SER Analysis of Scheduled TAS With MRC in the Presence of Non-Identical Channel Estimation Errors

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***Abstract*—In this letter, we present a performance analysis of scheduled transmit antenna selection with maximal ratio combining (TAS-MRC) in the presence of non-identical channel estimation errors. This letter derives the probability density function (PDF) of the instantaneous effective signal-to-noise ratio for the scheduled TAS-MRC over Rayleigh fading channels with non-identical channel estimation errors. Using this PDF, we derive exact closed-form expressions for the scheduled TAS-MRC symbol error rate in the presence of non-identical channel estimation errors. The analysis results show that the order of diversity of scheduled TAS-MRC is improved in terms of transmit spatial diversity and multiuser diversity, whereas the received diversity is diminished by non-identical channel estimation errors, regardless of the modulation type.**

***Index Terms*—Multiple-input multiple-output (MIMO), transmit antenna selection (TAS), user scheduling, non-identical channel estimation error, spatial diversity, multiuser diversity (MUD).**

I. Introduction

THE PROMISE shown by diversity technologies has led methods like transmit antenna selection (TAS), maximal ratio combining (MRC), and user scheduling methods to be widely investigated for future wireless communication systems.

TAS with MRC [1]–[6] can improve the transmit and receive spatial diversity; the MRC described in [7] is the optimal linear combining technique. User scheduling [8] also improves multiuser diversity (MUD). Thus, scheduled TAS with MRC, which combines TAS, MRC, and user scheduling, has been investigated. Several studies [9]–[12] analyzed the performance of a scheduled TAS with MRC that selects the user terminal and transmit antenna via feedback information from each user terminal. These previous studies derived an exact and tight closed-form expression for the symbol error rate (SER) under scheduled TAS with MRC, and both the outage capacity and outage probability over Rayleigh fading channels.

Because perfect channel estimation is impractical, channel estimation errors occur, meaning that the feedback information contains incorrect instantaneous effective signal-to-noise ratio (SNR) values. Additionally, because different channel estimation performance is provided to all user terminals in heterogeneous networks, the user terminals have non-identical channel estimation errors. Unfortunately, the previous studies [9]–[12] paid little attention to non-identical channel estimation errors in the scheduled TAS-MRC system. Thus, this letter presents scheduled TAS-MRC with non-identical channel estimation errors in heterogeneous networks.

The first contribution of this letter is the derivation of the probability density function (PDF) of the instantaneous effective SNR for the scheduled TAS-MRC with non-identical channel estimation errors over Rayleigh fading channels. Using the PDF, we derive exact SER expressions under scheduled TAS-MRC for both M-ary QAM and PSK modulations over Rayleigh fading channels. Through asymptotic analysis, we then quantify the order of diversity of the scheduled TAS-MRC in the presence of non-identical channel estimation errors. The results of this letter provide the insight that the receive diversity order is diminished in the scheduled TAS-MRC under non-identical channel estimation errors. This order reduction occurs because the MRC weighing matrix is not optimal for non-identical channel estimation errors.

II. System Overview

This letter presents a scheduled TAS-MRC system. The user terminal provides the maximum instantaneous effective SNR from the transmit antenna index to the base station via feedback channels. The base station selects the user with the maximum instantaneous effective SNR, and transmits data to the selected user through the single transmit antenna indicated by the user terminal. As perfect channel estimation is impractical, the receiver at the user terminal introduces some channel estimation error; then, the feedback information contains the incorrect instantaneous effective SNR value for the transmit antenna index. Additionally, because each user terminal has different channel estimation performance in heterogeneous networks, the user terminals have non-identical channel estimation errors. Thus, we consider the scheduled TAS-MRC in the presence of non-identical channel estimation errors for heterogeneous networks. We present a downlink multiple-input multiple-output (MIMO) system in which a base station is equipped with M_{T} transmit antennas and K user terminals (which are equipped with M_{R} receive antennas). This study assumes Rayleigh fading channels and very slowly varying channels.

