A Frequency-domain Sounding Scheme for LTE TDD Beamforming Systems

Baolong Zhou[1,2], Lingge Jiang[1], Shengjie Zhao[2], Lu Zhang[2], Chen He[1], Zhining Jiang[2], and Kun Zhao[2]
Department of Electronic Engineering, Shanghai Jiao Tong University[1], Shanghai, P. R. China
China Product R&D, Alcatel-Lucent Shanghai Bell[2], Shanghai, P.R.China
Email: baolong.zhou@alcatel-sbell.com.cn

***Abstract*—In the 3rd generation partnership project (3GPP) long term evolution (LTE) time division duplex (TDD) systems, base stations use uplink sounding reference signals (SRSs) to estimate downlink channel state information (CSI) for downlink beamforming transmissions. Because SRSs sent by up to 8 users are multiplexed on the same time-frequency resources, there exist mutual interferences among these SRSs over fading channels. Thus the current scheme inevitably impacts the estimation accuracy of CSI and thereby degrades the beamforming performance. Based on the characteristics of TDD systems, we propose a novel sounding scheme to improve the quality of CSI, in which according to the CQIs (channel quality indications) periodically reported by each user and the bandwidth requirement of each user, BS schedules each user to send SRSs only on the requisite bandwidth with best CQIs instead of on full bandwidth or specified sub-bandwidth as in the current LTE TDD systems. Simulations show that the proposed scheme outperforms the current scheme in estimation accuracy for various frequency-selective and/or time-selective fading channels, and is especially robust to frequency selective channels. The proposed scheme has been adopted as a candidate scheme for 3GPP LTE-Advanced.**

***Index Terms*—channel estimation error, Long Term Evolution (LTE), sounding, time division duplex (TDD)**

I. INTRODUCTION

The commercial deployment of cellular infrastructure based on the 3rd generation partnership project (3GPP) long term evolution (LTE) is becoming more and more widespread due to the continuous and strong demand of broadband mobile services, especially the appearance of smart handsets in recent years. LTE can work in FDD (frequency division duplex) mode or TDD (time division duplex) mode. In this paper we focus on LTE TDD systems. According to 3GPP specification [1], there are seven kinds of transmission modes (TMs) in LTE TDD systems. For the TMs 4, 5 and 6, the base station (BS) should know the downlink channel state information (CSI) for beamforming transmission.

As well known, accurate CSI is very important for multiple-input single-output (MISO) and multiple-input multiple-output (MIMO) beamforming systems. However, in practice CSI is always imperfect due to the existence of CSI delay, channel estimation error and quantization error, which would degrade the system performance. Hence, it is significant to optimize the performance of MISO/MIMO beamforming systems in the case of imperfect CSI.

Recently there are a lot of papers which optimized the performance of beamforming systems with imperfect CSI from the different perspectives. In [2], authors proposed to weight sounding pilots (used to measure CSI) using the level of interferences at each user to increase beamforming system throughput. A Kalman-filter-based prediction method was proposed to overcome the feedback delay effect in [3]. In [4], ergodic capacity bounds were investigated with channel estimation error and quantization error, and then were optimized over the number of both finite training symbols and limited feedback bits. The optimal bandwidth allocation between data channel and feedback channel was studied in [5] to maximize the average throughput in the data channel using MISO beamforming scheme. In [6], the authors investigated the optimal precoding algorithm and corresponding power allocation in the presence of imperfect CSI feedback, such as an imperfect channel coefficient feedback, channel mean feedback and channel covariance feedback. The optimal spatial and temporal power allocation was studied in [7] to minimize outage probability for a MISO system with delayed feedback. In [8], we optimized time-domain period of sounding to minimize the impact of CSI delay on TDD MISO beamforming systems.

In LTE TDD beamforming systems, a BS estimates downlink CSI via channel reciprocity based on uplink sounding reference signal (SRS) [9] [10] sent by users, and then uses it to generate beamforming vectors / matrices for downlink transmission. There are two kinds of sounding schemes as described in LTE Release 8 [9] and 9 [10]: one is full bandwidth scheme that each user sends SRSs on all physical resource blocks (PRBs, PRB is minimum resource allocation unit and one PRB is equivalent to one subband); the other is sub-bandwidth scheme that each user sends SRSs on the specified partial continuous PRBs. In each scheme SRSs of up to 8 users are multiplexed on the same time-frequency resource. Each user applies a unique time-domain cyclic shift, which allows the signals to be separated at the receiver, to own SRS sequence. However, the cyclic shifts do not perfectly orthogonalize these SRSs over fading channel at the BS. Thus the residual interferences would cause serious channel estimation errors, especially where most of the available cyclic shift values are utilized and/or the multi-path delay is large. So the current sounding schemes impact the accuracy of CSI as well as degrade the performance of beamforming systems.

