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OPTIMIZATION OF LAYER SELECTION WITH UNRELIABLE RI IN LTE SYSTEMS

Weidong Zhang, Ying Wang, Mingyue Xu
Cong Shi, Ping Zhang

Key Laboratory of Universal Wireless Communications, Ministry of Education
P.O. Box 92, Beijing University of Posts and Telecommunications
Beijing 100876, P.R. China
e-mail: same.zwd@gmail.com

Abstract. This paper investigates the optimization of transmission spatial layer selection with unreliable rank indicator (RI) in downlink LTE systems. Taking the block error rate (BLER) into consideration, we propose an accurate throughput calculation (ATC) algorithm at user equipment (UE) side as well as at evolved NodeB (eNB) side. On the basis of ATC algorithm, we propose an accurate RI selection algorithm to periodically choose the preferred number of transmission spatial layers at UE side. Further based on acknowledgement (ACK)/ negative acknowledgement (NACK) history, channel quality indicator (CQI) is adjusted at eNB side to achieve the throughput optimal target BLER. By substituting the derived BLER into ATC algorithm, the optimal number of transmitted spatial layers in current downlink channel is derived at eNB side. Simulation results show that both the proposed CQI adjustment scheme for spatial layer selection and RI selection algorithm yield up significant throughput improvement for different evaluation scenarios in LTE systems.

Keywords: LTE, MIMO, RI, transmission spatial layer, BLER, ATC algorithm, CQI adjustment

1 INTRODUCTION

3GPP Long Term Evolution, usually referred to as LTE, is a standard for wireless communication of high-speed data for mobile phones and data terminals [1]. An important aspect in LTE system is the introduction of the closed-loop concept [2], which requires the calculation of channel state information (CSI) at the transmitter. With the presence of perfect CSI, closed-loop systems provide the dynamical transmission modes control to perform channel adaption [3]. Even in the partial and/or imperfect CSI scenarios, LTE system performance can be improved significantly using the adaptive closed-loop algorithm [4].

In LTE system, the user equipment (UE) monitors the preferred transmission spatial layers and periodically reports this CSI information to the evolved NodeB (eNB) in physical uplink control channel (PUCCH). This feedback, called Rank Indicator (RI), is an indication of the number of the optimal transmission spatial layers on the current downlink wireless channel [3]. However, the reporting RI involves several technical challenges in LTE systems. Considering that RI is calculated at UE side and reported to eNB in PUCCH, the important factors that affect the reliable reporting RI can be typically classified as follows:

1) **Unreliable measurement problem caused by the inaccurate RI selection algorithm at UE side**. Typically, if the reporting RI is selected inaccurately, both of spatial multiplexing and link adaption would be unreliable in downlink transmission.
2) **Unreliable feedback problem caused by the feedback delay and period interval**. In case RI reporting is configured in physical uplink control channel (PUCCH), the periodic reporting interval of RI is set to several standardized values [2]. Moreover, the feedback delay of RI is needed to be considered in actual transmission. Based on the above-mentioned analysis, according to the received reporting RI, the transmission spatial layer selected by eNB is unsuitable for the current channel condition.

The objective of this paper is to study accurate RI selection algorithm at UE side and further adapt transmission for the feedback delay and period interval of RI reporting feedback at eNB side.

Firstly, we attempt to solve the unreliable measurement problem of reporting RI at UE side. Bai et al. [5] focused on the implementation of RI selection algorithm in LTE systems, and illustrated the comparison with different RI calculation schemes. Schwarz et al. [6, 7] jointly evaluated the precoding matrix indicator (PMI) and RI based on a mutual information metric, to reduce the computational burden for the UE. The above-mentioned references [5]–[7] studied a variety of techniques to select the values of RI and have not considered the block error rate (BLER) for each transmission spatial layer in actual transmission. However, to achieve the actual throughput of LTE system, the BLER in each transmission should be evaluated according to [8]. In this paper, we propose an accurate throughput calculation (ATC) algorithm by taking the BLER into consideration. Here, the BLER of each transmission spatial layer is derived by using the effective exponential SINR mapping (EESM) algorithm and curve of system to link level interface at UE side as well as at eNB side. After that, to maximize the system throughput, the optimal number of transmission spatial layers for current downlink wireless channel is obtained. Meanwhile, the reporting RI is transmitted from UE to eNB.

Secondly, we attempt to solve the unreliable measurement and feedback problem of reporting RI jointly at eNB side. Since eNB has no knowledge about the BLER for each transmission spatial layer in actual transmission, the channel quality indicator (CQI) is adjusted based on ACK/NACK history to achieve a given target BLER. Consequently, the proposed ATC algorithm can be implemented to select the optimal number of transmission spatial layers at the eNB. Note that the reporting RI is unutilized at eNB side in this case.

