

Channel Sounding for Multi-Sector Cooperation in OFDM-based Wireless Cellular Systems

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Abstract—In this paper, we consider channel sounding for multi-sector cooperative beamforming in orthogonal frequency division multiplexing-based wireless cellular systems. The use of conventional sounding schemes may suffer from interference from other sectors and also require large signaling overhead. To reduce the sounding interference near the sector boundary as well as the signaling overhead, we allocate the sounding physical resource unit (PRU) by exploiting the channel correlation in the frequency domain. The proposed scheme transmits the sounding signal through the PRUs which are less correlated to each other, significantly reducing the signaling overhead. The whole channel information can be extracted from the sounding PRUs by means of minimum-mean-square-error estimation. Finally, the performance of the proposed sounding scheme is verified by computer simulation, showing remarkable performance improvement over conventional schemes in the presence of channel correlation, while significantly reducing the signaling overhead.

Index Terms—cooperative beamforming; multi-user diversity; sounding overhead; frequency correlation; minimum-mean square-error estimation.

I. INTRODUCTION

The capacity of a multi-sector cellular system near the sector boundary is mainly limited by signal transmitted from other sectors, so-called other-sector interference (OSI). It is desirable to minimize the OSI effect for the enhancement of transmission performance near the sector boundary. Recent results have shown that the use of multi-sector cooperative beamforming can significantly improve the performance near the sector boundary when multi-sector channel information is known to the transmitter [1].

In time-division duplex (TDD) orthogonal frequency division multiplexing (OFDM)-based wireless systems such as IEEE 802.16m, the base station (BS) can estimate the downlink channel condition using sounding signal transmitted from each user [2], [3]. However, the performance of multi-sector cooperative beamforming may significantly be affected by the sounding signal transmitted from other sectors, so-called other sector sounding interference (OSSSI). The OSSSI problem can be alleviated by allocating different sounding resources to each sector (i.e., by means of sounding resource reuse (SRR)) [4]. However, it may not be possible to obtain a sufficient multi-user diversity (MUD) gain since the number of sounding users decreases by a factor of the SRR. To achieve the same MUD gain as the full reuse scheme, the SRR needs more sounding

symbols at an expense of uplink resource. In particular, IEEE 802.16m considers the use of three sounding symbols, which may severely degrade the uplink spectral efficiency due to a large sounding resource overhead (e.g., 15.8% of the uplink resource) [5]. It also requires a large number of signaling overhead for the transmission of sounding signal since the BS contiguously allocates the physical resource units (PRUs) for the sounding without consideration of channel characteristics [5].

In this paper, we propose an efficient channel sounding scheme for multi-sector cooperation in TDD-OFDM wireless cellular systems. The proposed scheme transmits the sounding signal only through the PRUs which are little correlated to each other, reducing the signaling overhead as well as the sounding interference. Then, the whole channel information can be estimated from the partial one by means of minimum-mean-square-error (MMSE) estimation fully exploiting the correlation in the frequency domain. It is shown that as the correlation in the frequency domain increases, the proposed scheme can provide significant performance improvement over conventional schemes.

The rest of this paper is organized as follows. Section II describes the system model and Section III describes the proposed sounding scheme. Section IV verifies the performance of the proposed scheme by computer simulation. Finally, conclusions are given in Section V.

II. SYSTEM MODEL

Consider the uplink of a single-input multiple-output (SIMO) TDD-OFDM cellular system where the whole bandwidth is divided into M PRUs each of which comprises F subcarriers, a total of MF subcarriers, and each cell comprises S sectors equipping with N receive antennas. Assuming that K users are uniformly distributed near the sector boundary, the $(N \times 1)$ sounding signal vector received by sector s through subcarrier f can be represented as

$$\mathbf{Y}_s(f) = \sum_{k=1}^K \mathbf{H}_{s,k}(f) P_k(f) + \mathbf{N}(f) \quad (1)$$

where $P_k(f)$ is the sounding signal transmitted from user k through subcarrier f , $\mathbf{N}(f)$ is the $(N \times 1)$ additive Gaussian

noise vector and $\mathbf{H}_{s,k}(f)$ is the $(N \times 1)$ channel vector from user k to sector s represented as

$$\mathbf{H}_{s,k}(f) = \begin{bmatrix} H_{s,k}(f, 1) \\ \vdots \\ H_{s,k}(f, N) \end{bmatrix}. \quad (2)$$