Based on the characteristics of TDD systems, we propose a frequency-domain sounding scheme to improve the quality of CSI, in which according to the CQIs (channel quality indications) periodically reported by each user and the bandwidth requirement of each user, BS dynamically schedules each user to send SRSs only on the requisite bandwidth with best CQIs instead of on full bandwidth or specified sub-bandwidth as in the current LTE TDD systems. In our proposed scheme, the characteristic of "distribution according to need" leads that the interferences among SRSs of different users are eliminated completely and the characteristic of "scheduling based on CQI" leads that SRSs are sent always on the best channel. Simulation results verify that the proposed

978-1-4673-0990-5/12/$31.00 ©2012 IEEE

scheme can obtain higher channel estimation accuracy than the current scheme for various frequency-selective and/or time-selective fading channels, and especially is robust to frequency selective channels. The proposed scheme has been adopted as a candidate scheme in LTE-Advanced system.

Notations: Upper and lower boldface letters denote matrices and (column) vectors, respectively. $(\cdot)^*$ and $\|\cdot\|$ denote complex conjugation and Frobenius norm, respectively. $\mathbf{I}$ denotes the identity matrix. $\varnothing$ denotes empty set. $\mathcal{CN}(\boldsymbol{\mu},\boldsymbol{\Sigma})$ denotes the complex Gaussian distribution with mean vector $\boldsymbol{\mu}$ and variance matrix $\boldsymbol{\Sigma}$. $\operatorname{diag}\{\mathbf{x}\}$ denotes a diagonal matrix with elements of vector $\mathbf{x}$ on its main diagonal, $\mathcal{F}$ and $\mathcal{F}^{-1}$ denote FFT (fast Fourier transform) and IFFT (inverse fast Fourier transform), respectively.

II. SYSTEM MODEL

Consider an LTE TDD system, where a BS with M receive antennas communicates with K single-antenna users. These users send SRSs on the same set of N_{sc} subcarriers at the same time. The channels between all users and BS are modeled as time-varying, spatially uncorrelated, frequency selective, and independently and identically distributed (i.i.d.) Rayleigh fading channel. The channel from user k to BS on the i-th subcarrier is denoted by an $M\times 1$ vector $\mathbf{h}_k(i)$, where $\mathbf{h}_k(i)\sim\mathcal{CN}(\mathbf{0},\mathbf{I})$.

In LTE TDD systems, SRSs are located in alternate subcarriers (referred as *comb* in terms of LTE terminology [9]) in frequency domain and are transmitted in the last two OFDM (orthogonal frequency division multiplexing) symbols of the special subframe (and/or the last OFDM symbol of uplink subframe) in time domain. It is used to estimate downlink CSI at BS for beamforming transmission besides measuring CQIs of uplink PRBs for uplink PRB scheduling. In order to let more users be accessed in one transmission time interval (TTI, one TTI equals one subframe duration), the SRSs of up to K users, as a set, are multiplexed on the same comb. The transmitted SRSs for each user are derived from a constant amplitude zero auto correlation (CAZAC) base sequence, which may be cyclically shifted in time domain by a unique number of samples, causing a time-domain circular shift of $\tau=(\alpha/K)T$, where α is a cyclic shift value uniquely assigned to each user in the set, T is the duration of one OFDM symbol.

Let $\mathbf{s}_k=\left[s_k(1),s_k(2),...,s_k(N_{sc})\right]$ denote the SRS sequence transmitted by user k, the element $s_k(i)$ of which is the SRS symbol on the i-th subcarrier. At the user side, $\mathbf{s}_k$ is mapped onto corresponding time-frequency resources located in the special subframe and/or uplink subframe, and transformed via IFFT into time-domain signals. Finally the time-domain signals with added cyclic prefix (CP) are sent out.