The rest of the paper is organized as follows. Section 2 introduces the LTE system model. Section 3 elaborates the ATC algorithm and RI selection algorithm at UE side. Section 4 proposes a CQI adjustment scheme for spatial layer selection at eNB side. In Section 5, we study the efficacy of the optimization selection schemes for transmission spatial layers using a LTE system-level simulator which are compared with no optimization scenarios. Section 6 concludes the paper.

2 SYSTEM MODEL

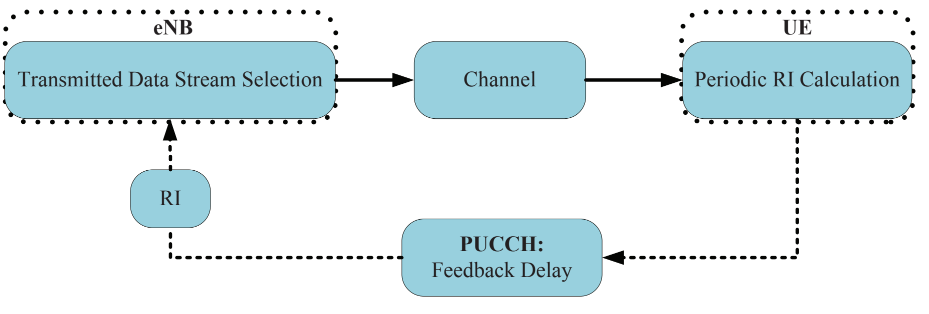

Figure 1. eNB and UE transmission principle of LTE systems

We consider a downlink signal user MIMO (SU-MIMO) system with N_t transmit antennas and N_r receive antennas at each active user, where $N_t = 4$ and $N_r = 2$, respectively. The MIMO channel is typically modeled by $H_l \in \mathbb{C}^{N_r \times N_t}$ in the l^{th} eNB, and the received signal vector can be written as [9]:

$$r_l = H_l F_l s_l + \widetilde{H}_l \widetilde{s}_l + n, \tag{1}$$

in which the second term represents the co-channel interference (CCI) caused by other eNBs, and the third term is the additive white Gaussian noise. $s_l \in \mathbb{C}^{N_s \times 1}$ denotes the desired transmit vector, where N_s represents the number of transmission spatial layers. Close-loop SU-MIMO system is considered in this paper, thus s_l is pre-multiplied by a precoding matrix $F_l \in \mathbb{C}^{N_t \times N_s}$ before entering into the MIMO channel. Here, F_l is selected based on codebook mapping in LTE system [2].

Considering the number of total serving eNBs is L, $\widetilde{H}_l$ and $\widetilde{s}_l$ are, respectively, defined as the MIMO channel and pre-multiplied transmit vector from all eNBs other than eNB l combined:

$$\begin{aligned}\widetilde{H}_l &= [H_1, \ldots, H_{l-1}, H_{l+1}, \ldots, H_L], \\ \widetilde{s}_l &= [(F_1 s_1)^T, \ldots, (F_{l-1} s_{l-1})^T, (F_{l+1} s_{l+1})^T, \ldots, (F_L s_L)^T]^T.\end{aligned}$$

The transmission principle used in LTE systems is depicted in Figure 1 and can be carried out in the following two steps:

Step 1: UE calculates the preferred number of transmitted spatial layers periodically and reports RI to eNB.

Based on Equation (1), using the maximum channel capacity (Max-CP) criterion based RI selection algorithm, UE periodically selects the RI such that the instantaneous system capacity can be maximized [10, 11]. In case the m^{th} RB is allocated to UE k in eNB l, the MIMO channel H_l and transmit vector s_l can be respectively expressed as: $H_l^{(k,m)}$ and $s_l^{(k,m)}$. Further, the numbers of transmission spatial layers are equal for all available resource blocks (RBs) of one UE [10], where RB is defined as transmit time-frequency channel in LTE systems [2]. Consequently, the RI value N_R for UE k can be selected as:

$$N_R = \underset{N_s \in 1, \cdots, \min(N_r, N_t)}{\arg\max} \sum_{m=1}^{M_k} C\left(s_l^{(k,m)}\right), s_l^{(k,m)} \in \mathbb{C}^{N_s \times 1}, \tag{2}$$

where $C(\cdot)$ is defined as capacity calculation function, and M_k denotes the available RBs for UE k. The preferred N_R would be reported to eNB in PUCCH.

Note that the BLER is not considered in the traditional calculation algorithm of transmission throughput at UE side. Consequently, under the Max-CP criterion, the RI calculation is inaccurate.

Step 2: Based on the received reporting RI, eNB selects the number of transmission spatial layers to transmit the desired signals for UE.

Note that eNB periodically receives the reporting RI, which is delayed in PUCCH. Based on the reporting RI, the transmission spatial layer selected by eNB is unreliable for the current channel condition, leading to a certain performance degradation in downlink transmission.