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When the user terminals use MRC and have different channel estimation error performance, the instantaneous effective SNR of the MRC receiver can be expressed as

$$\gamma_{\mathrm{MRC}} = \gamma_0 x_{\max}, \quad x_{\max} := \max_r(x_1, x_2, \ldots, x_{\mathrm{r}}, \ldots, x_{x_{\mathrm{KM_T}}}) \tag{1}$$

where γ_0 denotes the SNR and x has the following distribution (because we assume a Gaussian distributed channel estimation error [13])

$$f(x) = \sum_{m=1}^{M_{\mathrm{R}}} \frac{C_{m-1}^{M_{\mathrm{R}}-1}(\rho^2)}{\Gamma(m)} x^{m-1} e^{-x} \tag{2}$$

and

$$F(x) = \sum_{m=1}^{M_{\mathrm{R}}} C_{m-1}^{M_{\mathrm{R}}-1}(\rho^2)\left(1 - e^{-x}\sum_{n=0}^{m-1}\frac{x^n}{n!}\right) \tag{3}$$

where $\Gamma(\cdot)$ is the gamma function, $C_i^n(t) := \binom{n}{i} t^i (1-t)^{n-i}$ are Bernstein polynomials, and ρ is the channel correlation coefficient ($0 \le \rho \le 1$), as defined in [13].

III. Symbol Error Rate Analysis

This letter presents a method for deriving the exact PDF of the scheduled TAS-MRC in the presence of non-identical channel estimation errors. Using the distribution, we derive exact closed-form expressions for the SER with M-ary QAM and PSK modulations. Through asymptotic analysis, we quantify the order of diversity of the scheduled TAS-MRC with non-identical channel estimation errors.

A. Probability Density Function

Using the order statistics in [14], [15], the effective SNR x_{sch} of the scheduled TAS-MRC over non-identically distributed channel estimation errors is obtained by

$$f_{\mathrm{sch}}(x) = \frac{1}{(KM_{\mathrm{T}}-1)!} \times \sum^{KM_{\mathrm{T}}} F_{i_1}(x)\ldots F_{i_r}(x)\ldots F_{i_{KM_{\mathrm{T}}-1}}(x) f_{i_{KM_{\mathrm{T}}}}(x) \tag{4}$$

where $\sum^{KM_{\mathrm{T}}}$ denotes the sum of all $KM_{\mathrm{T}}!$ permutations $(i_1, i_2, \ldots, i_{KM_{\mathrm{T}}})$ from $(1, 2, \ldots, KM_{\mathrm{T}})$.

Lemma 1: The PDF of the scheduled TAS-MRC in the presence of non-identical channel estimation errors is given by

$$\begin{aligned} f_{\mathrm{sch}}(x) &= \frac{1}{(KM_{\mathrm{T}}-1)!}\sum^{KM_{\mathrm{T}}}\sum_M\sum_P\sum_N \\ &\times \sum_{m_{i_{KM_{\mathrm{T}}}}=1}^{\mathrm{M_R}} \prod_{r=1}^{KM_{\mathrm{T}}-1}\left[\frac{\binom{\mathrm{M_R}-1}{m_{i_r}-1}\rho_{i_r}^{2\,m_{i_r}-1}(1-\rho_{i_r}^2)^{\mathrm{M_R}-m_{i_r}}}{n_{i_r}!}\right](-1)^c \\ &\times \frac{\binom{\mathrm{M_R}-1}{m_{i_{KM_{\mathrm{T}}}}-1}\left(\rho^2_{i_{KM_{\mathrm{T}}}-1}\right)^{m_{i_{KM_{\mathrm{T}}}}-1}\left(1-\rho^2_{i_{KM_{\mathrm{T}}}-1}\right)^{\mathrm{M_R}-m_{i_{KM_{\mathrm{T}}}}}}{(m_{i_{KM_{\mathrm{T}}}}-1)!} \\ &\times e^{-(1+c)x} x^{d+m_{i_{KM_{\mathrm{T}}}}-1} \end{aligned} \tag{5}$$

where $\sum_M$, $\sum_P$, and $\sum_N$ denote $(KM_{\mathrm{T}}$-1)-fold summations and $c = \sum_{r=1}^{KM_{\mathrm{T}}-1} p_{i_r}$, $d = \sum_{r=1}^{KM_{\mathrm{T}}-1} n_{i_r}$.