At the BS side, after removing CP, implementing FFT and de-mapping subcarrier, the received signal on the i-th subcarrier (summing over all SRSs from all users in the set), denoted by $\mathbf{y}(i)$ of size $M\times 1$, is given by

$$\mathbf{y}(i)=\sum_{k=1}^{K}\mathbf{h}_k(i)s_k(i)+\mathbf{n}(i),\quad 0<i\le N_{sc},\tag{1}$$

where $\mathbf{n}(i)\sim\mathcal{CN}(\mathbf{0},\sigma_n^2\mathbf{I})$ is an additive white Gaussian noise (AWGN) vector on the i-th subcarrier at the BS. We rewrite (1) in a full-band form as

$$\mathbf{Y}=\sum_{k=1}^{K}\mathbf{H}_k\operatorname{diag}\{\mathbf{s}_k\}+\mathbf{N},\tag{2}$$

where $\mathbf{Y}=\left[\mathbf{y}(1),\mathbf{y}(2),...,\mathbf{y}(N_{sc})\right]$, $\mathbf{H}_k=\left[\mathbf{h}_k(1),\mathbf{h}_k(2),...,\mathbf{h}_k(N_{sc})\right]$, $\mathbf{N}=\left[\mathbf{n}(1),\mathbf{n}(2),...,\mathbf{n}(N_{sc})\right]$.

In the current sounding schemes, K equals to 8. Let $\alpha_k\in\{0,1,2,...,K-1\}$ denote the cyclic shift value assigned to user k. The SRS symbol $s_k(i)$ on the i-th subcarrier of user k can be generated in the frequency domain as [9] [10]

$$\begin{aligned}&s_k(i)=r_{\mathrm{bs}}(i)\exp(-j2\pi\alpha_k i/K),\\&0<i\le N_{sc},\ 0<k\le K,\end{aligned}\tag{3}$$

where i is the subcarrier index in the natural frequency order, and r_{bs} is the frequency-domain CAZAC base sequence with $\left|r_{\mathrm{bs}}(i)\right|^2=1$ for all i. The cyclic shift (in time-domain samples at baseband) resulting from the phase term is given by $(\alpha_k/K)N_{sc}$.

Substituting (3) into (1), the received signal at the BS is as follows:

$$\begin{aligned}&\mathbf{y}(i)=\sum_{k=1}^{K}\mathbf{h}_k(i)r_{\mathrm{bs}}(i)\exp(-j2\pi\alpha_k i/K)+\mathbf{n}(i),\\&0<i\le N_{sc}.\end{aligned}\tag{4}$$

Prior to channel estimation, the received signal is circularly cross-correlated with the CAZAC base sequence, which can be implemented in the frequency domain as a conjugate multiplication

$$\begin{aligned}\mathbf{z}(i)&=\mathbf{y}(i)r_{\mathrm{bs}}^*(i)\\&=\sum_{k=1}^{K}\mathbf{h}_k(i)\exp(-j2\pi\alpha_k i/K)+\mathbf{n}(i)r_{\mathrm{bs}}^*(i),\\&\quad 0<i\le N_{sc}.\end{aligned}\tag{5}$$

The (5) can be rewritten in full-band form as

$$\mathbf{Z}=\sum_{k=1}^{K}\mathbf{H}_k\boldsymbol{\theta}_k+\mathbf{N}_{\mathrm{eq}},\tag{6}$$

where $\mathbf{Z}\triangleq\left[\mathbf{z}(1),\mathbf{z}(2),...,\mathbf{z}(N_{sc})\right]$, $\boldsymbol{\theta}_k$ is an N_{sc}-dim phase shift diagonal matrix with elements $\exp(-j2\pi\alpha_k i/K)$ on its main diagonal, $\mathbf{N}_{\mathrm{eq}}\triangleq\left[\mathbf{n}_{\mathrm{eq}}(1),\mathbf{n}_{\mathrm{eq}}(2),...,\mathbf{n}_{\mathrm{eq}}(N_{sc})\right]$ with $\mathbf{n}_{\mathrm{eq}}(i)=\mathbf{n}(i)r_{\mathrm{bs}}^*(i),\ 0<i\le N_{sc}$.

