Impact of gain/phase variation on MIMO precoder selection for LTE UL

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***Abstract*—In this paper, the MIMO precoder selection of LTE uplink (UL) is evaluated taking into account the gain/phase variation between SRS and PUSCH. The gain/phase variation introduced by radio impairment is modeled and the impact on precoding gain is analyzed. The simulation results show that gain variation has a stronger impact on the precoding gain than phase variation. Specifically, a gain variation of 9 dB costs 5 dB in performance.**

I. INTRODUCTION

MIMO is considered as a key element of the air interface for high-speed wireless communications, and it provides both diversity gain and multiplexing gain. MIMO enables simultaneous transmission of multiple streams each of which is called a layer. MIMO assumes the use of a precoder, which matches the transmitted signal with the channel so as to increase the received signal power and also reduce inter-layer interference. Therefore, the use of a precoder improves the signal-to-interference-plus-noise-ratio (SINR) of each layer. In order to select the optimum precoder, the transmitter needs to know the physical channel seen by the transmit antennas.

In the 3GPP Long Term Evolution (LTE) uplink (UL), every decision on the transmission mode including precoder selection is made by the eNodeB and it is signaled to the transmitter of the user equipment (UE). Thus, it is necessary for the eNodeB to obtain the channel information, which can usually be facilitated by letting UE transmit a known signal. In LTE UL, demodulation reference signal (DM-RS) and sounding reference signal (SRS) help measure the channel from UE to eNodeB [1]. Note that DM-RS is precoded, while SRS is not precoded. As a result, the channel information obtained from DM-RS is the channel seen by the layers, i.e., the equivalent channel, not the channel seen by the antennas, i.e., the physical channel [2]. On the other hand, the channel measurement based on SRS provides the eNodeB with the physical channel and thus SRS is considered as a preferred option for precoder selection.

There may exist significant gain/phase variation between SRS and the physical uplink shared channel (PUSCH). One of the reasons is that the SRS is not always piggy-backed on top of PUSCH [1] and the Doppler shift may cause non-negligible channel variation between SRS and PUSCH. Another reason is that SRS and PUSCH may experience gain/phase variation due to radio impairment. For instance, significant gain variation tends to occur between SRS and PUSCH, when the bandwidth of SRS is different from that of PUSCH, because of inaccurate power control [3]. In this paper, this gain/phase variation caused by radio impairment is mathematically modeled with a fixed gain/phase variable on each transmitter chain, and its impact on the LTE UL is analyzed and evaluated using the simulation results.

The organization of this paper is as follows. In Section II, the system model assumed throughout the paper is described. In Section III, the gain/phase variation between SRS and PUSCH is modeled, and, in Section IV, the impact on precoding gain is analyzed. Section V presents the simulation results with gain/phase variation, and Section VI concludes the paper.

II. SYSTEM MODEL

In this section, the system model assumed for PUSCH is presented. It is assumed that there are N_t transmit antennas and N_r receive antennas, and an SC-FDMA symbol consists of R layers and K subcarriers. The $R \times 1$ vectors $\mathbf{s}_n$ and $\mathbf{x}_k$ represent the transmitted layer signal of the n-th instant in the time domain and the transmitted layer signal of the k-th subcarrier in the frequency domain, respectively. Assuming that DFT spreading is applied to each layer separately, it is expressed as

$$\mathbf{x} = \sqrt{E_s N}(\mathbf{F}_K \otimes \mathbf{I}_R)\mathbf{s}, \tag{1}$$

where the $RK \times 1$ vectors $\mathbf{s}$ and $\mathbf{x}$ are defined as

$$\mathbf{s} = \begin{pmatrix} \mathbf{s}_0^T & \mathbf{s}_1^T & \cdots & \mathbf{s}_{K-1}^T \end{pmatrix}^T,$$
$$\mathbf{x} = \begin{pmatrix} \mathbf{x}_0^T & \mathbf{x}_1^T & \cdots & \mathbf{x}_{K-1}^T \end{pmatrix}^T,$$

and E_s represents the transmit energy per symbol. Here the $K \times K$ matrix $\mathbf{F}_K$ represents K-point DFT, in other words, the element at the k_1-th row and the k_2-th column of $\mathbf{F}_K$ is given as

$$\begin{aligned} f_{k_1,k_2} &= \frac{1}{\sqrt{K}} \exp(-j2\pi \frac{k_1 k_2}{K}), \\ &k_1 = 0, \cdots, K-1, k_2 = 0, \cdots, K-1. \end{aligned} \tag{2}$$