Proof: After converting Eq. (3) into a compact form, we obtain

$$F(x) = \sum_{m=1}^{M_{\mathrm{R}}}\sum_{p=0}^{1}\sum_{n=0}^{p(m-1)} C_{m-1}^{M_{\mathrm{R}}-1}(\rho^2)(-1)^p e^{-px}\frac{x^n}{n!}, \tag{6}$$

Eq. (5) is derived by substituting Eq. (2) and the compact equation in Eq. (6) into Eq. (4). ■

B. SER for M-ary QAM

The SER for M-ary QAM, denoted by $P_{\mathrm{M-QAM}}(\gamma_0)$, is given by [16], [17]

$$P_{\mathrm{M-QAM}}(\gamma_0) = 1 - \left(1 - P_{\sqrt{\mathrm{M}}-\mathrm{PAM}}(\gamma_0)\right)^2 \tag{7}$$

where $P_{\sqrt{\mathrm{M}}-\mathrm{PAM}}(\gamma_0)$ is the SER of $\sqrt{\mathrm{M}}$-ary pulse-amplitude modulation (PAM). When the conditional SER of $P_{\sqrt{M}-PAM}(\gamma)$ is given by

$$P_{\sqrt{\mathrm{M}}-\mathrm{PAM}}(x) = \zeta Q\left(\sqrt{\eta\gamma_0 x}\right), \tag{8}$$

where $\zeta = 2(1-\frac{1}{\sqrt{\mathrm{M}}})$, $\eta = \frac{3}{\mathrm{M}-1}$, and $Q(\cdot)$ denotes the Q function, the SER of the scheduled TAS-MRC with non-identical channel estimation errors for $\sqrt{\mathrm{M}}$-ary PAM is given by

$$P_{\sqrt{\mathrm{M}}-\mathrm{PAM}}(\gamma_0) = \int_0^\infty P_{\sqrt{\mathrm{M}}-PAM}(x) f_{\mathrm{sch}}(x)dx. \tag{9}$$

Lemma 2: The exact closed-form expression of SER for $\sqrt{\mathrm{M}}$-ary PAM $P_{\sqrt{\mathrm{M}}-\mathrm{PAM}}(\gamma_0)$ is given by

$$\begin{aligned} P_{\sqrt{\mathrm{M}}-\mathrm{PAM}}(\gamma_0) &= \frac{\zeta}{2(KM_{\mathrm{T}}-1)!}\sum^{KM_{\mathrm{T}}}\sum_M\sum_P\sum_N \\ &\times \sum_{m_{i_{KM_{\mathrm{T}}}}=1}^{\mathrm{M_R}} \prod_{r=1}^{KM_{\mathrm{T}}-1}\left[\frac{\binom{\mathrm{M_R}-1}{m_{i_r}-1}\rho_{i_r}^{2\,m_{i_r}-1}(1-\rho_{i_r}^2)^{\mathrm{M_R}-m_{i_r}}}{n_{i_r}!}\right](-1)^c \\ &\times \frac{\binom{\mathrm{M_R}-1}{m_{i_{KM_{\mathrm{T}}}}-1}\left(\rho^2_{i_{KM_{\mathrm{T}}}-1}\right)^{m_{i_{KM_{\mathrm{T}}}}-1}\left(1-\rho^2_{i_{KM_{\mathrm{T}}}-1}\right)^{\mathrm{M_R}-m_{i_{KM_{\mathrm{T}}}}}}{(m_{i_{KM_{\mathrm{T}}}}-1)!} \\ &\times \frac{1}{(1+c)^{d+m_{i_{KM_{\mathrm{T}}}}}}(d+m_{i_{KM_{\mathrm{T}}}}-1)! \\ &\times \left[1 - \sum_{k=0}^{d+m_{i_{KM_{\mathrm{T}}}}-1}\mu\left(\frac{1-\mu^2}{4}\right)^k\binom{2k}{k}\right] \end{aligned} \tag{10}$$

where $\mu = \sqrt{\frac{\eta\gamma_0}{\eta\gamma_0+2(c+1)}}$.