In the following, we will handle the unreliable RI reporting problem mentioned in Step 1 and Step 2.

3 ACCURATE RI SELECTION ALGORITHM

Here, we attempt to solve the unreliable measurement problem of reporting RI at UE side and investigate Step 1 in this section. Assume that the channel quality feedback carries SINR. We can obtain the received SINR g for each transmission spatial layer by using linear minimum mean square error (MMSE) receiver. For the given g in dB, $TB(g)$ denotes the transport block (TB) corresponding to g. $b(g)$ is denoted as the BLER of transmission for TB, and derived in the following procedure at the UE.

- Firstly, obtain the modulation and coding scheme (MCS) of g.

  The mapping is between g and the $MCS(g)$ and can be determined so as to maximize the instantaneous rate while maintaining certain target bit error rate (BER) BER_q [12]. Here, $MCS(g)$ denotes the MCS of the given g.
- Secondly, taking the derived $MCS(g)$ and g into consideration, obtain $b(g)$ for each transmission spatial layer.

  Given $MCS(g)$ and BER_q, the mapping is between g and $b(g)$ in this procedure, which will be determined according to the curve of system to link level interface [13].

Consequently, $b(g)$ is finally obtained and the actual transmission throughput can be written as:

$$T\left(g_1^{(2)}, g_2^{(2)}\right) = \sum_{j=1}^{2} \left(1 - b\left(g_j^{(2)}\right)\right) TB\left(g_j^{(2)}\right) \tag{3}$$

where $g_1^{(2)}$ and $g_2^{(2)}$ represent the SINR of the first and second spatial layer, respectively. Otherwise, in case the number of transmission spatial layer is one, the actual transmission throughput for this layer can be written as:

$$T\left(g_1^{(1)}\right) = \left(1 - b\left(g_1^{(1)}\right)\right) TB\left(g_1^{(1)}\right). \tag{4}$$

where $g_1^{(1)}$ denotes the SINR for one spatial layer.

As defined in [10], the number of transmission spatial layers is set to be equal for all available RBs occupied by one user. Under the Max-CP criterion, considering ATC algorithm from (5) and (6), the accurate RI selection algorithm for UE k is presented as:

$$N_R = \begin{cases} 1, & \sum_{m=1}^{M_k} T\left(g_{1,m}^{(1)}\right) > \sum_{m=1}^{M_k} T\left(g_{1,m}^{(2)}, g_{2,m}^{(2)}\right), \quad (5) \\ 2, & \text{otherwise.} \quad (5') \end{cases}$$

where $g_{1,m}^{(1)}$ and $g_{j,m}^{(2)}, j = 1, 2$ represent the SINR of the first and second spatial layer for m^{th} RB, respectively. Using the proposed accurate RI selection algorithm, we have the following proposition.

Proposition 1. In low received SINR regime, the preferred value of N_R is 1. In high received SINR regime, the preferred value of N_R is 2.

Detailed proof of Proposition 1 is given in Appendix A. The regions of low and high received SINRs can be derived through system-level simulation in Section 4.

After the above-mentioned procedure, the reporting RI is periodically obtained from Equations (5) and (5'), and reported to eNB in PUCCH.

4 CQI ADJUSTMENT SCHEME FOR SPATIAL LAYER SELECTION

Here, we attempt to solve the unreliable measurement and feedback problem of reporting RI jointly at eNB side and investigate Step 2 in this section. Note that the reporting RI is unutilized at eNB side in this case. We implement the CQI adjustment scheme for spatial layer selection, which can be processed in the following procedure:

- Firstly, adjust CQI based on ACK/NACK history to achieve a certain target BLER in each transmission time interval (TTI). We consider the downlink system with M_k available RBs at the k^{th} active users. Using EESM algorithm, we can derive the equivalent SINR g^* of M_k RBs for each transmitted spatial layer. With respect to CQI offset $\triangle$, $b(g^*)$ can be modified as:

$$b(\triangle) = b(g^* + \triangle). \tag{6}$$

The CQI offset $\triangle$ is adjusted to achieve b^* by minimizing the mean-squared error (MSE) between $b(\triangle)$ and the target BLER b^* [14], which can be written as:

$$f(\triangle) = \min_{\triangle} |b(\triangle) - b^*|^2. \tag{7}$$

Since the long term BLER $b(\triangle)$ is difficult to derive, we can estimate $b(\triangle)$ using the ACK/NACK history within a sliding window of size w in each TTI. Let t_n denote the starting time of the n^{th} window for CQI offset update with $t_1 = 1$. $X(t)$ and $Y(t)$ denote the status of the first transmission ACK and NACK in subframe t, respectively. In case the transmission ACK is received at eNB, $X(t) = 1$; otherwise, $X(t) = 0$. In case the transmission NACK is received at eNB, $Y(t) = 1$; otherwise, $Y(t) = 0$. Given t_n, t_{n+1} is chosen such that the number of transmissions between t_{n+1} and $t_n + 1$ is w, i.e., $\sum_{t_n+1}^{t_{n+1}}(X(t)+Y(t)) = w$. $b(\triangle)$ is then estimated by

