Sum rate and Energy Efficiency of Massive MIMO Downlink with Channel Aging in Time Varying Ricean Fading Channel

Lihua Yang*, Longxiang Yang, Hongbo Zhu, and Yan Liang
Jiangsu Key Laboratory of Wireless Communication, Nanjing University of Posts and Telecommunications, Nanjing, Jiangsu 210003, China
[e-mail: yanglh@njupt.edu.cn; yanglx@njupt.edu.cn; zhuhb@njupt.edu.cn; liangyan@njupt.edu.cn]
*Corresponding author: Lihua Yang

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Abstract

Achievable sum rate and energy efficiency (EE) are investigated for the massive multiple-input multiple-output (Massive MIMO) downlink with channel aging in the time varying Ricean fading channel. Specifically, the expression of the achievable sum rate of the system for the maximum ratio transmission (MRT) precoder with aged channel state information (CSI) in the time varying Ricean fading channel is first presented. Based on the expression, the effect of both channel aging and the Ricean factor on the power scaling law are studied. It is found that the transmit power of base station (BS) is scaled down by $1/\sqrt{M}$ (where M is the number of the BS antennas) when the Ricean factor K is equal to zero (i.e., time varying Rayleigh fading channel), indicating that aged CSI does not affect the power scaling law. However, the transmit power of the BS is scaled down by $1/M$ for the time varying Ricean fading channel (where $K \neq 0$) indicating that the Ricean factor affects the power scaling law and sum rate, and channel aging only leads to a reduction of the sum rate. Second, the EE of the system is analyzed based on the general power consumption model. Both the theoretical analysis and the simulations show that the channel aging could degrade the sum rate and the EE of the system, and it does not affect the power scaling law.

Keywords: Massive MIMO downlink, channel aging, time varying Ricean fading, sum rate, energy efficiency, power scaling law.

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1. Introduction

MASSIVE multiple-input multiple-output (Massive MIMO) is an emerging technology that can significantly increase capacity and improve energy efficiency by deploying large antennas at the base station (BS) side. It has attracted worldwide attention from both academia and industry and is a promising technique for fifth-generation wireless communication systems [1]-[2]. Moreover, it also will meets futuristic potential applications such as wireless backhaul for small cells (SCs) or interference management in network-assisted D2D communications [3]-[5].

The advantages of Massive MIMO were initially demonstrated by providing the BS with ideal propagation environments. However, to understand the performance of the Massive MIMO system in practice, performance analysis in realistic propagation environments should be given. The effect of various practical propagation environments on the performance of the Massive MIMO system have been studied, including pilot contamination [6]-[7], line-of-sight (LOS) effect [8]-[9], channel estimation error [10], and phase noise drift [11].

There is another important factor affecting the performance of the system, which is the variation in the channel from when it is learned and when it is used for detection or beamforming, i.e., channel aging due to processing delay and the relative movement between the user and the BS. Recently, some research has investigated the effect of channel aging on the performance of the Massive MIMO system [12]-[14]. Reference [12] first discusses the effect of channel aging on both uplink and downlink of Massive MIMO system, and later extends the analysis to the downlink with regularized zero-forcing (ZF) precoding [13] and to the uplink with minimum mean square error (MMSE) receiver [14]. The analytical expressions in [12]-[14] are derived by using the deterministic equivalent approach, which relies on the key assumption of a large system regime, i.e., $M \to \infty$ and $U \to \infty$, where M is the number of the BS antennas and U is the number of users in the cell, so they only serve as accurate approximations. Hence, reference [15] presents simple tight lower bounds on the achievable sum rate and power scaling law for the Massive MIMO system.

However, the most previous works on Massive MIMO system with channel aging [13]-[16] concentrated on the system's sum rate instead of energy efficiency (EE, in bits/Joule), which is defined as the ratio of the sum rate to the total consumption power. Recently, EE has become a significant parameter in designing practical wireless communication systems, and some works have studied the achievable EE of Massive MIMO system [16]-[19]. Reference [16] first gives the analysis of the EE for the Massive MIMO system, while the considered the transmit power neglects the power required for both circuits and signal processing. To formulate a general power consumption model, reference [17] studies the EE of Massive MIMO system in the Rayleigh fading channel model. Later, the EE performance of the Massive MIMO downlink with ZF precoder in the Ricean fading channel is presented to examine the effect of the LOS on the EE of the systems in [18]. However, the analysis of EE in [16]-[18] are all based on the static channel, which cannot be applied to the time varying channel. To solve this problem, the effect of the channel aging caused by channel changes on the EE of the Massive MIMO system with zero-forcing (ZF) precoder is given in [19].

Since the available works on the effect of channel aging on the EE only considered the channel aging in the time varying Rayleigh fading channel, they cannot describe the effect of the channel aging on the EE performance in the time varying Ricean fading channel, which is the channel model of the high-speed railway (HSR) scenarios [20]-[21].

Motivated by the above mentioned aspect, this paper aims to investigate how channel aging influences the downlink sum rate and the EE of the Massive MIMO system in the time varying Ricean fading channel. Our main contributions are outlined as follows:

- The expression of the achievable sum rate of the Massive MIMO downlink system for the maximum ratio transmission (MRT) precoder with channel aging in the time varying Ricean fading channel is derived. Based on the expression, the effect of channel aging and Ricean factor on the sum rate can be efficiently evaluated.
- The effect of both channel aging and Ricean factor on the power scaling law is presented. The findings suggest that the Ricean factor affects the power scaling law and the sum rate, and channel aging only degrades the sum rate. The effect of channel aging on the sum rate can be ignored compared with that of the Ricean factor in the time varying Ricean fading channel.
- The EE for MRT precoder is obtained by using the general power consumption model, and the optimal EE is given by simulation.