Here $H_{s,k}(f, n)$ denotes the channel from user k to sector s at subcarrier f through the n -th receive antenna, represented as

$$H_{s,k}(f, n) = \alpha_{s,k} h_{s,k}(f, n) \quad (3)$$

where $\alpha_{s,k}$ ($0 \leq \alpha_{s,k} \leq 1$) is the propagation fading factor of the channel from user k to sector s and $h_{s,k}(f, n)$ is an independent and identically distributed (i.i.d) zero mean complex Gaussian random variable with unit variance. Assuming that the BS transmits signal to the target user using transmit antennas of neighboring sectors s and s' , the channel vector from user k to sectors s and s' at subcarrier f can be represented as

$$\mathbf{H}_k(f) = \begin{bmatrix} \mathbf{H}_{s,k}(f) \\ \mathbf{H}_{s',k}(f) \end{bmatrix}. \quad (4)$$

The channel vector $\mathbf{H}_k(f)$ can be estimated from $\mathbf{Y}_s(f)$ and $\mathbf{Y}_{s'}(f)$, but it may inaccurately be estimated in the presence of other sector/user interference or frequency selectivity [6]. Let σ_k^2 be the normalized mean-squared-error (MSE) of the channel estimation of user k . Assuming that $\alpha_{s,k} \simeq \alpha_{s',k} \simeq \alpha_k$ near the sector boundary since the distance between user k and adjacent two sectors is similar to each other, the estimated channel vector from user k to sectors s and s' at subcarrier f can be represented as [7]

$$\tilde{\mathbf{H}}_k(f) = \mathbf{H}_k(f) + \alpha_k \sigma_k \mathbf{Z}_k(f) \quad (5)$$

where $\mathbf{Z}_k(f)$ is a $(2N \times 1)$ i.i.d zero mean complex Gaussian random vector with unit variance. Then, $\mathbf{H}_k(f)$ can be represented as

$$\mathbf{H}_k(f) = \frac{1}{1 + \sigma_k^2} \tilde{\mathbf{H}}_k(f) + \frac{\alpha_k \sigma_k}{\sqrt{1 + \sigma_k^2}} \mathbf{Z}_k(f). \quad (6)$$

Let $R_{s,k}(\Delta f, n)$ be the frequency correlation of the channel between subcarrier $f - \Delta f$ and f through the n -th receive antenna, defined by

$$R_{s,k}(\Delta f, n) = E [h_{s,k}^*(f - \Delta f, n) h_{s,k}(f, n)] \quad (7)$$

where the superscript $*$ denotes complex conjugate. We assume that $R_{s,k}(\Delta f, n) \simeq R_{s,k}(\Delta f)$ unless explicitly stated otherwise.

III. PROPOSED SOUNDING SCHEME

In this section, we first analyze the effect of sounding MSE on multi-sector cooperative beamforming and the characteristics of the MSE with the MMSE estimation. Then, we propose a new sounding scheme by exploiting the channel correlation in the frequency domain.

A. Effect of Sounding MSE on Cooperative Beamforming

It can be shown that the signal-to-interference plus noise power ratio (SINR) of user k at subcarrier f can be estimated as

$$\tilde{\gamma}_k(f) = \gamma_0 \|\tilde{\mathbf{H}}_k(f)\|^2 \quad (8)$$

where γ_0 is the average SINR and $\|\cdot\|$ denotes the matrix norm. Then, the BS selects a user with the highest SINR for each subcarrier as [8]

$$\pi_f = \arg \max_{k=\{1, \dots, K\}} \{\tilde{\gamma}_k(f)\} \quad (9)$$

and generates a beam weight for the selected user π_f as [1]

$$\mathbf{w}_{\pi_f}(f) = \frac{\tilde{\mathbf{H}}_{\pi_f}^*(f)}{\|\tilde{\mathbf{H}}_{\pi_f}(f)\|}. \quad (10)$$