Following the DFT spreading, MIMO precoding is performed in the frequency domain and it is expressed as

$$\mathbf{v}_k = \mathbf{W}\mathbf{x}_k, \quad k = 0, \cdots, K-1, \tag{3}$$

where the $N_t \times 1$ vector $\mathbf{v}_k$ represents the transmitted antenna signal of the k-th subcarrier and the $N_t \times R$ matrix $\mathbf{W}$ represents the precoding matrix. Each column vector of a precoding matrix represents the antenna spreading weight of the corresponding layer. Consequently, the number of columns of a precoding matrix is equal to the number of layers, which

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is referred to as the rank of precoder. The precoding matrix is usually chosen from a pre-defined set of matrices, a so-called codebook. Note that wideband precoding, i.e., frequency-independent precoding is assumed here, as specified in LTE UL [2]. Letting the $N_r \times N_t$ matrix $\mathbf{H}_k$ denote the physical channel of the k-th subcarrier in the frequency domain, the equivalent channel of the k-th subcarrier, $\mathbf{E}_k$, is given as

$$\mathbf{E}_k = \mathbf{H}_k \mathbf{W}, \quad k = 0, \cdots, K-1. \tag{4}$$

Assuming that the length of cyclic prefix is greater than the channel delay spread, the $N_r \times 1$ vector representing the received antenna signal of the k-th subcarrier, $\mathbf{y}_k$, is given as

$$\mathbf{y}_k = \mathbf{E}_k \mathbf{x}_k + \mathbf{w}_k, \quad k = 0, \cdots, K-1, \tag{5}$$

where the $N_r \times 1$ vector $\mathbf{w}_k$ represents the noise-plus-interference signal of the k-th subcarrier.

Here minimum mean square error (MMSE) equalization is used, which consists of frequency-domain (FD) MMSE equalization and inverse DFT (IDFT) despreading [4]. Defining the noise covariance matrix of the k-th subcarrier as $\mathbf{R}_{\mathbf{w}_k} = E[\mathbf{w}_k \mathbf{w}_k^H]$, the output of the FD MMSE equalization at the k-th subcarrier, $\tilde{\mathbf{x}}_k$, is given by

$$\tilde{\mathbf{x}}_k = \mathbf{E}_k^H (\mathbf{E}_k \mathbf{E}_k^H + \frac{1}{E_s N} \mathbf{R}_{\mathbf{w}_k})^{-1} \mathbf{y}_k, \ \ k = 0, \cdots, K-1. \tag{6}$$

Letting $\alpha_{r,k}$ and $SINR_{r,k}^F$ denote the gain and SINR of $\tilde{x}_{k,r}$ (the r-th element of $\tilde{\mathbf{x}}_k$), respectively, $\alpha_{r,k}$ is given as the r-th diagonal element of $\mathbf{E}_k^H (\mathbf{E}_k \mathbf{E}_k^H + \frac{1}{E_s N} \mathbf{R}_{\mathbf{w}_k})^{-1} \mathbf{E}_k^H$ and $SINR_{r,k}^F$ is given as $SINR_{r,k}^F = \alpha_{r,k}/(1 - \alpha_{r,k})$. Subsequently, the output of the IDFT despreading $\tilde{\mathbf{s}}$ is related to $\tilde{\mathbf{x}}$ as

$$\tilde{\mathbf{s}} = \frac{1}{\sqrt{E_s N}} (\mathbf{F}_K^H \otimes \mathbf{I}_R) \tilde{\mathbf{x}}, \tag{7}$$

where the $RK \times 1$ vectors $\tilde{\mathbf{s}}$ and $\tilde{\mathbf{x}}$ are defined as

$$\tilde{\mathbf{s}} = (\ \tilde{\mathbf{s}}_0^T \quad \tilde{\mathbf{s}}_1^T \quad \cdots \quad \tilde{\mathbf{s}}_{K-1}^T \ )^T,$$

$$\tilde{\mathbf{x}} = (\ \tilde{\mathbf{x}}_0^T \quad \tilde{\mathbf{x}}_1^T \quad \cdots \quad \tilde{\mathbf{x}}_{K-1}^T \ )^T.$$