The rest of this paper is organized as follows: Section 2 briefly introduces the signal model. Section 3 discusses the achievable downlink sum rate with channel aging for the time varying Ricean fading channel, and section 4 gives the energy efficiency analysis. Section 5 discusses simulation results, and conclusions are given in Section 6.

2. Signal Model

The uplink of a single cell Massive MIMO system is considered, where the BS has M antennas and serves U (U<<M) single antenna users. Assume that the channel is flat fading, and channel coefficients do not change within one symbol, but vary from symbol to symbol [12]. Therefore, the channel between the U users and BS during the n^{th} symbol is

$$\mathbf{G}_n = \mathbf{H}_n \mathbf{D}^{1/2} \tag{1}$$

where $\mathbf{D}$ is the $U \times U$ diagonal matrix, and $[\mathbf{D}]_{uu} = \beta_u$, β_u is large-scale fading including path loss, shading, etc., and it is assumed to be constant for all n. $\mathbf{H}_n$ is the $M \times U$ matrix, and $[\mathbf{H}_n]_{mu} = h_{m,u,n}$. $h_{m,u,n}$ is the small-scale fading coefficient between the m^{th} antenna of BS and the u^{th} user during the n^{th} symbol, and $h_{m,u,n}$ is assumed to be independent and identically distributed (i.i.d.).

Consider the time varying Ricean fading channel, one has

$$\mathbf{H}_n = \mathbf{H}_n^L \left[\mathbf{\Omega} \left(\mathbf{\Omega} + \mathbf{I}_U \right)^{-1} \right]^{1/2} + \mathbf{H}_n^s \left[\left(\mathbf{\Omega} + \mathbf{I}_U \right)^{-1} \right]^{1/2} \tag{2}$$

where $\mathbf{H}_n^L$ is the $M \times U$ LOS component matrix and $\mathbf{H}_n^s$ is the $M \times U$ scattered component matrix. The elements of $\mathbf{H}_n^s$ are i.i.d. with zero mean and unit variance. $\mathbf{\Omega}$ is the $U \times U$ diagonal matrix, and $[\mathbf{\Omega}]_{uu} = K_u$, where K_u is the Ricean factor of the u^{th} user, and it is the radio of LOS and the scattered components. $\mathbf{I}_U$ is the $U \times U$ unit matrix. $\mathbf{H}_n^L$ can be expressed as

$$\left[\mathbf{H}_n^L\right]_{um} = e^{-j(m-1)\frac{2\pi d}{\lambda}\sin(\theta_{u,n})} \tag{3}$$

where d denotes the inter-antenna spacing, λ is the carrier wavelength, and $d = \lambda/2$. $\theta_{u,n}$ is the angle of departure (AOD) for the u^{th} user during the n^{th} symbol.

Consider the special case with rank-1 mean for the time varying Ricean fading channel, Eq. (2) can be rewritten as

$$\mathbf{H}_n = \sqrt{\frac{K}{K+1}}\mathbf{H}_n^L + \sqrt{\frac{1}{K+1}}\mathbf{H}_n^s \tag{4}$$

Substituting Eq. (4) into Eq. (1), one can obtain the following

$$\mathbf{G}_n = \sqrt{\frac{K}{K+1}}\mathbf{G}_n^L + \sqrt{\frac{1}{K+1}}\mathbf{G}_n^s \tag{5}$$

where $\mathbf{G}_n^L = \mathbf{H}_n^L\mathbf{D}^{1/2}, \mathbf{G}_n^s = \mathbf{H}_n^s\mathbf{D}^{1/2}$.

2.1 Channel Estimation

The time division duplex (TDD) model will be considered in the paper. In practice, the channel matrix $\mathbf{G}_n$ is estimated at the BS for the TDD model. For the time varying Ricean fading channel, we assume that the deterministic LOS component and Ricean factor matrix $\mathbf{\Omega}$ are known at both the transmitter and receiver. Therefore, only the scattered component matrix $\mathbf{G}_n^s$ must be estimated.

The BS estimates the channel using the pilots. Let τ $(\tau \geq U)$ be the length of the pilot, the pilot sequences used by the U users can be represented by a $U \times \tau$ matrix $\sqrt{p_p}\mathbf{\Phi}$, and $\mathbf{\Phi}\mathbf{\Phi}^\dagger = \sqrt{K+1}\mathbf{I}_U$, where $(\cdot)^\dagger$ denotes conjugate transpose, p_p is the transmit power of the pilots, and $p_p = \tau p_u$, p_u is each user's transmit power. Therefore, the $M \times \tau$ received pilot signal at the BS is

$$\mathbf{y}_n^p = \sqrt{p_p}\mathbf{G}_n\mathbf{\Phi} + \hat{\mathbf{z}}_n \tag{6}$$

where $\hat{\mathbf{z}}_n$ is the $M \times \tau$ additive white Gaussian noise (AWGN) matrix, whose elements are i.i.d. $CN(0,1)$.

