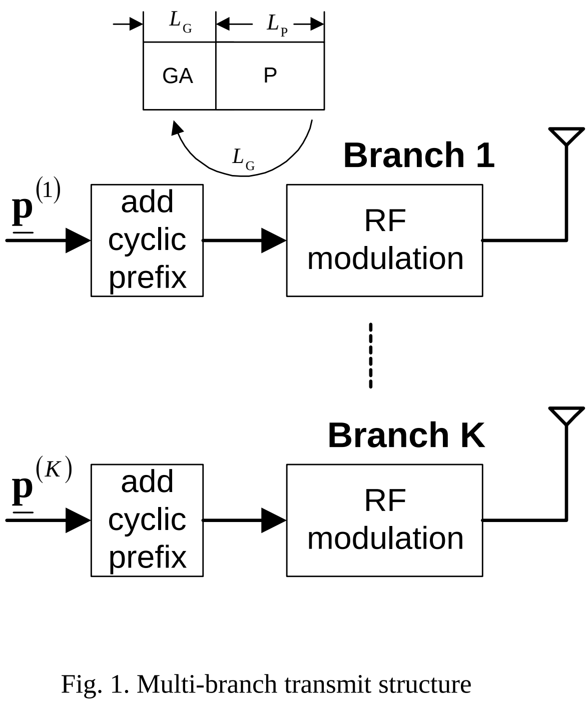

Fig. 1. Multi-branch transmit structure corresponding to time domain channel estimation

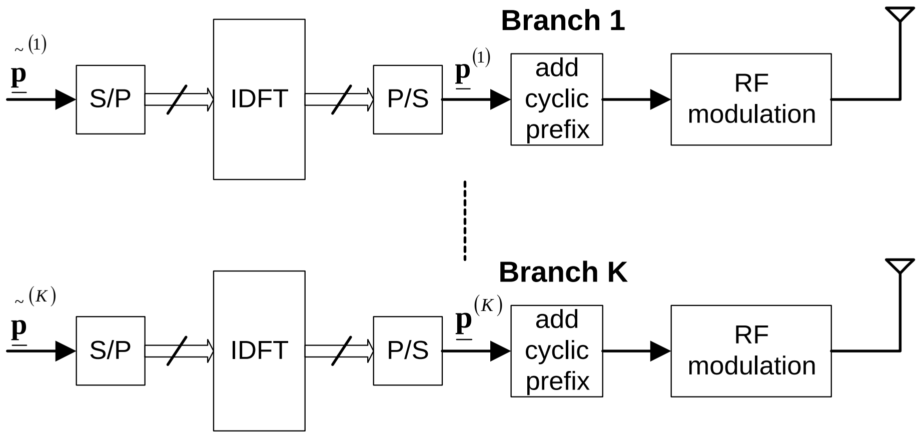

Fig. 2. Multi-branch transmit structure corresponding to frequency domain channel estimation

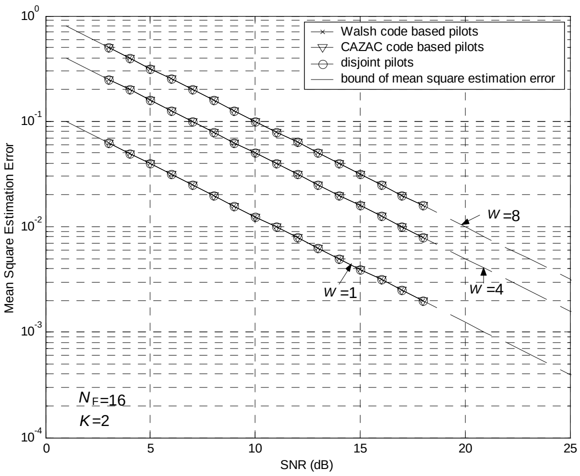

Fig. 3. Performance of frequency domain optimum pilots applying to time domain JCE

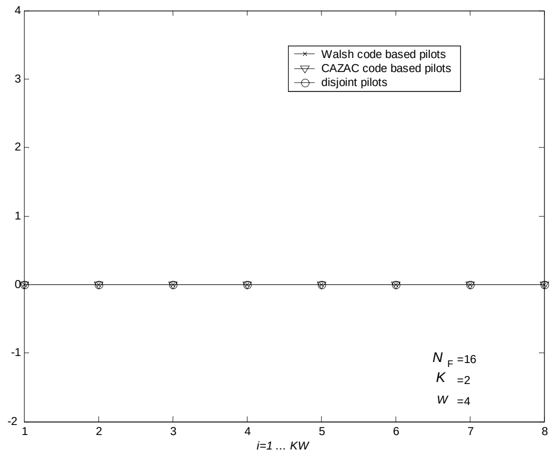

Fig. 4. Time domain SNR degradation of pilots, which are constructed from frequency domain optimum JCE design criteria.