$$\hat{b}(\triangle) = \frac{\sum_{t_n+1}^{t_{n+1}} Y(t)}{w}, \tag{8}$$

in which $\hat{b}(\triangle)$ denotes the short term BLER. To solve Equation (9), we use the gradient descent method:

$$\triangle_{n+1} = \triangle_n - \left(\hat{b}(\triangle_n) - b^*\right), \tag{9}$$

where $\triangle_n$ denotes the CQI offset at the n^{th} iteration. Note that in case the number of transmission spatial layers are two, (8)–(11) are processed for the first and second spatial layer separately. The value of target BLER b^* is equal for the two layers, while $\triangle_j^{(2)}, j = 1, 2$ and $\triangle_1^{(1)}$ denote, respectively, the CQI offset for $g_j^{(2)}$ and $g_1^{(1)}$. According to [14], we can show that there exists a constant $0 < \eta < 1$ such that

$$|E\{\triangle_{n+1}\} - \triangle^*| < \eta \, |E\{\triangle_n\} - \triangle^*| \, . \tag{10}$$

Therefore, $E\{\triangle_{n+1}\}$ converges to $\triangle^*$ exponentially. As provided in [15], $E\{(\triangle_n - \triangle^*)\}$ also converges. Since previous two results concern the convergence of $\triangle_n$, by using the martingale inequality [16], we have

$$\mathbb{P}\{\lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^{n} \hat{b_i}(\triangle_i) = b^*\} = 1. \tag{11}$$

Consequently, the time average $\hat{b}(\triangle_n)$ converges. From ATC algorithm presented in (5) and (6), under the Max-CP criterion, the system throughput of the k^{th} user can be written as:

$$T_k(b^*) = \begin{cases} \displaystyle\sum_{m=1}^{M_k} \sum_{j=1}^{2} (1 - b^*) TB \left(g_{j,m}^{(2)} + \triangle_j^{(2)} \right), & N_s = 2 \qquad (12) \\ \displaystyle\sum_{m=1}^{M_k} (1 - b^*) TB \left(g_{1,m}^{(1)} + \triangle_1^{(1)} \right). & N_s = 1 \qquad (12') \end{cases}$$

- Secondly, find the throughput optimal target BLER.

  To maximize the system throughput, the optimization problem can be expressed as:

$$\hat{b}^* = \arg\max_{b^*} \sum_{k=1}^{K} T_k(b^*). \tag{13}$$

  The optimal target BLER $\hat{b}^*$ can be obtained by sweeping through different values of b^*, which means when $b(\triangle)$ converges to $\hat{b}^*$, the system throughput is maximized. After that, $\hat{b}^*$ is utilized as the throughput optimal target BLER for spatial layer selection.

  Let $T_k^{(1)}(\hat{b}^*)$ and $T_k^{(2)}(\hat{b}^*)$ denote the system throughput of the k^{th} user for $N_s = 1$ and $N_s = 2$, respectively. The number of transmission spatial layers for user k is selected as:

$$N_s = \begin{cases} 1, & T_k^{(2)}\left(\hat{b}^*\right) > T_k^{(1)}\left(\hat{b}^*\right), \qquad (14) \\ 2, & \text{otherwise.} \qquad (14') \end{cases}$$

After the above-mentioned procedure, eNB transmits the desired signals for totally K UEs in the preferred transmission spatial layers derived in each TTI. To verify the efficacy of our proposed CQI adjustment scheme for spatial layer selection and accurate RI selection algorithm, the simulation results are presented in the following section.

5 SIMULATION RESULTS AND DISCUSSIONS

We evaluate the performance of the optimization selection schemes for transmission spatial layers using a LTE system level simulator, and compare with no optimization scenarios. The channel modeling parameters, including fast fading, shadow fading and path loss models are set based on ITU channel model [8, 17]. To verify the efficacy of our optimization algorithm for spatial layer selection in both outdoor and indoor environment, we consider two evaluation scenarios: Indoor Hotspot (InH) and Rural Macro (RMa) models. All the simulation parameters, including transmit power, topology of the two evaluation scenarios, etc., are set based on [8] and partly presented in Table 1 and Table 2, respectively. Monte Carlo simulation is performed for each subframe and iterated over the total of 1 000 subframes.