To estimate $\mathbf{G}_n^s$, Eq. (6) can be further written as

$$\mathbf{y}_n^{p,s} = \sqrt{\frac{p_p}{K+1}}\mathbf{G}_n^s\mathbf{\Phi} + \hat{\mathbf{z}}_n \tag{7}$$

For Eq. (7), the BS first correlates with $\mathbf{\Phi}^\dagger$ to obtain

$$\begin{aligned}\bar{\mathbf{y}}_n^p &= \frac{1}{\sqrt{p_p}}\mathbf{y}_n^{p,s}\mathbf{\Phi}^\dagger \\ &= \mathbf{G}_n^s + \frac{1}{\sqrt{p_p}}\mathbf{B}_n\end{aligned} \tag{8}$$

where $\mathbf{B}_n = \hat{\mathbf{z}}_n\mathbf{\Phi}^\dagger$, which has i.i.d. $CN(0,1)$ elements. From Eq. (8), one can obtain the scattered channel between the u^{th} user and the BS

$$\bar{\mathbf{y}}_{n,u} = \mathbf{g}_{n,u}^{s} + \frac{1}{\sqrt{p_p}}\mathbf{b}_{n,u} \tag{9}$$

where $\mathbf{g}_{n,u}^{s}$ and $\mathbf{b}_{n,u}$ are the u^{th} column of the matrices $\mathbf{G}_n^s$ and $\mathbf{B}_n$ respectively.

By the MMSE channel estimation method, one can obtain

$$\begin{aligned}\hat{\mathbf{G}}_n^s &= \bar{\mathbf{y}}_n^p \left(\frac{1}{p_p}\mathbf{D}^{-1} + \mathbf{I}_U\right)^{-1} \\ &= \left(\mathbf{G}_n^s + \frac{1}{\sqrt{p_p}}\mathbf{B}_n\right)\left(\frac{1}{p_p}\mathbf{D}^{-1} + \mathbf{I}_U\right)^{-1}\end{aligned} \tag{10}$$

As such, $\mathbf{g}_{n,u}^{s}$ can be decomposed into

$$\mathbf{g}_{n,u}^{s} = \hat{\mathbf{g}}_{n,u}^{s} + \bar{\mathbf{g}}_{n,u}^{s} \tag{11}$$

where $\hat{\mathbf{g}}_{n,u}^{s}$ and $\bar{\mathbf{g}}_{n,u}^{s}$ are the channel estimation and estimation error for the scattered channel coefficient, respectively. Each element of $\hat{\mathbf{g}}_{n,u}^{s}$ is a Gaussian variable with zero mean and variance $\beta_u \eta_u / (K+1)$ elements, and $\bar{\mathbf{g}}_{n,u}^{s}$ is a matrix with zero mean and $\beta_u (1-\eta_u)/(K+1)$ variance elements, where $\eta_u = p_p \beta_u / (p_p \beta_u + 1)$, $\hat{\mathbf{g}}_{n,u}^{s}$ and $\bar{\mathbf{g}}_{n,u}^{s}$ are independent due to the orthogonality property of linear MMSE estimator.

Therefore, the final channel estimation $\hat{\mathbf{G}}_n$ at the BS is

$$\hat{\mathbf{G}}_n = \sqrt{\frac{K}{K+1}}\mathbf{G}_n^L + \sqrt{\frac{1}{K+1}}\hat{\mathbf{G}}_n^s \tag{12}$$

In Eq. (12), the u^{th} column $\hat{\mathbf{g}}_{n,u}$ of the matrix $\hat{\mathbf{G}}_n$ can be expressed as

$$\hat{\mathbf{g}}_{n,u} = \mathbf{g}_{n,u}^{L} + \hat{\mathbf{g}}_{n,u}^{s} \tag{13}$$

where $E\left\|\hat{\mathbf{g}}_{n,u}\right\|^2 = M\beta_u (K+\eta_u)/(K+1)$.

2.2 Channel Aging

To facilitate the derivation, the LOS component $\mathbf{g}_{n,u}^{L}$ in the Ricean channel is assumed to be the constant i.e., $\mathbf{g}_{n,u}^{L} = \mathbf{g}_{u}^{L}$, and the scattered component $\mathbf{g}_{n,u}^{s}$ is time varying. Therefore, only the effect of channel aging caused by the scattered component of the system is considered.

By autoregressive (AR) model, the scattered component $\mathbf{g}_{n,u}^{s}$ at time n+1 can be expressed as

$$\mathbf{g}_{n+1,u}^{s} = \alpha \mathbf{g}_{n,u}^{s} + \mathbf{e}_{n+1,u} \tag{14}$$

where α is the parameter of the AR model, $\mathbf{e}_{n+1,u}$ is the model error, and $\mathbf{e}_{n+1,u} \sim CN\left(0, \boldsymbol{\sigma}_{\mathbf{e}_u}^2\right)$. Considering the Jakes fading model, one can obtain by solving the Yule-Walker equation

$$\begin{aligned} &\alpha = J_0\left(2\pi f_D T_s\right) \\ &\boldsymbol{\sigma}_{\mathbf{e}_u}^2 = \mathbf{I}_M \otimes \left(1-\alpha^2\right) M\beta_u / \left(K+1\right) \end{aligned} \tag{15}$$

where T_s is the channel sampling duration, f_D is the maximum Doppler frequency shift, and $f_D T$ is the normalized Doppler shift. $f_D = f_c v / C$, f_c is the carrier frequency, v is the users' velocity, and C is the speed of light. $\mathbf{I}_M$ denotes the $M \times M$ unit matrix, and $\otimes$ is the Kronecker product operation, and $J_0(\cdot)$ is the zero order Bessel function of the first kind.