Proof: Eq. (10) is derived from Eq. (8), Eq. (9), and integration by parts as shown in [16].

By substituting Eq. (10) into Eq. (7), the exact SER closed-form expression of the scheduled TAS-MRC with M-ary QAM, denoted by $P_{\mathrm{M-QAM}}(\gamma_0)$, can be derived over the Rayleigh fading channels in the presence of non-identical channel estimation errors.

As γ_0 approaches infinity (i.e., $\gamma_0 \rightarrow \infty$), Eq. (2) is dominant at $m = 1$. Then, the distribution of the MRC receiver with channel estimation errors is approximated as

$$f(x) \approx (1-\rho^2)^{\mathrm{M_R}-1} \tag{11}$$

and

$$F(x) \approx (1-\rho^2)^{\mathrm{M_R}-1} x. \tag{12}$$

Using the order statistics in [14], [15], the PDF of the received SNR for the scheduled TAS-MRC in the presence of non-identical channel estimation errors for $\rho_r^2 < 1$ can be approximated as follows:

$$f_{\mathrm{sch}}(x) \approx K \prod_{r=1}^{K\mathrm{M_T}} (1-\rho_r^2)^{\mathrm{M_R}-1} x^{K\mathrm{M_T}-1}. \tag{13}$$

Lemma 3: $P_{\mathrm{M-QAM}}(\gamma_0)$ of the scheduled TAS-MRC with non-identical channel estimation errors for $\rho_k^2 < 1$ is approximated by

$$P_{\mathrm{M-QAM}}(\gamma_0) \approx \zeta 2^{K\mathrm{M_T}} \prod_{r=1}^{K\mathrm{M_T}} \left[(1-\rho_r^2)^{\mathrm{M_R}-1}\right] \times \frac{\Gamma(K\mathrm{M_T}+0.5)}{\sqrt{\pi}} (\eta\gamma_0)^{-K\mathrm{M_T}}. \tag{14}$$

Proof: As $P_{\mathrm{M-QAM}}(\gamma_0) \approx 2P_{\sqrt{\mathrm{M}}-\mathrm{PAM}}(\gamma_0)$ at high SNRs, Eq. (14) is derived using Eq. (13) and the integration in [18].

C. SER for M-ary PSK

The exact SER of the scheduled TAS-MRC for M-ary PSK with non-identical channel estimation errors over Rayleigh fading channels is given by

$$P_{\mathrm{M-PSK}}(\gamma_0) = \int_0^\infty \frac{1}{\pi} \int_0^{(\mathrm{M}-1)\pi/\mathrm{M}} e^{-\kappa\gamma_0 x} d\theta f_{\mathrm{sch}}(x) dx \tag{15}$$

where $\kappa = sin^2(\pi/\mathrm{M})/\sin^2(\theta)$.

Lemma 4: The exact SER closed-form expression of the scheduled TAS-MRC with M-ary PSK under non-identical channel estimation errors is given by