The received signal $r_{\pi_f}(f)$ and the effective SINR $\gamma_{\pi_f}(f)$ of user π_f at subcarrier f can be represented as, respectively,

$$r_{\pi_f}(f) = \mathbf{H}_{\pi_f}^T(f) \mathbf{w}_{\pi_f}(f) X_{\pi_f}(f) + N(f), \quad (11)$$

$$\begin{aligned} \gamma_{\pi_f}(f) &= 2\gamma_0 \left| \mathbf{H}_{\pi_f}^T(f) \mathbf{w}_{\pi_f}(f) \right|^2 \\ &= 2\gamma_0 \left| \frac{\frac{1}{1 + \sigma_{\pi_f}^2} \|\tilde{\mathbf{H}}_{\pi_f}(f)\|^2 + \frac{\alpha_{\pi_f} \sigma_{\pi_f}}{\sqrt{1 + \sigma_{\pi_f}^2}} \mathbf{Z}_{\pi_f}^T(f) \tilde{\mathbf{H}}_{\pi_f}^*(f)}{\|\tilde{\mathbf{H}}_{\pi_f}(f)\|^2} \right|^2 \end{aligned} \quad (12)$$

where the superscript T denotes transpose, $X_{\pi_f}(f)$ denotes the desired signal of user π_f at subcarrier f and $N(f)$ is the additive Gaussian noise term.

When $\sigma_{\pi_f}^2 \simeq \sigma^2$ and $\alpha_{\pi_f} \simeq \alpha$, it can be shown that the average effective SINR is bounded as

$$\begin{aligned} \bar{\gamma} &= E [\gamma_{\pi_f}(f)] \\ &= \frac{2\gamma_0}{1 + \sigma^2} \left(\frac{1}{1 + \sigma^2} E \left[\|\tilde{\mathbf{H}}_{\pi_f}(f)\|^2 \right] + \alpha^2 \sigma^2 \right) \\ &\leq \frac{2\alpha^2 \gamma_0}{1 + \sigma^2} \left(2N \sum_{k=1}^K \frac{1}{k} + \sigma^2 \right). \end{aligned} \quad (13)$$

It can be seen that $\bar{\gamma}$ increases as K increases and/or σ^2 decreases. It may be desirable to use a sounding scheme that can support a large number of users with low sounding MSE.

B. The MSE of the MMSE Estimation

Consider the estimation of $\mathbf{H}_{s,k}(f)$ with the use of a T_k -tap MMSE filter. Letting $\Phi_{k,f}$ be the filter tap sequence comprising T_k subcarriers defined by

$$\Phi_{k,f} = [\Phi_{k,f}(1) \Phi_{k,f}(2) \dots \Phi_{k,f}(T_k)] \quad (14)$$

where $\Phi_{k,f}(i)$ is the i -th element of $\Phi_{k,f}$, then $\tilde{\mathbf{H}}_{s,k}(f)$ can be represented as

$$\tilde{\mathbf{H}}_{s,k}(f) = \left(\mathbf{C}_{s,k}(f, \Phi_{k,f}) \mathbf{R}_{s,k}^{-1}(\Phi_{k,f}) \tilde{\mathbf{H}}_{s,k}^T(\Phi_{k,f}) \right)^T. \quad (15)$$

Here $\mathbf{C}_{s,k}(f, \Phi_{k,f})$ is the $(1 \times T_k)$ cross covariance vector defined by

$$\mathbf{C}_{s,k}(f, \Phi_{k,f}) = \begin{bmatrix} R_{s,k}(f - \Phi_{k,f}(1)) \\ R_{s,k}(f - \Phi_{k,f}(2)) \\ \vdots \\ R_{s,k}(f - \Phi_{k,f}(T_k)) \end{bmatrix}^T, \quad (16)$$

$\mathbf{R}_{s,k}(\Phi_{k,f})$ is the $(T_k \times T_k)$ auto correlation matrix given as

$$\mathbf{R}_{s,k}(\Phi_{k,f}) = \begin{bmatrix} R_{s,k}\left(\begin{smallmatrix} \Phi_{k,f}(1) \\ -\Phi_{k,f}(1) \end{smallmatrix}\right) \dots R_{s,k}\left(\begin{smallmatrix} \Phi_{k,f}(1) \\ -\Phi_{k,f}(T_k) \end{smallmatrix}\right) \\ \vdots \quad \ddots \quad \vdots \\ R_{s,k}\left(\begin{smallmatrix} \Phi_{k,f}(T_k) \\ -\Phi_{k,f}(1) \end{smallmatrix}\right) \dots R_{s,k}\left(\begin{smallmatrix} \Phi_{k,f}(T_k) \\ -\Phi_{k,f}(T_k) \end{smallmatrix}\right) \end{bmatrix}, \quad (17)$$