Parameter	Value
Inter-cell distance	1 732 m
System bandwidth	10 MHz
Number of available RBs	50
Total eNB Tx power	46 dBm
Number of eNBs/sectors	$19/19*3$
Distribution of UEs served by eNB	randomly
Minimum separation UE to eNB	35 m
Receive method	MMSE

Table 1. Simulation parameters of InH model

Parameter	Value
Inter-cell distance	60 m
System bandwidth	20 MHz
Number of available RBs	100
Total eNB Tx power	21 dBm
Number of eNBs/sectors	$2/2*1$
Distribution of UEs served by eNB	randomly
Minimum separation UE to eNB	3 m
Receive method	MMSE

Table 2. Simulation parameters of RMa model

The number of UEs distributed per sector is set by $K = 10$ in the region of each eNB. Full buffer traffic model is utilized and UEs are scheduled by the channel aware proportionally fair (PF) algorithm. Using the accurate RI calculation algorithm, we derive that in case the values of both $g_1^{(2)}$ and $g_2^{(2)}$ are lower than $-8\,\mathrm{dB}$, $N_R = 1$ is set to be constant in LTE systems. In case the values of both $g_1^{(2)}$ and $g_2^{(2)}$ are higher than $25dB$, $N_R = 2$ is selected accordingly.

Table 3 and Table 4 compare the achieved BLER using the CQI adjustment for spatial layer selection in InH and RMa scenarios, respectively, where the target BLER varies from 2 % to 20 %. The spectral efficiency is defined as the sum of average throughput per unit bandwidth per second supported by a cell's eNB [8]. According to [14], for simplicity and without loss of generality, we only need to analyses statistical data of one UE.

Target BLER	Achieved BLER	Spectral Efficiency
2 %	3.44 %	3.03219
5 %	6.38 %	3.100385
10 %	11.23 %	2.984931
15 %	16.16 %	2.801933
20 %	21.07 %	2.651841

Table 3. The achieved BLER and spectral efficiency for InH scenarios

Target BLER	Achieved BlER	Spectral Efficiency
2 %	3.64 %	1.124
5 %	6.53 %	1.185
10 %	11.15 %	1.375
15 %	16.77 %	1.223
20 %	22.07 %	1.143

Table 4. The achieved BLER and spectral efficiency for RMa scenarios

From Table 3 and Table 4, we can observe that the optimal target BLER $\hat{b}^*$ is 5 % in InH scenarios and 10 % in RMa scenarios, respectively.

For InH scenarios, the downlink spectral efficiency performance of the optimization selection schemes for transmission spatial layers is evaluated by comparing with no optimization scenarios in Figure 2. In the baseline scheme, no optimization scheme is utilized to solve the unreliable RI measurement and feedback problem. In case the period interval of RI feedback is $1ms$, only the feedback delay is taken into consideration. It is observed that using the CQI adjustment scheme for spatial layer selection, the downlink average spectral efficiency is improved significantly; and compared with the baseline scheme, the system performance is better via using the accurate RI selection algorithm.

In Figure 3, the comparisons are illustrated among the optimization schemes and no optimization scheme for RMa scenarios. Intuitively, the performance improvement is more significant than InH scenarios. It is observed that using CQI

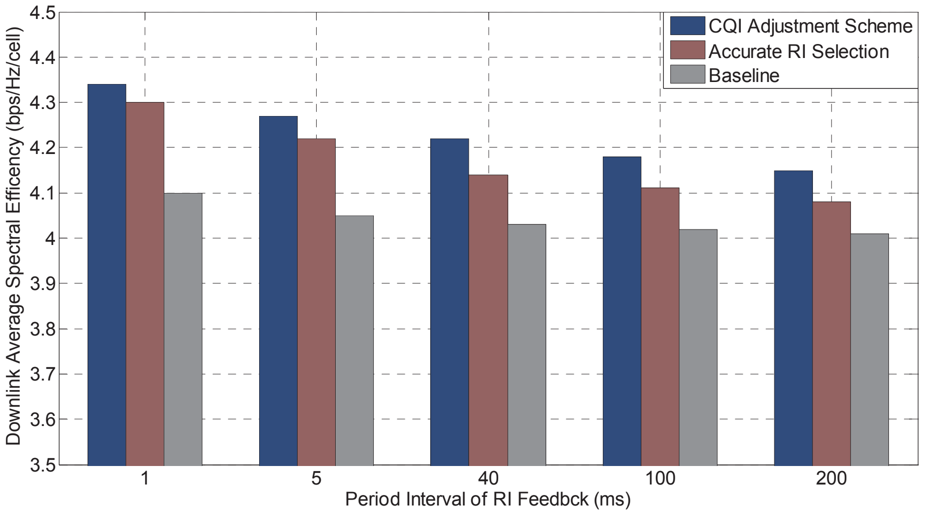

Figure 2. Downlink average spectral efficiency for InH scenarios

adjustment scheme for spatial layer selection, the downlink average spectral efficiency is about 20 % higher than baseline scheme, and 5 % higher than the accurate RI selection algorithm. Using the RI selection algorithm at UE side, the average spectral efficiency performance is improved by 10 %–15 % with respect to the different RI feedback intervals.