By plugging (1), (5) and (6) into (7), it can be easily proven that the time-domain (TD) SINR of the r-th layer and the n-th instant, $SINR_{r,n}^T$, is expressed as

$$SINR_{r,n}^T = (\frac{1}{K} \sum_{k=0}^{K-1} (SINR_{r,k}^F + 1)^{-1})^{-1} - 1. \tag{8}$$

This is consistent with the fact that the TD SINR remains constant within an SC-FDMA symbol, i.e., it is independent of the time index n [4]. More importantly, (8) implies that the MIMO precoding maximizing the FD SINR tends to maximize the TD SINR, especially, in slightly-dispersive channels. Thus, for simplicity, we focus on the frequency domain in the following section and the subcarrier subscript k is dropped.

III. Radio-induced gain/phase variation

The physical channel can be seen as a cascade of the wireless channel and the radio-induced channel. Therefore, assuming that the wireless channel remains constant, the potential variation of the physical channel between SRS and PUSCH results from the variation of the radio-induced channel. In this section, the radio-induced gain/phase variation between SRS and PUSCH is modeled, taking into account the relevant radio (transmitter) impairment.

The transmit power change of UE can be seen as one of the major sources of radio-induced gain/phase variation. The transmit power is set by several parameters including the bandwidth, following the open-loop/closed-loop power control principle [3]. In practice, the actual transmit power may deviate from the nominal transmit power, because of inaccurate gain control [7]. Recalling that SRS and PUSCH may have different bandwidths [1], the nominal transmit power may change between SRS and PUSCH, which in turn tends to cause non-negligible gain variation between SRS and PUSCH. In detail, the power variation between SRS and PUSCH increases with the required power change between SRS and PUSCH, and the maximum power variation amounts to $\pm 9\ dB$ [7]. In addition, such a power change introduces phase variation between SRS and PUSCH, for example, when high-efficiency gain-switchable power amplifiers are used, or when the power amplifiers experience substantial amplitude-dependent phase shift, the so-called AM-to-PM distortion. It should be noted that, in general, each of the transmitters introduces different gain/phase variation between SRS and PUSCH, since each transmitter is equipped with its own power amplifier. In other words, the relative gain and phase of multiple transmitters also varies over time, i.e., between SRS and PUSCH.

Let the gain and phase introduced by the i-th power amplifier be denoted by p_i and the phase introduced by the i-th local oscillator be denoted by ϕ_i. The effective gain and phase of the i-th transmitter chain are expressed as

$$d_i = p_i \cdot \exp(j\phi_i), \quad i = 1, \cdots, N_t. \tag{9}$$

Let's assume that the wireless channel remains constant between SRS and PUSCH. Without loss of generality, the physical channel for PUSCH, $\mathbf{H}$, is newly defined so that it includes not only the wireless channel but also the radio-induced gain and phase experienced by PUSCH. Therefore, it is possible to consider the gain and phase experienced by PUSCH as the reference. Consequently, the gain and phase experienced by SRS, which are represented by d_i for the i-th transmitter chain, are nothing but the gain/phase variation betweeen SRS and PUSCH. When the $N_t \times N_t$ matrix $\mathbf{D}$ is defined as a diagonal matrix whose diagonal element is given by d_i, the physical channel experienced by SRS is expressed as $\mathbf{HD}$.