and $\tilde{\mathbf{H}}_{s,k}(\Phi_{k,f})$ is the $(N \times T_k)$ estimated channel matrix represented as

$$\tilde{\mathbf{H}}_{s,k}(\Phi_{k,f}) = \begin{bmatrix} \tilde{\mathbf{H}}_{s,k}(\Phi_{k,f}(1))^T \\ \tilde{\mathbf{H}}_{s,k}(\Phi_{k,f}(2))^T \\ \vdots \\ \tilde{\mathbf{H}}_{s,k}(\Phi_{k,f}(T_k))^T \end{bmatrix}^T. \quad (18)$$

Then, the MSE σ^2 of the MMSE estimation is given by

$$\sigma^2 = 1 - E \left[\mathbf{C}_{s,k}(f, \Phi_{k,f}) \mathbf{R}_{s,k}^{-1}(\Phi_{k,f}) \mathbf{C}_{s,k}^H(f, \Phi_{k,f}) \right] \quad (19)$$

where the superscript H denotes matrix Hermitian. It can be seen from (19) that σ^2 decreases as the magnitude of $\mathbf{C}_{s,k}(f, \Phi_{k,f})$ increases, while that of $\mathbf{R}_{s,k}(\Phi_{k,f})$ decreases. Note that the magnitude of a vector or matrix is defined as the sum of absolute value of elements.

C. The Proposed Sounding Scheme

To minimize the estimation error as well as the sounding overhead, we consider the allocation of sounding PRUs to minimize $\mathbf{R}_{s,k}(\Phi_{k,f})$ and the selection of MMSE filter taps to maximize $\mathbf{C}_{s,k}(f, \Phi_{k,f})$ in the presence of channel correlation in the frequency domain.

We first consider the transmission of sounding signal only through PRUs which are little correlated to each other (i.e., low magnitude of $\mathbf{R}_{s,k}(\Phi_{k,f})$). We also consider the reduction of signaling overhead for the sounding indication. The BS determines a set of PRUs of user k for the sounding, Ω_k , and then informs the user the index of all the selected PRUs, which may require a large indication signaling overhead (e.g., M bits).

This signaling overhead can be reduced by generating an initial index g_k of user k as

$$g_k = (4k^2 + k + 1) \bmod M \quad (20)$$

where "mod" denotes the modulo operation. The set Ω_k of user k can be determined from g_k as follows:

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Number of PRU (M)	48
Number of subcarriers per PRU (F)	18
Number of BS antennas (N)	2
Multiplexing type	Frequency division multiplexing
Decimation index (D)	6
Average SINR (γ_0)	0 dB

Step 1: Initialize the index and the sounding PRU set as

$$g_k = (4k^2 + k + 1) \bmod M, \Omega_k = \{g_k\}, \text{ and go to step 3.}$$

Step 2: Update the set of PRUs for the sounding as

$$\text{for } \hat{m} = \arg \min_{m'_k \notin \Omega_k} \left(\max_{\hat{m}_k \in \Omega_k} |R_{s,k}((m'_k - \hat{m}_k)F)| \right), \\ \Omega_k \leftarrow \Omega_k \cup \{\hat{m}\}.$$

Step 3: If $|\Omega_k| < O_k$, go to step 2. Else stop.

Here $|\Omega_k|$ is the cardinality of Ω_k and O_k is the number of sounding PRUs for user k to be determined by the BS. For a given O_k , user k can generate the same Ω_k as the BS. Once Ω_k is determined, user k in sector s transmits the sounding signal through subcarrier set Θ_k determined as

$$\Theta_k = \left\{ \hat{f}_k \left| \hat{f}_k = \hat{m}_k F + \frac{sF}{S} + (dD + k) \bmod \frac{F}{S} \right. \right\}, \quad (21) \\ \text{for } \hat{m}_k \in \Omega_k \text{ and } 0 \leq d \leq \frac{F}{DS} - 1$$

where D is the decimation index.