In order to separate multiple multiplexed SRSs via cyclic shift in time domain, the frequency-domain signal in (6) need to be transformed into time-domain signal via IFFT

$$\mathcal{F}^{-1}(\mathbf{Z})=\sum_{k=1}^{K}\tilde{\mathbf{H}}_k(n-m_k)+\mathcal{F}^{-1}(\mathbf{N}_{\mathrm{eq}}),\quad 0<n\le N_{sc},\tag{7}$$

where $\tilde{\mathbf{H}}_k(n-m_k) \triangleq \left[\tilde{\mathbf{h}}_k(1-m_k), \tilde{\mathbf{h}}_k(2-m_k), \ldots, \tilde{\mathbf{h}}_k(N_{sc}-m_k)\right]$ is a discrete time-domain channel matrix, $\tilde{\mathbf{h}}_k(n-m_k)$ is a discrete time-domain channel vector, n is the discrete time index, $m_k = (\alpha_k/K)N_{sc}$ is cyclic shift in time-domain sample as described before.

Finally, by applying time-domain filter $\mathbf{w}_k$ with window length N_{sc}/K, inverse time-domain circular shift with m_k delay samples and FFT to (7), we can get the frequency -domain estimated channel $\hat{\mathbf{H}}_k$ for user k.

$$\hat{\mathbf{H}}_k = \mathbf{H}_k^{'} + \underbrace{\sum_{l=1, l\neq k}^{K} \mathbf{H}_l^{'}\boldsymbol{\theta}_k^{'}}_{\text{interference}} + \underbrace{\mathbf{N}_{\text{eq}}^{'}}_{\text{noise}}, \tag{8}$$

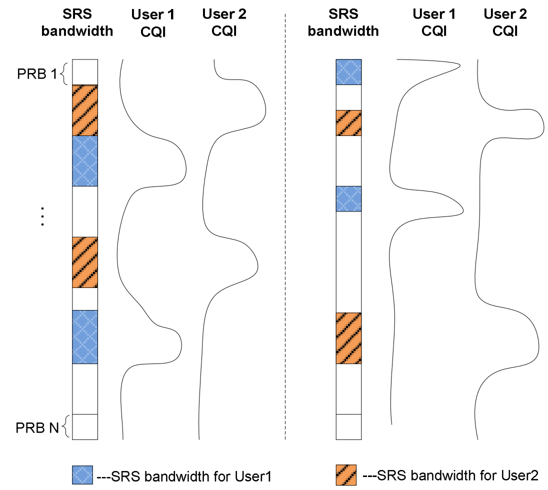
where $\mathbf{H}_k^{'}$ is the expected frequency-domain channel corresponding to the windowed time-domain signal $\tilde{\mathbf{H}}_k\mathbf{w}_k$, $\mathbf{H}_l^{'}$ is the frequency-domain interference channel corresponding to residual interference signal $\tilde{\mathbf{H}}_l\mathbf{w}_k$. $\boldsymbol{\theta}_k^{'}$ is a phase shift diagonal matrix with element $\exp\left(-j\Delta\theta_{(l,k)}\cdot i\right)$, $\Delta\theta_{(l,k)} = 2\pi(\alpha_l - \alpha_k)/K$, $\mathbf{N}_{\text{eq}}^{'}$ is caused by AWGN.

From (8), we can see the estimated channel $\hat{\mathbf{H}}_k$ is severely impacted by interferences from other users in current sounding scheme. Furthermore the interferences increase as the number of multiplexed users increases and the length of multi-path delay, which is reflected by $\tilde{\mathbf{H}}_l\mathbf{w}_k$, increases.

III. Proposed Sounding Scheme for LTE TDD System

The sounding schemes above are shared by LTE FDD and LTE TDD, however, the own characteristics of TDD systems can be used to improve the current sounding schemes. In this section, we introduce our proposed sounding scheme for LTE TDD systems: according to the CQIs periodically reported by each user and the bandwidth requirement of each user, BS dynamically schedules each user to send SRSs only on the allocated PRBs with best CQIs instead of on all PRBs or specified PRBs. Please see Fig.1, which indicates the states of SRS bandwidth allocation at two different times for two users, for well understanding our proposed design. In LTE TDD systems, BS can deduce out each user's number of allocated PRBs according to the CQIs and traffic type of each user, so in our proposed scheme we can use each user's number of allocated PRBs, denoted by N_k^{RB}, as the metric of deciding each user's SRS bandwidth size. The intuition behind this is that only CSIs corresponding to allocated PRBs are needed for the beamforming transmission, so it is reasonable that we let each user send SRS only on allocated PRBs rather than on all PRBs or specified PRBs as in the current schemes. Moreover, each user periodically reports the CQIs of all PRBs to BS, so BS can dynamically allocate the N_k^{RB} PRBs with best CQIs to each user and thus can schedule that each user sends SRSs on the allocated PRBs with best CQIs.