IV. Impact of gain/phase variation

Figure 1 shows the codebook for 2 transmit antennas. (Refer to [2] for the codebook for 4 transmit antennas.) Since each codebook consists of N_t subsets of precoder matrices of the same rank, the precoder selection can be seen as the selection of two parameters, rank index (RI) and precoding matrix index (PMI). The former corresponds to the PMI selection that maximizes the throughput within each subset, while the latter corresponds to the RI selection that maximizes the throughput across N_t subsets. The precoder selection may optimize several performance metrics, and, throughout this paper, the link-level throughput is chosen as the performance metric. In detail, the physical channel $\mathbf{H}_k$ is estimated through SRS measurement, the throughput for each precoding matrix is predicted based on the TD SINR in (8), and the precoder (both RI and PMI) maximizing the throughput is selected.

Let's take a look at the codebook for 2 transmit antennas. As mentioned in the previous section, the SRS measurement provides $\mathbf{HD}$, instead of $\mathbf{H}$, which may cause inappropriate precoder selection. (Note that, if there exists no gain/phase variation between SRS and PUSCH, $\mathbf{D}$ becomes an identity matrix.) The equivalent channel $\mathbf{E}$ is related to the physical channel $\mathbf{H}$ as

$$\mathbf{E} = \mathbf{HDW}. \tag{10}$$

The noise-plus-interference $\mathbf{w}_k$ is assumed to be independent and Gaussian distributed with

$$\mathbf{R}_{\mathbf{w}_k} = N_0 \mathbf{I}_{N_r}.$$

For simplicity, E_s/N_0 is assumed to be sufficiently high so that MMSE equalization can be approximated by zero forcing (ZF) equalization. The FD SINR is simply expressed as the inverse of diagonal elements of $((E_s N) \cdot \mathbf{E}^H \mathbf{R}_{\mathbf{w}}^{-1} \mathbf{E})^{-1}$. By denoting the precoding matrix of RI i and PMI j by $\mathbf{W}^{i,j}$ and the corresponding SINR of the r-th layer by $SINR_r^{i,j}$, it follows that

$$\begin{aligned}
SINR_0^{0,0} =& |d_1|^2 \cdot \|\mathbf{h}_1\|^2 + |d_2|^2 \cdot \|\mathbf{h}_2\|^2 \\
&+ 2 \cdot \mathcal{R}\{(+1) \cdot (d_1^* d_2) \cdot \mathbf{h}_1^H \mathbf{h}_2\} \\
SINR_0^{0,1} =& |d_1|^2 \cdot \|\mathbf{h}_1\|^2 + |d_2|^2 \cdot \|\mathbf{h}_2\|^2 \\
&+ 2 \cdot \mathcal{R}\{(-1) \cdot (d_1^* d_2) \cdot \mathbf{h}_1^H \mathbf{h}_2\} \\
SINR_0^{0,2} =& |d_1|^2 \cdot \|\mathbf{h}_1\|^2 + |d_2|^2 \cdot \|\mathbf{h}_2\|^2 \\
&+ 2 \cdot \mathcal{R}\{(+j) \cdot (d_1^* d_2) \cdot \mathbf{h}_1^H \mathbf{h}_2\} \\
SINR_0^{0,3} =& |d_1|^2 \cdot \|\mathbf{h}_1\|^2 + |d_2|^2 \cdot \|\mathbf{h}_2\|^2 \\
&+ 2 \cdot \mathcal{R}\{(-j) \cdot (d_1^* d_2) \cdot \mathbf{h}_1^H \mathbf{h}_2\} \\
SINR_0^{0,4} =& |d_1|^2 \cdot \|\mathbf{h}_1\|^2 \\
SINR_0^{0,5} =& |d_2|^2 \cdot \|\mathbf{h}_2\|^2
\end{aligned} \tag{11}$$

for the rank-1 codebook ($i = 0$) and

$$\begin{aligned}
SINR_0^{1,0} &= |d_1|^2 \cdot (\|\mathbf{h}_1\|^2 - \frac{|\mathbf{h}_1^H \mathbf{h}_2|^2}{\|\mathbf{h}_2\|^2}) \\
SINR_1^{1,0} &= |d_2|^2 \cdot (\|\mathbf{h}_2\|^2 - \frac{|\mathbf{h}_1^H \mathbf{h}_2|^2}{\|\mathbf{h}_1\|^2})
\end{aligned} \tag{12}$$

for the rank-2 codebook ($i = 1$), when it is normalized by a common factor $\frac{E_s N}{2N_0}$. Here $\mathbf{h}_1$ and $\mathbf{h}_2$ are the column vectors of $\mathbf{H}$.