Therefore, a model for the scattered component $\mathbf{g}_{n+1,u}^s$ accounting for the combined effects of the channel estimation error and channel aging can be expressed as

$$\mathbf{g}_{n+1,u}^s = \alpha \mathbf{g}_{n,u}^s + \mathbf{e}_{n+1,u} = \alpha \hat{\mathbf{g}}_{n,u}^s + \overline{\mathbf{e}}_{n+1,u} \tag{16}$$

where $\overline{\mathbf{e}}_{n+1,u} = \alpha \overline{\mathbf{g}}_{n,u}^s + \mathbf{e}_{n+1,u}$, $\overline{\mathbf{e}}_{n+1,u}$ is independent with $\hat{\mathbf{g}}_{n,u}^s$ due to the independence between $\overline{\mathbf{g}}_{n,u}^s$ and $\mathbf{e}_{n+1,u}$. As a result, each element of $\overline{\mathbf{e}}_{n+1,u}$ is a complex Gaussian random variable with zero mean and $\beta_u\left(1-\alpha^2\eta_u\right)/\left(K+1\right)$ variance.

2.3 Downlink Transmission

Let $\mathbf{x}_{n+1} \in C^{U\times 1}$ be the signal that the BS transmits to U users, $\mathbf{w}_{n+1} \in C^{M\times U}$ is the precoding matrix. The signal at time n+1 after precoding is

$$\mathbf{S}_{n+1} = \sqrt{P_b}\,\mathbf{w}_{n+1}\mathbf{x}_{n+1} \tag{17}$$

where P_b is the transmit power of the BS and it should be satisfied with $\mathrm{E}\left\|\mathbf{S}_{n+1}\right\|^2 = P_b$. By adopting the channel reciprocity, the signals received by U users at time n+1 is

$$\begin{aligned} \mathbf{y}_{n+1} &= \mathbf{G}_{n+1}^T \mathbf{S}_{n+1} + \mathbf{z}_{n+1} \\ &= \sqrt{p_b}\,\mathbf{G}_{n+1}^T \mathbf{w}_{n+1} \mathbf{x}_{n+1} + \mathbf{z}_{n+1} \end{aligned} \tag{18}$$

where $\mathbf{z}_{n+1}$ is the AWGN with zero mean and unit variance. Therefore, the received signal for the u^{th} user is

$$\mathbf{y}_{n+1,u} = \sqrt{p_b}\,\mathbf{g}_{n+1,u}^T \mathbf{w}_{n+1,u} x_{n+1,u} + \mathbf{z}_{n+1,u} + \sqrt{p_b}\sum_{i\neq u} \mathbf{g}_{n+1,u}^T \mathbf{w}_{n+1,i} x_{n+1,i} \tag{19}$$

where $\mathbf{g}_{n+1,u}$ and $\mathbf{w}_{n+1,u}$ mean the u^{th} column of $\mathbf{G}_{n+1}$ and $\mathbf{w}_{n+1}$ respectively. $x_{n+1,u}$ is the u^{th} element of $\mathbf{x}_{n+1}$.

In the paper, the MRT precoder will be considered, so the precoding matrix $\mathbf{w}_{n+1}$ is

$$\mathbf{w}_{n+1} = \delta \overline{\mathbf{G}}_{n+1}^* \tag{20}$$

where δ is a normalization constant which meets the power condition $\mathrm{E}\left\|\mathbf{w}_{n+1}\mathbf{x}_{n+1}\right\|^2 = 1$, and $\overline{\mathbf{G}}_{n+1}^*$ is the channel matrix obtained by BS. After some simple mathematical computations, it can obtain the value of δ as

$$\delta = \sqrt{\frac{K+1}{\sum_{i=1}^{U} M\beta_i\left(K+\alpha^2\eta_i\right)}} \tag{21}$$

3. Achievable downlink Sum rate

Employing the technique used in [12] and [15], the u^{th} user only has knowledge of $\mathrm{E}\left[\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,u}\right]$, and the remaining items are regarded as the AWGN. Consequently, the received signal of the u^{th} user in Eq. (19) can be rewritten as

$$\mathbf{y}_{n+1,u} = \sqrt{p_b}\,\mathrm{E}\left[\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,u}\right]x_{n+1,u} + \bar{\mathbf{z}}_{n+1,u} \tag{22}$$

where

$$\begin{aligned}\bar{\mathbf{z}}_{n+1,u} &= \mathbf{z}_{n+1,u} + \sqrt{p_b}\sum_{i\neq u}\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,i}x_{n+1,i} + \sqrt{p_b}\,\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,u}x_{n+1,u} \\ &\quad - \sqrt{p_b}\,\mathrm{E}\left[\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,u}\right]x_{n+1,u}\end{aligned} \tag{23}$$

Based on Eq.(22), the u^{th} user's rate R_u (sub-optimal) is

$$R_u = \log_2\left(1 + \frac{\left|\mathrm{E}\left[\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,u}\right]x_{n+1,u}\right|^2}{\mathrm{var}\left(\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,u}\right) + \sum_{i\neq u}E\left|\mathbf{g}_{n+1,u}^{T}\mathbf{w}_{n+1,i}\right|^2 + \frac{1}{p_b}}\right) \tag{24}$$

where $\mathrm{var}(\cdot)$ is the covariance operation.