$$\begin{aligned} P_{\mathrm{M-PSK}}(\gamma_0) &= \frac{\zeta}{2(K\mathrm{M_T}-1)!} \sum^{K\mathrm{M_T}} \sum_{M} \sum_{P} \sum_{N} \\ &\times \sum_{m_{i_{K\mathrm{M_T}}}=1}^{\mathrm{M_R}} \prod_{r=1}^{K\mathrm{M_T}-1} \left[\frac{\binom{\mathrm{M_R}-1}{m_{i_r}-1} \rho_{i_r}^{2\, m_{i_r}-1} (1-\rho_{i_r}^2)^{\mathrm{M_R}-m_{i_r}}}{n_{i_r}!} \right] (-1)^c \\ &\times \frac{\binom{\mathrm{M_R}-1}{m_{i_{K\mathrm{M_T}}}-1} \left(\rho_{i_{K\mathrm{M_T}-1}}^2\right)^{m_{i_{K\mathrm{M_T}}}-1} (1-\rho_{i_{K\mathrm{M_T}-1}}^2)^{\mathrm{M_R}-m_{i_{K\mathrm{M_T}}}}}{(m_{i_{K\mathrm{M_T}}}-1)!} \\ &\times \frac{1}{(1+c)^{d+m_{i_{K\mathrm{M_T}}}}} (d+m_{i_{K\mathrm{M_T}}}-1)! \\ &\times C\left(a_1 = \frac{sin^2\frac{\pi}{M}\gamma_0}{1+c}, a_2 = d+m_{i_{K\mathrm{M_T}}}\right) \end{aligned} \tag{16}$$

where $C(a_1, a_2)$ is defined in [19] (Eq. 5A.17).

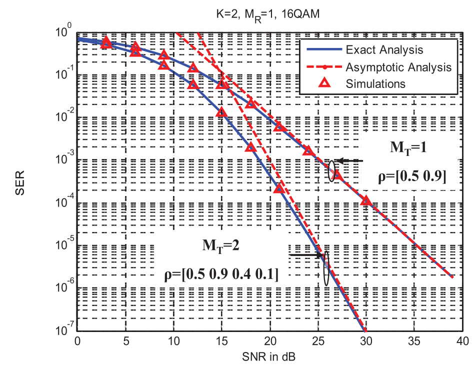

Fig. 1. SER (16QAM) of the scheduled TAS-MRC with non-identical channel estimation errors as a function of $\mathrm{M_T}$.

Proof: Eq. (16) is derived using Eq. (5), Eq. (15), and the Laplace transform in [19].

Lemma 5: The SER with M-ary PSK of the scheduled TAS-MRC for $\rho_k^2 < 1$ at high SNRs is approximated as follows:

$$\begin{aligned} P_{\mathrm{M-PSK}}(\gamma_0) &\approx \int_0^\infty \alpha Q\left(\sqrt{\beta\gamma_0 x}\right) f_{\mathrm{sch}}(x) dx \\ &\approx \alpha 2^{K\mathrm{M_T}-1} \prod_{r=1}^{K\mathrm{M_T}} \left[(1-\rho_r^2)^{\mathrm{M_R}-1}\right] \\ &\times \frac{\Gamma(K\mathrm{M_T}+0.5)}{\sqrt{\pi}} (\beta\gamma_0)^{-K\mathrm{M_T}}. \end{aligned} \tag{17}$$

Proof: Similar to QAM modulation, Eq. (17) is derived using the approximate PDF of Eq. (13) and [18].

From Eq. (14) and Eq. (17), we know that the diversity order of the scheduled TAS-MRC in the presence of non-identical channel estimation errors reduces to $K\mathrm{M_T}$, regardless of modulation type, while having the full diversity order of $K\mathrm{M_T}\mathrm{M_R}$ for perfect channel estimation, as shown in [9], [10]. The receive diversity is obtained using MRC at the receiver. The weighting matrix of MRC is the complex conjugate of the channel matrix, which is the optimal linear combining method [7]. However, by applying the weighing matrix with non-identical channel estimation errors, the weighing matrix is not optimal, which reduces the receive diversity order, regardless of modulation type.

IV. Numerical Results and Discussion

In this section, we present numerical SER results for the scheduled TAS-MRC with non-identical channel estimation errors.

Fig. 1 shows the exact SER analysis of the scheduled TAS-MRC with non-identical channel estimation errors as a function of the number of transmit antennas $\mathrm{M_T}$. The SER improves as $\mathrm{M_T}$ increases. Thus, the SER for $\mathrm{M_T} = 2$ provides better performance than that for $\mathrm{M_T} = 1$. The results show that the transmit spatial diversity by TAS improves the SER performance of the scheduled TAS-MCR in the presence of non-identical channel estimation errors.