In single-user MIMO (SU-MIMO) systems, the allocated PRBs to each user don't overlap in frequency domain, so the SRSs sent by each user never overlap in frequency domain according to the characteristic of "distribution according to need" in our proposed sounding scheme, thus the interferences among these SRSs multiplexed on the same comb are completely eliminated in our proposed scheme by separating these SRSs in frequency domain.



(a) time n (b) time $n+\Delta$

Fig. 1, CQI-based SRS bandwidth allocation on one comb. According to the bandwidth requirement and the periodically reported CQIs, each user is allocated necessary SRS bandwidth with best CQIs.

As mentioned in Section Ⅱ, SRSs are also used to estimate CQIs of all uplink PRBs for the purpose of uplink PRB scheduling. Although the proposed scheme requests each user send uplink SRSs only on the subcarriers of N_k^{RB} allocated PRBs with the best CQIs, the proposed scheme has almost little impact on uplink PRB scheduling. In TDD systems, due to the channel reciprocity, the downlink/uplink PRBs with the same time-frequency indices have the same CQIs under the condition of no inter-cell interferences. Even though inter-cell interferences are considered for the users at the centre of cell, the inter-cell interferences can almost be ignored because the cell-centre users are closed to the desired BS. For the users at the edge of cell, the inter-cell interferences can also be ignored if ICIC (Inter-Cell Interference Coordination) technique is taken at the edge of cell. Therefore the proposed scheme can make sure that each user is allocated the best uplink PRBs and thus has almost little impact on uplink PRB scheduling.

Assume $\mathbb{A}_k$ denoting the set of alternate subcarriers of PRBs allocated to user k, $\mathbb{A}_1$, $\mathbb{A}_2$ …, and $\mathbb{A}_K$ belong to the same comb and meet the following constraints in the proposed scheme.

$$\begin{aligned} &\mathbb{A}_k \cap \mathbb{A}_l = \varnothing, \ \ 0 < k, l \le K, \ l \ne k, \\ &\sum_{k=1}^{K} |\mathbb{A}_k| = N_{sc}, \end{aligned} \tag{9}$$

where $|\mathbb{A}_k|$ denotes the cardinality of set $\mathbb{A}_k$. So the SRS symbol $s_k(i)$ on the i-th subcarrier of user k can be generated in the frequency domain as

$$s_k(i)=\begin{cases}\beta_k r_{\mathrm{bs}}(i)\exp(-j2\pi\alpha_k i/K) & i\in\mathbb{A}_k,\\ 0 & i\notin\mathbb{A}_k,\end{cases}\quad (10)$$
$$0<k\le K,$$

where β_k is the amplitude of the transmitted signal to meet the transmit power constraint. Thus the SRS sequence of user k can be expressed in full-band form as

$$\mathbf{s}_k=\{s_k(i)\},\ 0<i\le N_{sc}. \quad (11)$$

Substituting (10) into (1), the received signal on the i-th subcarrier at BS can be obtained as follows

$$\mathbf{y}(i)=\sum_{k=1}^{K}\mathbf{h}_k(i)\beta_k r_{\mathrm{bs}}(i)\exp(-j2\pi\alpha_k i/K)+\mathbf{n}(i),\ 0<i\le N_{sc}. \quad (12)$$

Especially a user set consisting of less than K users can be supported in this model simply by setting some β_k to zero. Similar to (2), the full-bandwidth received signal at BS is given by

$$\mathbf{Y}=\sum_{k=1}^{K}\mathbf{H}_k\mathrm{diag}\{\mathbf{s}_k\}+\mathbf{N}. \quad (13)$$

Define SRSs frequency-domain filter for user k as $\mathrm{diag}\{\mathbf{w}_k\}$ with $\mathbf{w}_k=\{w_k(i)\}$, $w_k(i)$ is defined as

$$w_k(i)=\begin{cases}1, & i\in\mathbb{A}_k,\\ 0, & i\notin\mathbb{A}_k.\end{cases} \quad (14)$$