Therefore, the CQI adjustment scheme for transmission spatial layer selection is effective to improve system performance, and the accurate RI selection algorithm can be implemented at UE side effectively.

6 CONCLUSION

In this paper, we investigate the optimization of transmission spatial layer selection with unreliable RI in downlink LTE systems. Considering the BLERs for different spatial layers, we firstly propose ATC algorithm which can be utilized at UE side as well as at eNB side. Secondly, based on ATC algorithm, we propose an accurate RI selection algorithm to choose the preferred number of transmission spatial layers at UE side, where the corresponding RI is reported to eNB. Thirdly, we adapt transmission to achieve the throughput optimal target BLER by adjusting channel quality indicator (CQI) based on ACK/NACK history at eNB side. By substituting the derived BLER into ATC algorithm, the optimal number of transmitted spatial layers in current downlink channel is derived at eNB side. Simulation results show the accuracy of the proposed CQI adjustment scheme for transmission spatial layer and RI selection algorithm in LTE systems.

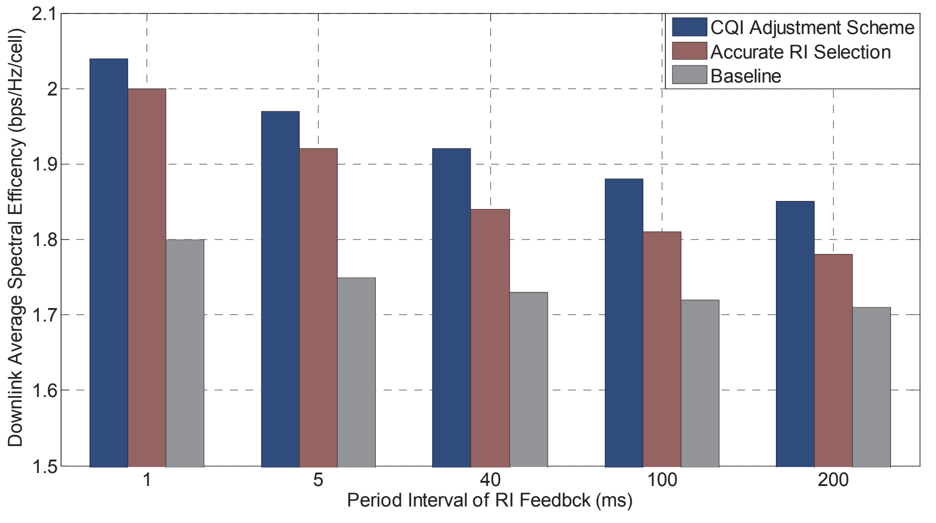

Figure 3. Downlink average spectral efficiency for RMa scenarios

A PROOF OF PROPOSITION 1

For simplicity and without loss of generality, we only consider a single cell distributed in OFDM-MIMO systems. Let $H \in \mathbb{C}^{N_r \times N_t}$ denote the channel from the eNB to UE. The subcarrier specified MIMO channel capacity of each RB is given by [18]:

$$T = \log_2 det\left(I + \frac{P}{n} H H^H\right), \tag{15}$$

where $(\cdot)^H$ denotes the conjugate transposition. P and n are signal and noise power, respectively. Denote $\gamma = \frac{P}{n}$, and assume that eNB allocates transmission power uniformly over all transmission spatial layers. Consequently, in case the number of spatial layers is two, Equation (17) can be deduced as:

$$T\left(g_1^{(2)}, g_2^{(2)}\right) = \sum_{i=1}^{2} \log_2\left(1 + \frac{\gamma}{N_{min}} \lambda_i\right), \tag{16}$$

where $\lambda_1 := \max\{\lambda_i\}, \lambda_2 := \min\{\lambda_i\}$, and $N_{min} := \min(N_t, N_r)$. We suppose that the channel gain for the first and second spatial layer is λ_1 and λ_2, respectively, which further implies that $g_1^{(2)} = \frac{\gamma}{2}\lambda_1$ and $g_2^{(2)} = \frac{\gamma}{2}\lambda_2$.

Otherwise, in case the number of spatial layers is one, Equation (17) can be deduced as:

$$T\left(g_1^{(1)}\right) = \log_2(1 + \gamma\lambda_1), \tag{17}$$

where the transmit power of the second spatial layer is set to 0, which further implies that $g_1^{(1)} = \gamma\lambda_1$.