Fig. 2 shows the exact SER analysis of the scheduled TAS-MRC with non-identical channel estimation errors as a function of the number of user terminals K. The SER improves as K increases. Thus, the SER for $K = 2$ provides better

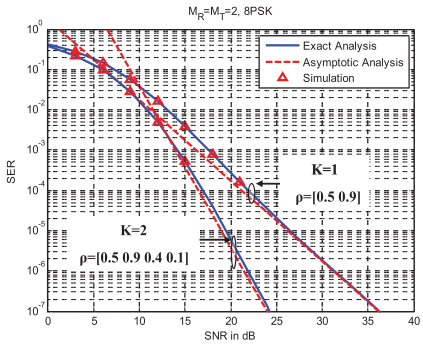

Fig. 2. SER (8PSK) of the scheduled TAS-MRC with non-identical channel estimation errors as a function of K.

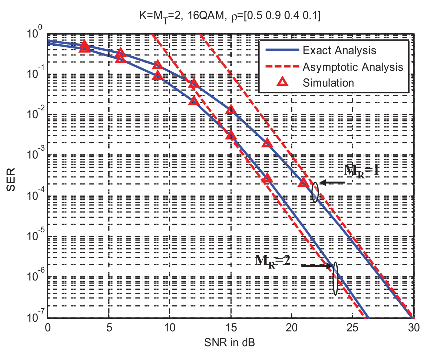

Fig. 3. SER (16QAM) of the scheduled TAS-MRC with non-identical channel estimation errors as a function of $\mathrm{M_R}$.

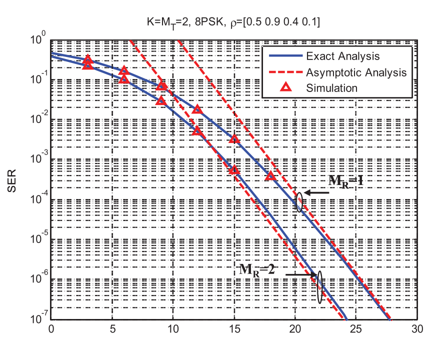

Fig. 4. SER (8PSK) of the scheduled TAS-MRC with non-identical channel estimation errors as a function of $\mathrm{M_R}$.

performance than that for $K = 1$, because the selected user has a higher instantaneous effective SNR in proportion to the number of users. This is the MUD phenomenon. From the results, we can see that MUD as a result of user scheduling improves the SER performance of the scheduled TAS-MCR in the presence of non-identical channel estimation errors.

Fig. 3 and Fig. 4 show the exact SER analysis of the scheduled TAS-MRC with non-identical channel estimation errors as a function of the number of receive antennas $\mathrm{M_R}$. The SER improves as $\mathrm{M_R}$ increases; the diversity order remains constant, regardless of $\mathrm{M_R}$. This performance gain is a result of the SNR gain given by MRC. Thus, the SER with $\mathrm{M_R} = 2$ provides better performance than that with $\mathrm{M_R} = 1$. From the results, we can see that the increase in diversity order by MRC is diminished by the non-identical channel estimation errors in the scheduled TAS-MRC.

V. Conclusions

In this letter, we studied the performance of the scheduled TAS-MRC in the presence of non-identical channel estimation errors. We derived the PDF of the instantaneous effective SNR for the scheduled TAS-MRC with non-identical channel estimation errors over Rayleigh fading channels. Using this distribution, we derived exact closed-form expressions for the SER under scheduled TAS-MRC for both QAM and PSK modulations. The analysis results showed that the order of diversity under scheduled TAS-MRC in the presence of non-identical channel estimation errors was reduced to $K\mathrm{M_T}$, regardless of modulation type, and that the perfect channel estimation condition occurred at $K\mathrm{M_T}\mathrm{M_R}$.

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