Theorem-1: For MRT precoder, the achievable rate of the u^{th} user under the channel aging is given as

$$R_u = \log_2\left(1 + \frac{M\beta_u^{2}\left(K+\alpha^2\eta_u\right)^2}{\left(\beta_u + \frac{1}{p_b}\right)\sum_{i=1}^{U}\beta_i\left(K+1\right)\left(K+\alpha^2\eta_i\right)}\right) \tag{25}$$

Proof: the proof is omitted here for saving space.

Eq. (25) clearly shoows the effect of the channel aging on the achievable rate of the u^{th} user. According to the expression, it turns out that the channel aging would lead to a decrease of the u^{th} user's achievable rate. Moreover, the achievable rate decreases more significantly as the user moves faster. Now considering the asymptotic large antennas regime $M\rightarrow\infty$, the power scaling law with the channel aging in the Massive MIMO downlink is given.

Theorem-2: For MRT precoder with the channel aging, If the transmit power of the BS is reduced by a factor of $1/M^{\gamma}$, i.e., $p_b = E_b/M^{\gamma}$, where $\gamma > 0$ and E_b is fixed, one has

$$R_u^{age} \longrightarrow \log_2\left(1 + \frac{\beta_u^{2}\left(K^2 + \frac{\alpha^4\tau^2E_u^{2}\beta_u^{2}}{M}\right)E_b}{K\left(K+1\right)M^{\gamma-1}\sum_{i=1}^{U}\beta_i + \left(K+1\right)\alpha^2\tau E_u M^{\gamma-\frac{3}{2}}\sum_{i=1}^{U}\beta_i^2}\right) \tag{26}$$

Proof: Using the uplink power scaling law verified in [16] and substituting $p_p = \tau p_u = \tau E_u / \sqrt{M}$ into Eq. (25), the after some simple mathematical computations, the result can be got.

Theorem-2 suggests that the asymptotic achievable rate R_u^{age} depends on K and γ. In the case of K=0, the channel is the time varying Rayleigh fading channel, in this case, when $\gamma > 1/2$, R_u^{age} converges to zero. When $\gamma < 1/2$, R_u^{age} grows without bound. When $\gamma = 1/2$, R_u^{age} converges to a non-zero limit, and we obtain the following corollary-1.

Corollary-1: For MRT precoder with channel aging, If the BS scales down its transmit power at most by $p_b = E_b / \sqrt{M}$, where E_b is fixed, the achievable rate of the u^{th} user in the case of Ricean factor K=0 is

$$R_u^{age} \longrightarrow \log_2\left(1+\frac{\alpha^2 \tau \beta_u^{\,4} E_u E_b}{\sum_{i=1}^{U} \beta_i^2}\right) \tag{27}$$

Corollary-1 suggests that channel aging does not affect the power scaling law, i.e., $p_b = E_b / \sqrt{M}$, and it only leads to a reduction of the achievable rate that has been illustrated in [15].

In the case of $K \neq 0$ for Eq. (26), the channel is the time varying Ricean fading channel. In this case, when $\gamma > 1$, R_u^{age} converges to zero. When $\gamma < 1$, R_u^{age} grows without bound. When $\gamma = 1$, R_u^{age} converges to a non-zero limit, and we obtain the following Corollary-2.

Corollary-2: For the MRT precoder with channel aging, If the BS scales down its transmit power at most by $p_b = E_b / M$, where E_b is fixed, the achievable rate of the u^{th} user in the case of Ricean factor $K \neq 0$ is

$$R_u^{age} \longrightarrow \log_2\left(1+\frac{\beta_u^{\,2} K E_b}{(K+1)\sum_{i=1}^{U} \beta_i}\right) \tag{28}$$

From corollary-2, one can see that the transmit power of the BS can be scaled down to $p_b = E_b / M$ for the time varying Ricean fading channel, which suggests that the Ricean factor affects the power scaling law and the achievable rate. Channel aging does not affect the power scaling law, and it only leads to a reduction of the achievable rate.

4. Energy Efficiency Analysis

4.1 Power Consumption Model

A widely used model indicated in [22] is taken into account to discuss the effect of channel aging on the EE of the system. The totle power consumption (in Joule/channel use) of the system denotes

$$P_{total} = P_{PA} + P_{CS} \tag{29}$$

where P_{PA} is the power consumed by power amplifier (PA) and P_{CS} is the power required by the circuits and signal processing, and

$$P_{PA} = \frac{P_T}{\varsigma} = \sum_{i=1}^{U} \frac{E\left\|\mathbf{w}_i\right\|^2}{\varsigma} \tag{30}$$

where P_T is the normalized transmit power of the BS, ς represents the efficiency of PA, and $0 < \varsigma < 1$. For the MRT precoder with channel aging, P_{PA} is $(K+1)\, p_b / \left[\varsigma M \sum_{i=1}^{U} \beta_i \left(K + \alpha^2 \eta_i\right)\right]$. In Eq. (29), P_{CS} is given as

$$P_{CS} = P_{TC} + P_0 + P_{CE} + P_{LP} + P_{CD} \tag{31}$$

where P_{TC} is the transceiver chains power consisting of $MP_{BS} + P_{SYN} + UP_{UE}$, where P_{BS} is consumed by circuit components attached to the BS, P_{SYN} is required for the local-oscillator and P_{UE} accounts for all receiver components. P_0 is fixed power required for cooling system, etc. P_{CE} is the channel estimation power and $P_{CE} = MU/(LT)$, where L is the computational efficiency, and T is the length of coherence interval. The precoding power P_{LP} for MRT is $2MU/(LT) + (1 - \tau/T)MU/L$. P_{CD} represents coding and decoding power, and $P_{CD} = U\left(P_{cod} + P_{dec}\right)$, where P_{cod} is power required for channel coding and modulation, and P_{dec} is the power consumed by decoding symbols.