According to [19], the differences between $T(g_1^{(2)}, g_2^{(2)})$ and $T(g_1^{(1)})$ are determined by the system channel correlation degree. The relative condition number of HH^H is exploited to quantify the channel correlation degree in [18] and can be expressed as:

$$\mathcal{K} = \frac{\lambda_1}{\lambda_2}. \tag{18}$$

In case the number of spatial layers is two, denote $\mathcal{E} = det(HH^H)$, which further implies $\mathcal{E} = \lambda_1 \cdot \lambda_2$. Compared with the case that the number of spatial layers is one, the MIMO channel capacity gain can be written as:

$$\begin{aligned} \Omega &= T\left(g_1^{(2)}, g_2^{(2)}\right) - T\left(g_1^{(1)}\right) \\ &= \sum_{i=1}^{2} \log_2\left(1 + \frac{\gamma}{2}\lambda_i\right) - \log_2(1 + \gamma\lambda_1). \end{aligned} \tag{19}$$

From Equation (19), denote $\mathcal{E} = \lambda_1 \cdot \lambda_2$; the derivative of Ω with respect to λ_1 can be given as follows:

$$\frac{\partial\Omega}{\partial\lambda_1} = -\frac{\left(\frac{2\mathcal{E}}{\lambda_1^2\gamma} + \frac{2\mathcal{E}}{\lambda_1\gamma} + \frac{2\mathcal{E}}{\lambda_1} + \gamma\mathcal{E} + \frac{2}{\gamma}\right)}{(1+\gamma\lambda_1)\left(1 + \frac{\gamma\mathcal{E}}{2\lambda}\right)\left(1 + \frac{\gamma\lambda_1}{2}\right)}. \tag{20}$$

Intuitively, $\frac{\partial\Omega}{\partial\lambda_1} < 0$. We can derive that $\mathcal{K} = \frac{\lambda_1^2}{\mathcal{E}}$ from (18), thus Ω is a monotonically decreasing function with respect to $\mathcal{K}$. After mathematical deduction, (19) can be simplified as:

$$\Omega(\lambda_1) = \frac{\gamma^2\mathcal{E}}{4} + \frac{\gamma}{2}\left(\frac{\mathcal{E}}{\lambda_1} - \lambda_1\right). \tag{21}$$

Letting $\Omega(\lambda_1) = 0$, we have

$$\begin{aligned} \mathcal{K}_{th} &= \frac{\gamma^2}{8}\mathcal{E} + \frac{\gamma}{4}\sqrt{\frac{\gamma^2}{4}\mathcal{E}^2 + 4\mathcal{E}} + 1 \\ &= \frac{g_1^{(2)}g_2^{(2)}}{2} + \sqrt{\frac{g_1^{(2)}g_2^{(2)}}{2} + g_1^{(2)}g_2^{(2)}} + 1, \end{aligned} \tag{22}$$

where $\mathcal{K}_{th}$ denotes the threshold of relative condition number. From Equations (5) and (5'), in case $\mathcal{K} > \mathcal{K}_{th}$, $\Omega(\lambda_1) < 0$ and $N_R = 1$. Otherwise $\Omega(\lambda_1) > 0$ and $N_R = 2$.

In case $g_1^{(2)} \to 0$ and $g_2^{(2)} \to 0$, which further implies $g_1^{(1)} \to 0$, the value of K_{th} approximates to 1 according to (22). From (18), it follows that $\mathcal{K} > 1$, and this further implies that $\Omega < 0$, $N_R = 1$.

In case the values of $g_1^{(2)}$, $g_2^{(2)}$ and $g_1^{(1)}$ are in high regime, the value of $\mathcal{K}_{th}$ is large intuitively, leading to a smaller probability of the condition that $\mathcal{K} > \mathcal{K}_{th}$. This further implies that $\Omega > 0$ and $N_R = 2$.

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REFERENCES

[1] Zyren, J.—McCoy, W.: Overview of the 3GPP Long Term Evolution Physical Layer. Freescale Semiconductor, Inc., white paper, 2007.

[2] 3GPP TS 36.213, Physical Layer Procedures for E-UTRA. v9.1.0, May 2010; `ftp://ftp.3gpp.org`.

[3] 3GPP TS 36.211, Physical Channels and Modulation for E-UTRA. v9.1.0, March 2010; `ftp://ftp.3gpp.org`.

[4] Zarakovitis, C.—Ni, Q.—Skordoulis, D.—Hadjinicolaou, M.: Power-Efficient Cross-Layer Design for OFDMA Systems with Heterogeneous QoS, Imperfect CSI and Outage Considerations. IEEE Transactions on Vehicular Technology, 2011, No. 99, pp. 1.

[5] Bai, Z.—Spiegel, C.—Bruck, G.—Jung, P.—Horvat, M.—Berkmann, J.—Drewes, C.—Gunzelmann, B.: On the Physical Layer Performance with Rank Indicator Selection in LTE/LTE-Advanced System. In Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops) 2010, pp. 393–398.

[6] Schwarz, S.—Mehlfuhrer, C.—Rupp, M.: Calculation of the Spatial Preprocessing and Link Adaption Feedback for 3GPP UMTS/LTE. 6^{th} Conference on Wireless Advanced (WiAD) 2010, pp. 1–6.