Based on (9), (10) and (14), the following relationship can be deduced

$$\mathrm{diag}\{\mathbf{s}_k\}\mathrm{diag}\{\mathbf{w}_l\}=\begin{cases}\mathrm{diag}\{\mathbf{s}_k\} & k=l,\\ \mathbf{O} & k\ne l,\end{cases} \quad (15)$$

where $\mathbf{O}$ means the zero matrix of size $N_{sc}\times N_{sc}$. Now apply SRSs frequency-domain filter $\mathrm{diag}\{\mathbf{w}_k\}$ to (13), the received signal, denoted by $\mathbf{Y}_k$, of user k can be obtained

$$\begin{aligned}\mathbf{Y}_k&=\sum_{l=1}^{K}\mathbf{H}_l\mathrm{diag}\{\mathbf{s}_l\}\mathrm{diag}\{\mathbf{w}_k\}+\mathbf{N}\mathrm{diag}\{\mathbf{w}_k\}\\&=\mathbf{H}_k\mathrm{diag}\{\mathbf{s}_k\}\mathrm{diag}\{\mathbf{w}_k\}+\underbrace{\sum_{l=1,l\ne k}^{K}\mathbf{H}_l\mathrm{diag}\{\mathbf{s}_l\}\mathrm{diag}\{\mathbf{w}_k\}}_{\text{interferences}}+\mathbf{N}_{\mathrm{eq},k}\\&=\mathbf{H}_k\mathrm{diag}\{\mathbf{s}_k\}+\mathbf{N}_{\mathrm{eq},k},\end{aligned} \quad (16)$$

where $\mathbf{N}_{\mathrm{eq},k}\triangleq\mathbf{N}\mathrm{diag}\{\mathbf{w}_k\}$, $\mathbf{Y}_k\triangleq[\mathbf{y}_k(1),\mathbf{y}_k(2),...,\mathbf{y}_k(N_{sc})]$ with $\mathbf{y}_k(i)$ ($M\times 1$) which is the received signal vector of user k at the i-th subcarrier at BS. (16) indicates clearly that the interferences caused by other users multiplexed on the same comb, which always exist in fading channel in current scheme, are completely eliminated in the proposed scheme.

Then we can use the minimum mean square error (MMSE) estimator to estimate the channel of each user. The MMSE estimator at the i-th subcarrier of user k is as follows

$$\mathbf{G}_{\mathrm{mmse},k}(i)=\mathbf{R}_h s_k^*(i)\left[s_k(i)\mathbf{R}_h s_k^*(i)+\mathbf{R}_N\right]^{-1},\ i\in\mathbb{A}_k, \quad (17)$$

where $\mathbf{R}_h$ and $\mathbf{R}_N$ are the covariance matrices of channel and noise respectively, $s_k(i)$ is sounding symbol sent by user k. So the estimation channel on the i-th subcarrier of user k can be obtained as follows

$$\hat{\mathbf{h}}_k(i)=\mathbf{G}_{\mathrm{mmse},k}(i)\mathbf{y}_k(i),\ i\in\mathbb{A}_k,\ 0<k\le K. \quad (18)$$

Thus according to (18), we can get downlink CSIs for all users in set.

IV. SIMULATION RESULTS

Consider an LTE TDD system, where the BS with 4 antennas communicates with 8 users, each user is equipped with one antenna. The channels are assumed to be time-varying, spatially uncorrelated, frequency selective and Rayleigh fading. Jakes model [11] is used to simulate the time-varying channels. MMSE channel estimator in (17) is used by BS to estimate downlink CSI. Each user sends SRSs on the allocated subcarriers in the proposed scheme (equally subcarrier allocation for each user) while on the all subcarriers in the current LTE TDD scheme. We run 30 radio frames (10 subframes per radio frame) for each simulation case. Simulation parameters, most of which comes from [9] [12], are listed in Table 1 and Table 2.