The PMI selection is equivalent to maximizing the SINR within the rank-1 codebook, since a single transport block is mapped to the layer. Thus, it can be understood from (11) that the PMI selection depends on which element in the set $\{\pm 1, \pm j\}$ is closest to $(d_1^* d_2) \cdot \mathbf{h}_1^H \mathbf{h}_2$, since it is equivalent to maximizing the SINR over the subset of the rank-1 codebook $\{\mathbf{W}_{0,0}, \mathbf{W}_{0,1}, \mathbf{W}_{0,2}, \mathbf{W}_{0,3}\}$. (Note that the rest of the rank-1 precoding matrices $\mathbf{W}_{0,4}$ and $\mathbf{W}_{0,5}$ do not need to be considered, since they always lead to a lower SINR.) Once the PMI selection is performed for the rank-1 codebook, the maximum throughput of the rank-1 codebook (calculated from (11)) is compared with that of the rank-2 codebook (calculated from (12)), and the rank maximizing the throughput is selected. From the fact that the maximum allowable payload size is approximately seen as a concave function of SINR, it is understood that the rank-2 codebook always provides a higher throughput than the rank-1 codebook, if the physical channel is orthogonal ($\mathbf{h}_1^H \mathbf{h}_2 = 0$). However, the orthogonality of channel is not always guaranteed, and the rank-1 codebook may lead to a much higher throughput, for example, in case of ill-conditioned channel. Since the payload size is in practice limited by the highest MCS [6], the higher the average receive SNR becomes, the more likely the rank-2 codebook is selected so as to maximize the throughput.

PMI	RI	
	0	1
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	-
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	-
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-
4	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\end{bmatrix}$	-
5	$\frac{1}{\sqrt{2}}\begin{bmatrix}0\\1\end{bmatrix}$	-

Fig. 1. Codebook for 2 transmit antennas.

From (11) and (12), it is understood that the gain variation does not affect the PMI selection, since the SINRs for the rank-1 codebook are equally affected and thus the precoder maximizing the throughput for SRS also maximizes the throughput for PUSCH (It is easily found in (11) that, if d_1 and d_2 are real, the SINRs are dependent on $\mathbf{h}_1^H \mathbf{h}_2$ alone, regardless of d_1 and d_2). However, the gain variation generally has a significant impact on the RI selection. Let's assume a significant gain increase for SRS, e.g., $d_1 = d_2 = 2.82$. From (11) and (12), it can be shown that this is equivalent to the SINR increase of 9 dB for the entire codebook. According to the SRS measurement, the eNodeB tends to recommend the rank-2 codebook more frequently than with appropriate precoder selection, since it might appear to eNodeB that the payload size of the rank-1 codebook is limited by the highest MCS and that the rank-2 codebook provides a higher throughput. However, in reality, it is highly likely that the rank-1 codebook never reaches the highest MCS with PUSCH and that it is more desirable to recommend the rank-1 codebook. In this situation, the precoder selection based on SRS measurement overestimates the physical channel experienced by PUSCH, which may lead into a significant throughput loss. Likewise, the gain decrease also affects the precoder selection and, interestingly, it is more detrimental to the throughput performance, since it is possible to recommend the rank-1 codebook instead of the rank-2 codebook because of the SINR decrease.