The channel information at subcarrier $\hat{f}_k$ in Θ_k can first be estimated by the least square (LS) method. To estimate the whole channel information based on $\tilde{\mathbf{H}}_{s,k}(\hat{f}_k)$, we apply MMSE filtering to sounding subcarriers highly correlated with subcarrier f (i.e., high magnitude of $\mathbf{C}_{s,k}(f, \Phi_{k,f})$). The tap sequence $\Phi_{k,f}$ can be determined as follows:

Step 1: Initialize

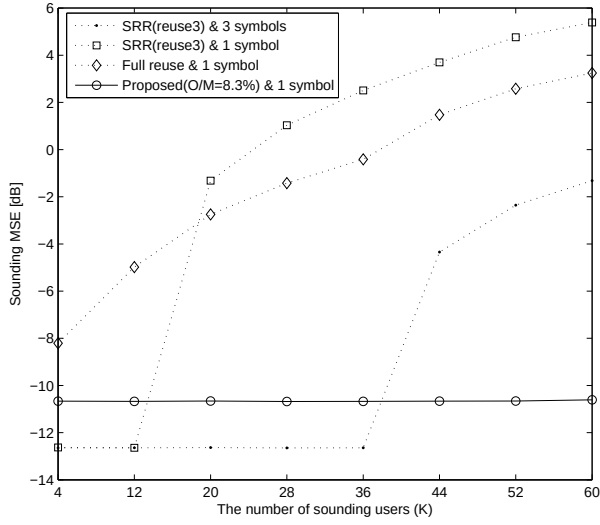
$$i = 1 \text{ and } \Phi_{k,f} = \emptyset.$$

Step 2: Update the tap sequence as

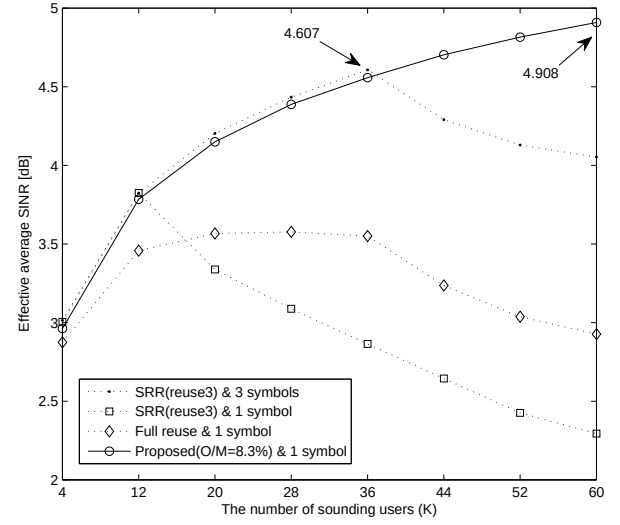
$$\Phi_{k,f}(i) = \arg \max_{\hat{f}_k \in \Theta_k - \Phi_{k,f}} |R_{s,k}(f - \hat{f}_k)|.$$

Step 3: If $|\Phi_{k,f}| < T_k$, $i \leftarrow i + 1$ and go to step 2. Else stop.

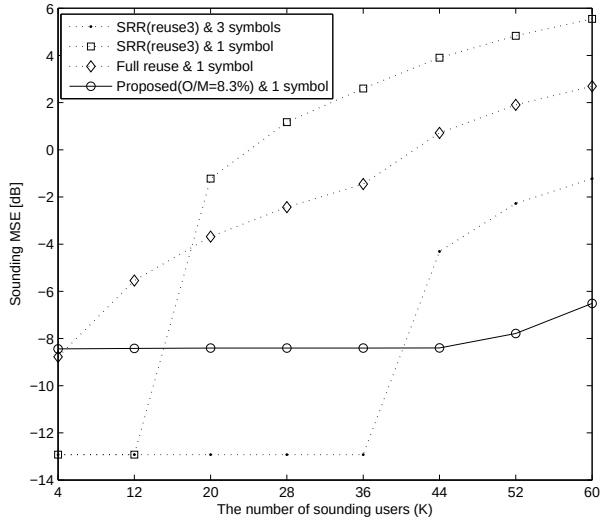
Then, $\mathbf{H}_{s,k}(f)$ can be estimated by means of the MMSE filtering (15). Thus, the proposed scheme can estimate the channel information of all subcarriers without the use of sounding signal transmitted through the whole subcarriers.