4.2 Energy Efficiency (EE)

EE means the ratio between the sum rate and the total consumption power. Adopting the given power consumption model, one can get

$$EE = \frac{\frac{T-\tau}{T} \sum_{u=1}^{U} R_u}{P_{total}} \tag{32}$$

For the MRT precoder, the EE is

$$EE = \frac{\frac{T-\tau}{T} \sum_{u=1}^{U} \log_2 \left(1 + \frac{M \beta_u^2 \left(K + \alpha^2 \eta_u\right)^2}{\left(\beta_u + \frac{1}{p_b}\right) \sum_{i=1}^{U} \beta_i (K+1)\left(K + \alpha^2 \eta_i\right)} \right)}{\frac{(K+1)\, p_b}{\varsigma M \sum_{i=1}^{U} \beta_i \left(K + \alpha^2 \eta_i\right)} + MP_{BS} + P_{SYN} + U\left(P_{UE} + P_{cod} + P_{dec}\right) + P_0 + \frac{3MU}{LT} + \left(1 - \frac{\tau}{T}\right)\frac{MU}{L}} \tag{33}$$

Eq. (33) shows that the user moves faster, the value of α is larger and the value of EE is smaller, in other words, the channel aging also decreases the EE of the system. Therefore, it is very important to find the optimal number of the antennas and the number of users with the maixmal EE in the emergence of the channel aging, which will be found by the simulations in the following.

5. Simulation Results

Consider a single cell with a radius of 1000 meters and assume a guard of r_h=100 meters that specifies the distance between the nearest user and the BS. All the users are uniformly distributed in the cell. Large scale fading is modeled as $\beta_u = z_u / \left(r_u / r_h \right)^{\mu}$, where z_u is a log-normal random variable with standard deviation σ (σ=8dB) denoting the shadow fading effect, r_u represents the distance between the u^{th} user and the BS, and μ (μ=3.8) is the path loss exponent. In the simulation, we assume that every user has the same Ricean factor, the number of single-antenna users per cell U=10, $\tau = U$.

Fig. 1 shows the achievable sum rate versus the normalized Doppler shift $f_D T_s$ for different Ricean factors. From **Fig. 1**, one can see that there are some ripples for sum rate. Before the sum rate gets to bottom for the first time, as the Doppler shift becomes large, the sum rate loss becomes increasingly substantial, that is because the larger the Doppler shift, the stronger the channel aging effect. In addition, the larger Ricean factor, the larger achievable sum rate. Moreover, as the Ricean factor increases, the effect of the channel aging on the sum rate will be weaken.

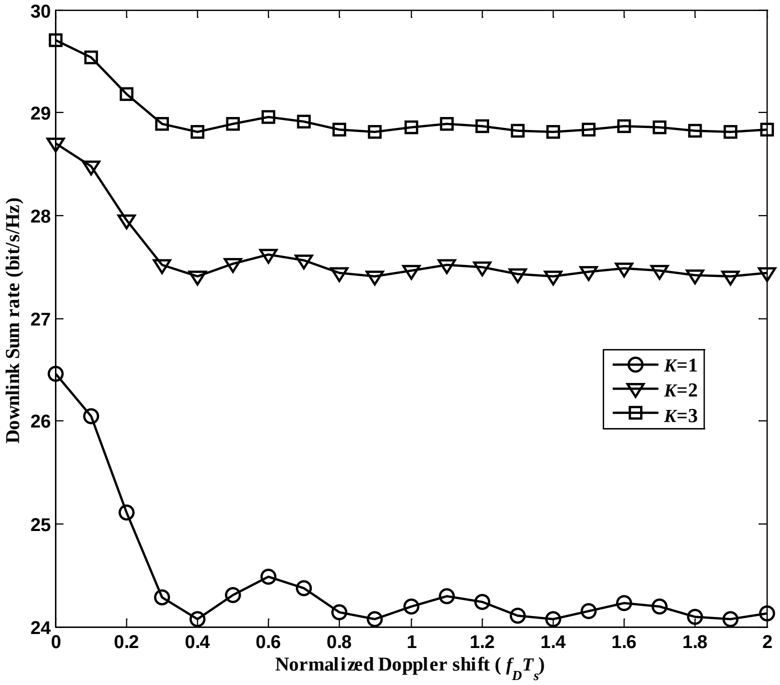

Fig. 1. Downlink sum rate versus the normalized Doppler shift for P_p=10dB, P_b=20dB, and M=128.

Fig. 2 illustrates the sum rate changes with the varying of the transmit power of the BS. It is easy to know that the sum rate will tend to a constant as the transmit power of the BS increases. Moreover, as the Ricean factor increases, the achievable sum rate will be improved.