On the other hand, from (11), it can be understood that the phase variation between SRS and PUSCH possibly degrades the PMI selection gain. From (11), it readily follows that the PMI selection is affected only when the inter-antenna phase difference, $d_1^* d_2$, varies between SRS and PUSCH. However, the phase variation has a comparatively small impact on the RI selection, since the SINRs for the rank-2 codebook remain constant between SRS and PUSCH, since $|d_1| = |d_2| = 1$. In fact, if the inter-antenna phase difference is an integer multiple of 90°, i.e., $d_1^* d_2$ is one of the elements of $\{\pm 1, \pm j\}$, the RI selection remains unaffected in theory, regardless of how much the phase varies between SRS and PUSCH. This is not surprising at all, in the sense that the rank-1 codebook has the phase granularity of 90° and it is perfectly aligned with the phase variation.

Regarding the 4-TX codebook, the gain variation affects the PMI selection as well as the RI selection, in contrast to the 2-TX codebook. For example, the PMI selection within the rank-1 codebook is affected by gain variation, since the SINRs are dependent on $\mathbf{h}_1^H \mathbf{h}_3$, $\mathbf{h}_1^H \mathbf{h}_4$, $\mathbf{h}_2^H \mathbf{h}_3$, $\mathbf{h}_2^H \mathbf{h}_4$ and $\mathbf{h}_3^H \mathbf{h}_4$ as well as $\mathbf{h}_1^H \mathbf{h}_2$. For example, if $(d_1^* d_2)$ is more dominant than $(d_1^* d_3)$, $(d_1^* d_4)$, $(d_2^* d_3)$, $(d_2^* d_4)$, and $(d_3^* d_4)$, the PMI selection becomes highly dependent on $\mathbf{h}_1^H \mathbf{h}_2$. On the other hand, if $(d_1^* d_3)$ is more dominant, the PMI selection largely depends on $\mathbf{h}_1^H \mathbf{h}_3$ and vice versa. This explains the influence of gain variation on the PMI selection. However, our simulation results show that the RI selection is more sensitive to gain variation than the PMI selection.

Furthermore, unlike the 2-TX codebook, both the RI selection and PMI selection of the 4-TX codebook are affected by the phase variation, although it has a relatively larger impact on the PMI selection. Also, the PMI selection of the rank-1 codebook is affected only when the inter-antenna phase difference (characterized by $(d_1^* d_2)$, $(d_1^* d_3)$, $(d_1^* d_4)$, $(d_2^* d_3)$, $(d_2^* d_4)$ and $(d_3^* d_4)$) varies between SRS and PUSCH. Note that, as opposed to the 2-TX codebook, even when the inter-antenna phase difference is chosen from the set $\{\pm 1, \pm j\}$, the RI selection of the 4-TX codebook is affected. For example, the rank-1 codebook does not have a full phase granularity of 45° and thus the phase variation does not only permutes the SINR values but change some of them. (Note that the full phase granularity of the rank-1 codebook is obtained with 64 precoding matrices.)

V. Simulation Results

Here slightly-dispersive channel, the Extended Pedestrian A (EPA), is assumed. The throughput is measured, ignoring the retransmission based on hybrid automatic repeat-request (HARQ). The cell bandwidth of 10MHz and the user bandwidth of 1.08MHz are assumed. The MIMO configuration is set to 2x2 or 4x4, no antenna correlation is considered and ideal channel estimation is assumed.

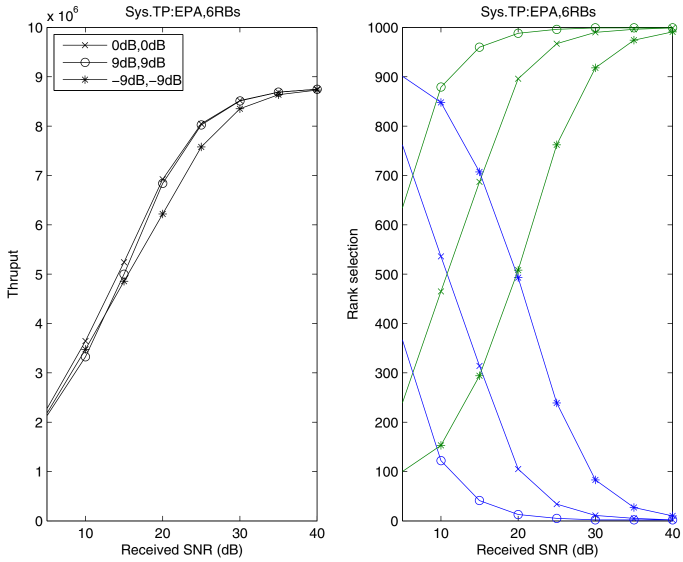

Fig. 2. Impact of gain variation on 2TX codebook: throughput and rank distribution for rank 1 (blue) and rank 2 (green).