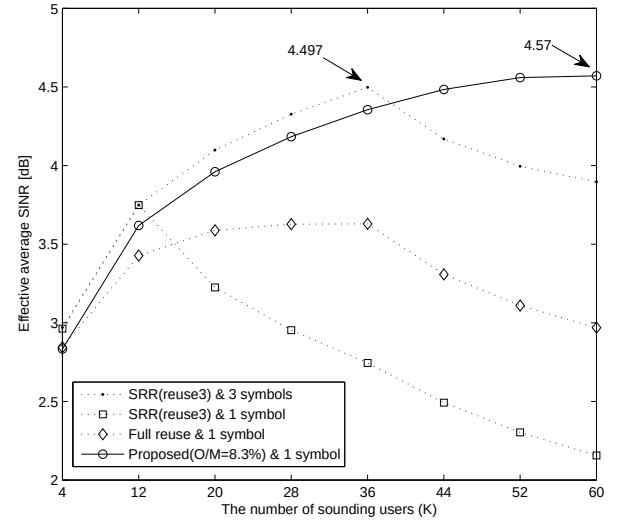
(a) When $\tau = 45$ ns (Pedestrian A) and $T_k \simeq T = 1$.



(a) When $\tau = 45$ ns and $T_k \simeq T = 1$.



(b) When $\tau = 750$ ns (Pedestrian B) and $T_k \simeq T = 4$.



(b) When $\tau = 45$ ns and $T_k \simeq T = 4$.

Fig. 1. Sounding MSE according to K .

Fig. 2. Average effective SINR according to K .

IV. PERFORMANCE EVALUATION

The performance of the proposed scheme is compared to that of conventional sounding schemes (i.e., $O_k \simeq O = M$) by computer simulation. The simulation environment is almost identical to that of IEEE 802.16m system [9] as summarized in Table I, where the whole 864 subcarriers are divided into 48 PRUs. We assume that users transmit sounding signal by means of frequency division multiplexing where the decimation index is 18 and the channel has an average SINR of 0

dB.

Fig 1 depicts the sounding MSE of the proposed scheme according to K when the root mean square delay of the channel τ is 45 ns or 750 ns (i.e., corresponding to the Pedestrian A or Pedestrian B channel model, respectively). We assume that the conventional schemes estimate the whole channel using an MMSE filter whose taps are randomly selected in the same subband (i.e., 4 contiguous PRUs) of the estimation target subcarriers. It can be seen that the MSE of the full reuse

scheme linearly increases as K increases due to the OSS. This is mainly because each sector independently allocates the sounding signal in the full reuse scheme. It can also be seen that the MSE of the single symbol SRR scheme of IEEE 802.16m sharply increases when $K > 12$. This is mainly due to the fact that the maximum number of orthogonal sounding users in the single symbol SRR is 12 since each sector has 6 subcarriers per PRU for the sounding. It can also be seen that when $K > 36$, the MSE of the multi-symbol SRR scheme of IEEE 802.16m rapidly increases because the maximum number of orthogonal users is 36 [5]. On the other hand, the proposed scheme provides almost the same MSE indifferently from the number of sounding users because it can estimate the whole channel with sounding signal transmitted through a small number of subcarriers by exploiting the channel correlation in the frequency domain, making it possible to increase the number of orthogonal sounding users.

Fig. 2 depicts the average effective SINR of the multi-sector cooperative beamforming according to K . It can be seen that the beamforming performance of the conventional schemes is degraded for a large number of users due to the sounding interference. On the other hand, the proposed scheme allows the multi-sector beamforming to provide performance similar to the three-symbol SRR scheme, while significantly reducing the resource for the sounding (e.g., the use of single symbol requires 5.3% of the uplink resource compared to 15.8% of the uplink resource in the three-symbol SRR) and the signaling overhead (e.g., $O=4$, $O/M=8.3\%$).

V. CONCLUSION

We have proposed a channel sounding scheme for multi-sector cooperation in TDD-OFDM wireless cellular systems. By exploiting the channel correlation in the frequency domain, the proposed sounding scheme can improve multi-sector cooperative beamforming performance, while significantly reducing the signaling overhead for the sounding. The proposed scheme sequentially determines PRUs for the sounding and the filter taps for the channel estimation according to the channel correlation, making the implementation quite feasible. The simulation results show that the proposed scheme is quite effective in the presence of channel correlation in the frequency domain.

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