Fig. 3 shows the achievable sum rate versus the Ricean factor. 'Current channel' means the channel is not affected by channel aging. It can be seen that the achievable sum rate approximates the fixed values as $K \to \infty$. In the small Ricean factor region, the larger Doppler shift, the smaller achievable sum rate in the case of channel aging. However, as the

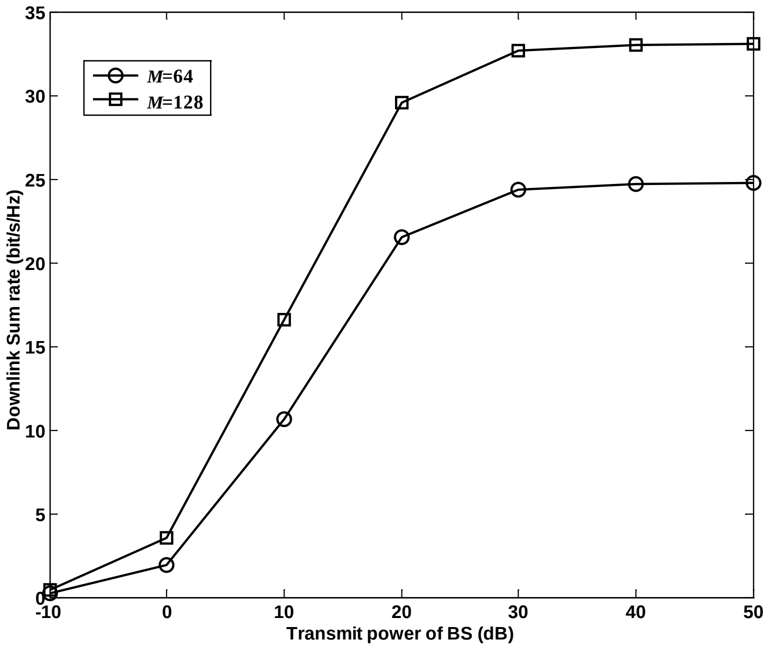

Fig. 2. Downlink sum rate versus the transmit power of the BS for P_p=10dB, $f_D T_s$=0.1, and K=3.

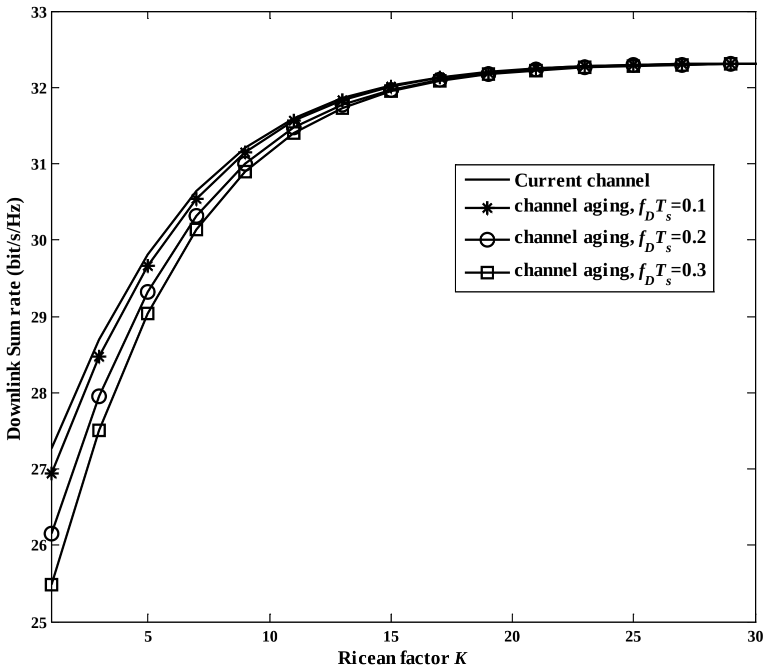

Fig. 3. Downlink sum rate versus the Ricean factor K for P_p=10dB, M=128.

Ricean factor increases, the achievable sum rate for the current channel and channel aging will converge to the same fixed value. This means that a higher Ricean factor reduces the effect of channel aging.

Fig. 4 shows the effect of the channel aging on the EE of the system for the different Ricean factors. From **Fig. 4**, one can see that there are some ripples for EE of the system, which similar to **Fig. 1**. when the Ricean factor K is equal to zero, increasing the number of BS antennas M does not compensate for the loss of the EE due to the Doppler shift after the EE gets to zero for the first time. Besides, as the Ricean factor K increases, the EE of the system will be improved. Moreover, the increase of the BS antenna will lead to lower energy efficiency as the Ricean factor K increases, which means that the Ricean factor can reduce the effect of channel aging on the EE of the system and also can reduce the number of the required BS antennas M (which can also be illustrated in **Fig. 5**).