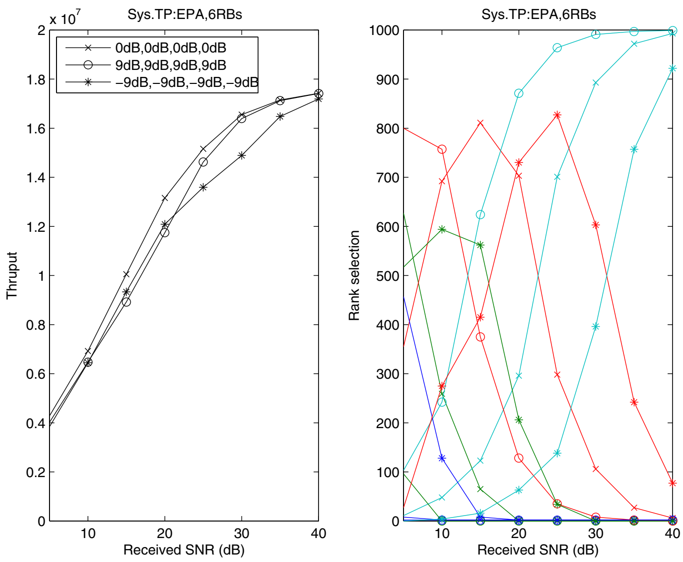

Fig. 3. Impact of gain variation on 4TX codebook: throughput and rank distribution for rank 1 (blue) and rank 2 (green) and rank 3 (red) and rank 4 (cyon).

A. Impact of gain variation

Figure 2 shows the throughput and rank distribution of the 2-TX codebook in the presence of gain variation. The gain decrease of 9 dB ($d_1 = d_2 = 0.36$) significantly degrades the throughput performance, specifically, more than 2 dB loss, since it shifts the rank distribution by 9 dB such that the rank-1 codebook is selected more frequently than appropriate. It is worth mentioning that, as the gain variation approaches $+\infty$ dB (or $-\infty$ dB), the asymptotic precoder is the fixed rank-2 precoder (or the fixed rank-1 precoder).

Figure 3 shows the throughput and rank distribution of the 4-TX codebook in the presence of gain variation. The 4-TX codebook is more vulnerable to gain variation than the 2-TX

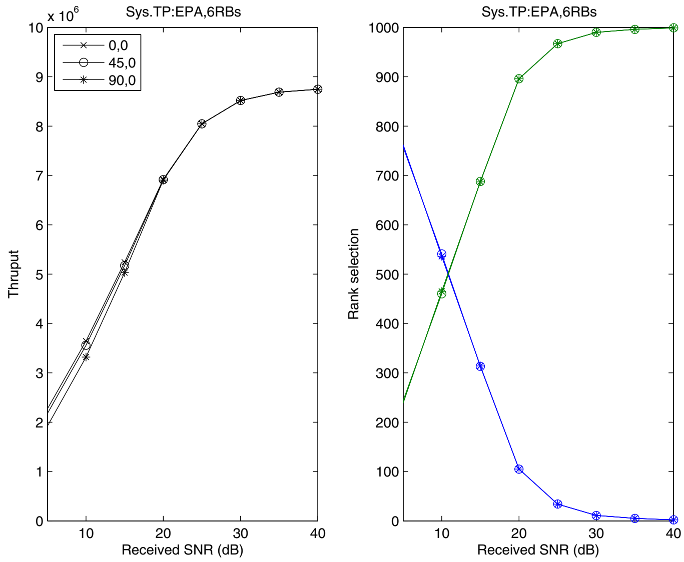

Fig. 4. Impact of phase variation on 2TX codebook: throughput and rank distribution for rank 1 (blue) and rank 2 (green).