[7] Schwarz, S.—Wrulich, M.—Rupp, M.: Mutual Information Based Calculation of the Precoding Matrix Indicator for 3GPP UMTS/LTE. International ITG Workshop on Smart Antennas (WSA) 2010, pp. 52–58.

[8] ITU-R Rep. M.2135, Guidelines for evaluation of radio interface technologies for IMT-Advanced, July 2009.

[9] Cheng, P.—Tao, M.—Zhang, W.: A New SLNR-Based Linear Precoding for Downlink Multi-User Multi-Stream MIMO Systems. Communications Letters, Vol. 14, 2010, No. 11, pp. 1008–1010.

[10] 3GPP TS 36.101, User Equipment (UE) Radio Transmission and Reception for E-UTRA. v9.10.0, Jan. 2012; `ftp://ftp.3gpp.org`.

[11] Foschini, G.—Gans, M.: On limits of Wireless Communications in a Fading Environment when Using Multiple Antennas. Wireless personal communications, Vol. 6, 1998, No. 3, pp. 311–335.

[12] Zheng, H.—Viswanathan, H.: Optimizing the ARQ Performance in Downlink Packet Data Systems With Scheduling. IEEE Transactions on Wireless Communications, Vol. 4, 2005, No. 2, pp. 495–506.

[13] Sawahashi, M.—Kishiyama, Y.—Morimoto, A.—Nishikawa, D.—Tanno, M.: Coordinated Multipoint Transmission/Reception Techniques for LTE-

Advanced [Coordinated and Distributed MIMO]. IEEE Wireless Communications, Vol. 17, 2010, No. 3, pp. 26–34.

[14] Cui, T.—Lu, F.—Sethuraman, V.—Goteti, A.—Rao, S.—Subrahmanya, P.: Throughput Optimization in High Speed Downlink Packet Access (HSDPA). IEEE Transactions on Wireless Communications, Vol. 10, 2011, No. 2, pp. 474–483.

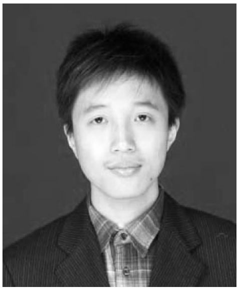
[15] Kushner, H.—Yin, G.: Stochastic Approximation and Recursive Algorithms and Applications. Springer Verlag 2003.

[16] Billingsley, P.: Convergence of Probability Measures. New York 1968.

[17] Dahlman, E.: 3G Evolution: HSPA and LTE for Mobile Broadband. Academic Press 2008.

[18] Tse, D.—Viswanath, P.: Fundamentals of Wireless Communication. Cambridge University Press 2005.

[19] Yu, J.—Lin, F.—Teng, Y.—Yue, G.: MIMO-OFDM Transmission Adaptation Using Rank. 18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications 2007, pp. 1–5.



Weidong Zhang received the B. Sc. degree in telecommunication engineering from Beijing University of Posts and Telecommunications (BUPT) in 2008. Now he is working toward his Ph.D. degree in the field of telecommunication and information systems at Wireless Technology Innovation Institute, BUPT. His research interests include femtocell technology, MIMO and dynamic radio resource management in future wireless networks.

Ying Wang received the B. Sc. and M. Sc. degrees in electronics engineering from Northwest Polytechnical University in 1998 and 2000, respectively, and her Ph. D. in circuits and systems from Beijing University of Posts and Telecommunications (BUPT) in 2003. Now she is a Professor at BUPT and a researcher at Wireless Technology Innovation Institute. Her research interests are in the area of the cooperative relaying system, radio resource management and mobility management in the beyond 3G and 3G systems.

Mingyue Xu received the B. Sc. degree in telecommunication engineering from Beijing University of Posts and Telecommunications (BUPT) in 2010. Now she is working in the field of telecommunication and information systems at Wireless Technology Innovation Institute, BUPT. Her research interests include relay technology, MIMO and cognitive radio systems.

Cong Shi received the B. Sc. degree in electronic engineering from Xidian University, China, in 2008. Now he is working toward his Ph. D. degree in the field of telecommunication and information systems at Wireless Technology Innovation Institute, Beijing University of Posts and Telecommunications (BUPT). His research interests include MIMO-OFDM techniques and dynamic resource allocation in future wireless networks.

Ping Zhang received the M. Sc. degree from Northwest Polytechnic University, Xian, China, in 1986 and the Ph. D. degree from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 1990, both in electrical engineering. From 1994 to 1995, he was a post-doctoral researcher in the PCS Department, Korea Telecom Wireless Systems Development Center. Now he is a Professor at BUPT, the Director of Wireless Technology Innovation Institute, member of China 3G and B3G group. His research interests cover key techniques of B3G and 3G systems, including MIMO-OFDM, radio resource management and cognitive radio.