Table 1 Simulation parameters

Parameter		value
Radio frame configuration		D S U U D D S U U D
Nbr of SRS subframes (N_{sf})		180
Bandwidth (MHz)		20
SNR(dB)		0---30
SRS bandwidth		96 PRBs
PRB size	Frequency domain	180 KHz
	Time domain	0.5 ms
Carrier frequency(GHz)		2.6
Doppler spread(Hz)		5(low), 70(Mid), 300(High)
Number of users (K)		8
Number of BS antenna(M)		4
Number of SRS subcarriers per user (N_k^{sc})		72 for the proposed scheme 576 for the current scheme

Table 2 Multi-path delay parameters

Delay type	Value (ns)
Small delay	[0 30 70 90 110 190 410]
Mid delay	[0 30 150 310 370 710 1090 1730 2510]
Large delay	[0 50 120 200 230 500 1600 2300 4600]

We use the average normalized mean square error (NMSE) of channel estimation to evaluate the estimation accuracy for the proposed scheme and the current scheme. It is defined as

$$NMSE=\frac{1}{N_{sf}KMN_k^{sc}}\sum_{n=1}^{N_{sf}}\sum_{k=1}^{K}\sum_{i=1}^{N_k^{sc}}\frac{\left\|\hat{\mathbf{h}}_k(i,n)-\mathbf{h}_k(i,n)\right\|^2}{\left\|\mathbf{h}_k(i,n)\right\|^2}. \quad (19)$$

Fig. 2 shows the NMSE in the cases with small, mid and large multi-path delay but with the same Doppler spread (5Hz) for the proposed scheme and the current scheme. It can be observed that the NMSE performance of the proposed scheme is better than that of the current scheme in the case of mid and large multi-path delay, and is almost the same as that of current scheme in the case small multi-path delay. The reason is that in the case of mid and large multi-path delay, the interferences from SRSs of all other users are strong and are the primary factors dominating estimation accuracy. In the proposed scheme the interferences among SRSs don't exist due to the frequency-domain orthogonalization and frequency -domain separation among SRSs of each user.

However, in the current scheme the interferences inevitably exist because the current scheme separates SRSs in time domain and the mid and large multi-path delay damages severely the time-domain orthogonalization of SRSs. In the case of small multi-path delay, the interferences among SRSs are small, which is a noise-limited system, the virtue (overcome interferences) of the proposed scheme is buried, so the performance of the proposed scheme is almost the same as that of the current scheme. Furthermore, by comparing NMSE curves of different multi-path delay, we find the proposed scheme is robust to the multi-path delay (or frequency selectivity) while the performance of the current scheme degrades as the multi-path delay increases. The reason is that multi-path delay doesn't damage on frequency-domain orthogonalization of SRSs but damages the time-domain orthogonalization of SRSs.

Fig. 3 shows the NMSE in the cases with low, mid and high Doppler spread but with the same Mid multi-path delay for the proposed scheme and the current scheme. It can be seen that the NMSE performance of the proposed scheme degrades as the Doppler spread increases while the performance of the current scheme doesn't change with the Doppler spread. The reason is that the Doppler spread damages the frequency-domain orthogonalization of SRSs in the proposed scheme but doesn't damage the time-domain orthogonalization of SRSs in the current scheme. So as the Doppler spread increases, the interferences among SRSs increase in the proposed scheme but remain unchanged in the current scheme. However, the NMSE performance of the proposed scheme is still better than that of the current scheme in the case of low, mid and high Doppler spread. The reason is that the interferences caused by Doppler spread are less than one caused by mid multi-path delay.

V. Conclusion

In this paper, we have proposed a frequency-domain sounding scheme for LTE TDD systems in order to improve the channel estimation accuracy. Simulation results indicate that the proposed scheme outperforms the current scheme in estimation accuracy for various frequency-selective and time-selective fading channels. Furthermore the proposed scheme is robust to the channel frequency selectivity. Especially our research is applicable to the uplink sounding reference signal design in LTE-Advanced systems and has been adopted as a candidate scheme for 3GPP LTE-Advanced. It should be pointed out that out proposed scheme can be extended to multi-user MIMO systems by slight modifications.

References

[1] 3GPP TSG RAN: TS36.213v10.0.1 E-UTRA; Physical layer procedures, Dec.2010.

[2] R. Abualhiga and H. Haas, "Implicit Pilot-Borne Interference Feedback for Multiuser MIMO TDD Systems," in Proc. of the International Symposium on Spread Spectrum Techniques and Applications. Bologna, Italy: IEEE, pp. 334–338, Aug. 25–28, 2008.