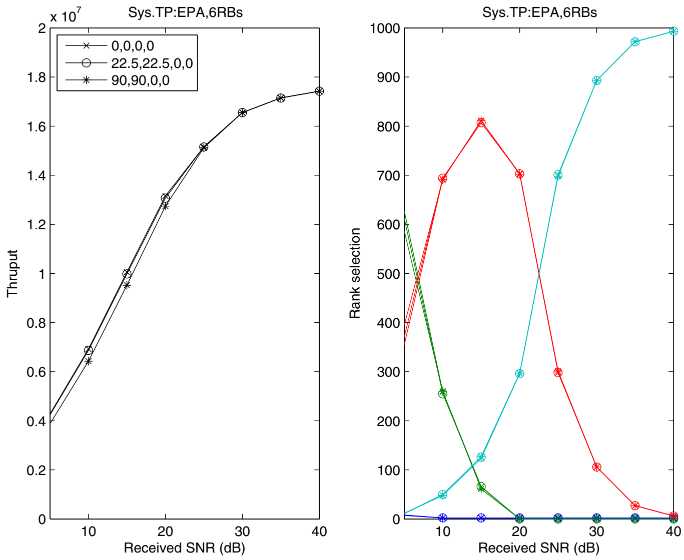

Fig. 5. Impact of phase variation on 4TX codebook: throughput and rank distribution for rank 1 (blue) and rank 2 (green) and rank 3 (red) and rank 4 (cyon).

codebook, since it provides a higher RI selection gain. The gain increase of 9 dB, i.e., $d_1 = d_2 = d_3 = d_4 = 2.82$, degrades the throughput performance by about 2 dB, while the same amount of gain decrease, i.e., $d_1 = d_2 = d_3 = d_4 = 0.36$, degrades the performance by more than 5 dB.

B. Impact of phase variation

Figure 4 shows the impact of phase variation on the 2-TX codebook. It is shown that the precoder selection is somewhat insensitive to the variation of inter-antenna phase difference. For example, the phase variation as high as $90°$ degrades the performance by less than 1 dB. In addition, it is shown that the RI selection remains almost intact in the presence of phase variation, as pointed out in the previous section. The insensitivity to the phase variation can be explained by the fact that the PMI selection gain of the 2-TX codebook is only marginal, when the RI selection is performed appropriately. Notice that the precoder approaches the case with the RI selection only, as the phase variation increases.

Figure 5 shows the impact of phase variation on the 4-TX codebook. Similar to the 2-TX codebook, the RI selection remains to be appropriate in the presence of phase variation. It can be found out that the impact of phase variation on the 4-TX codebook is as small as the impact on the 2-TX codebook. Specifically, the phase variation of $90°$ causes the performance loss of less than 1 dB. This is a bit surprising since the phase variation has a strong impact on the PMI selection and a non-negligible fraction of precoding gain of the 4-TX codebook comes from appropriate PMI selection. The reason is that the phase granularity of the 4-TX codebook is so coarse that a modest amount of phase variation is almost ignorable to the PMI selection. Recall that the rank-1 codebook does not even provide the full phase granularity of $45°$. Similar to the 2-TX codebook, in theory, the precoder approaches the case with the RI selection only, as the phase variation increases.

Although Figure 4 and Figure 5 do not show significant impact of phase variation, it is important to note that the performance degradation becomes more serious, as the antenna correlation increases. Also, when the phase variation is modelled as random variables (rather than fixed deterministic variables), the performance loss increases slightly.

VI. Conclusions

The impact of SRS measurement error on the precoder selection for LTE UL is analyzed and evaluated. Taking into account radio impairment, the potential gain/phase variation between SRS and PUSCH are discussed and the impact on the precoding gain is analyzed. It is shown that gain variation has a stronger impact than phase variation, for instance, up to 5 dB loss for equal gain decrease of 9 dB.

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