[3] L. Ding, B. Jiang, and X.Q. Gao, "On the Prediction of Time-varying Channels in MISO Beamforming Systems," WCSP2009, Page(s):1 – 5.

[4] W. Santipach and M. L. Honig, "Capacity of beamforming with limited training and feedback," in *Proc. IEEE Int. Symp. on Inform. Theory (ISIT)*, Seattle, WA, July 2006.

[5] Y. Xie, C. N. Georghiades and K. Rohani, "Optimal bandwidth allocation for the data and feedback channels in MISO-FDD systems," IEEE Trans. on Commun., Vol54, No2, Feb 2006.

[6] Jin Zhang and Lehnert, J.S., "Throughput-Optimal Precoding and Rate Allocation for MISO Systems With Noisy Feedback Channels," IEEE Trans. on Inf. Theory, vol. 54, pp. 2139 - 2155, 2008**.**

[7] Annapureddy etc, "Spatial and Temporal Power Allocation for MISO Systems with Delayed Feedback," Signals, Systems and Computers, Fortieth Asilomar Conference on Page(s): 809 – 813, 2006.

[8] B.L. Zhou, etc "Optimal Uplink Pilot Time Interval Design for TDD MISO Beamforming Systems with Channel Estimation Error and Delay," in IEEE International Conference on Communications (ICC 2011), Tokyo, Japan, 5-9 June, 2011..

[9] 3GPP. 3GPP TSG RAN: TS36.212v8.9.0 E-UTRA; Physical Channels and Modulation, Dec.2009

[10] 3GPP. 3GPP TSG RAN: TS36.211v9.1.0 E-UTRA; Physical Channels and Modulation, Mar. 2010;

[11] T S. Rappaport, Wireless Commun Principles and Practice, New York ：PRENTICE HALL, 1998.

[12] 3GPP. 3GPP TSG RAN: TS36.101v8.3.0 E-UTRA; User Equipment (UE) radio transmission and reception, Jan. 2011

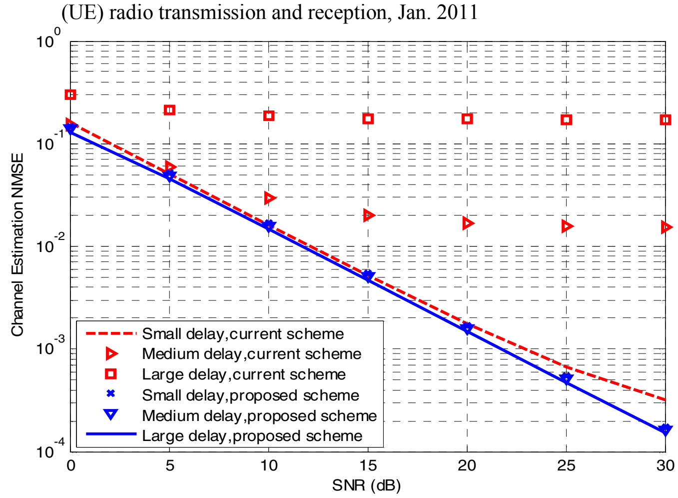


Fig.2. Channel estimate NMSE for small, mid and large multi-path delay

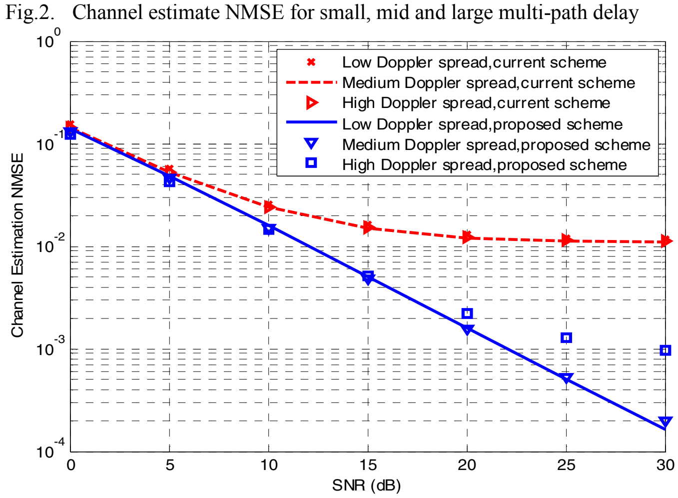


Fig. 3. Channel estimate NMSE for low, mid and high Doppler spread.