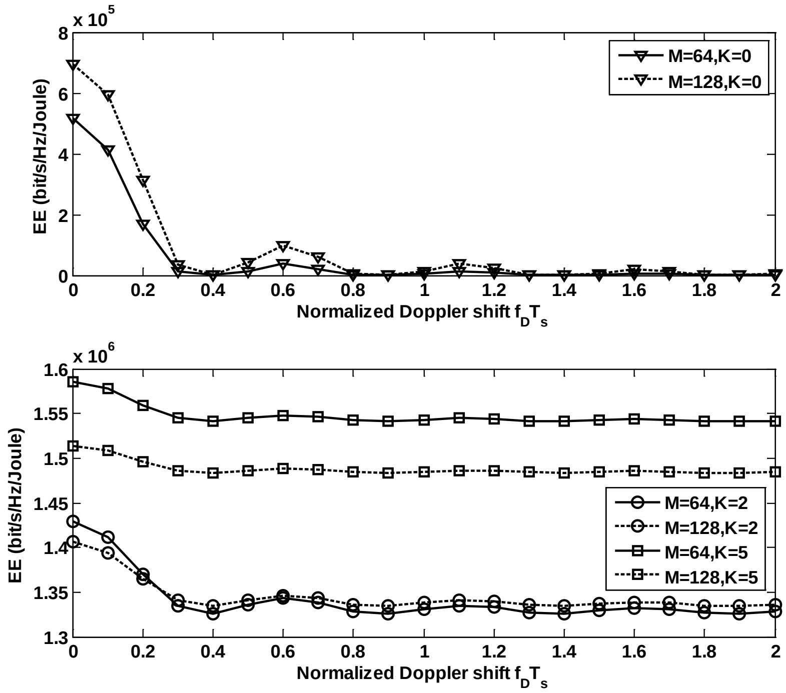

Fig. 4. EE against the normalized Doppler shift $f_D T_s$ for the different Ricean factors when P_p=10dB.

Fig. 5 shows the effect of the channel aging on the EE under the different values of number of the BS antennas M and the number of the users U. From **Fig. 5**, one can see that the optimum values of M and U are different for the different Ricean factors K, i.e., when K=0, M=146 and U=26; when K=2, M=56 and U=11; when K=10, M=31 and U=6. While without channel aging, the optimum value is M=136 and U=26 when K=0. In other words, to achieve maximal EE under the channel aging, in the case of the same Ricean factor, the number of the antennas should be increased and the number of the users is constant. Moreover, in the case of channel aging, as the Ricean factor increases, both the number of the antennas and users will be reduced.

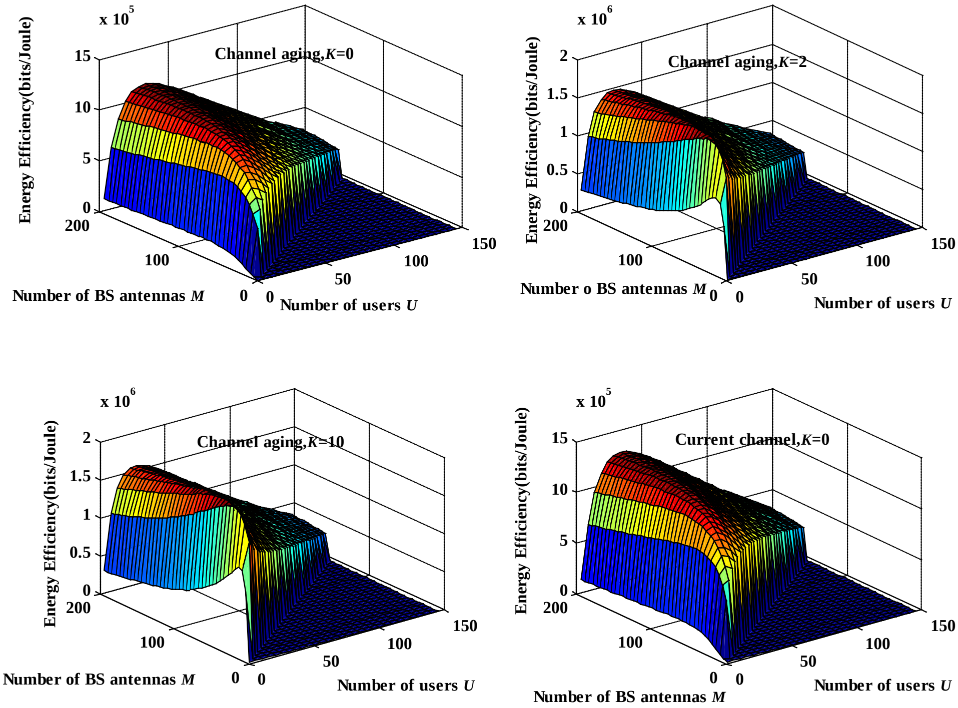

Fig. 5. EE under the different values of number of the BS antennas M and the number of the users U for the different Ricean factors.

6. Conclusion

The achievable sum rate and EE of the downlink Massive MIMO system with the aged CSI in the time varying Ricean fading channel is studied in this paper. For the MRT precoder with aged CSI, we derived the sum rate of the system for the time varying Ricean fading channel. In addition, we described the effect of both channel aging and the Ricean factor on the power scaling law. Based on the general power consumption model, the EE of the system is analyzed. Both the theoretical analysis and the simulations show that the channel aging could degrade the sum rate and the EE of the system, and it does not affect the power scaling law. Moreover, the Ricean factor can reduce the optimal number of required BS antennas and users, and it also can reduce the effect of the channel aging on the performance of the system.

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Lihua Yang was born in Jiangsu, china in 1984. She received her B.S. degree in Electronics and communications engineering at Xi'an University of Science and Technology, 2007 and her M.S. degree in signal processing at Xidian University 2008. She received the Ph.D. degree in the communication and information systems at Xidian University on March 2013. She is currently a Lecturer of the College of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications. Her research interests focus on the key technologies of the physical layer in the mobile wireless communications, and the network coding.

Longxiang Yang is with the College of Communications and Information Engineering, Nanjing University of Posts and Telecommunications (NJUPT), Nanjing, China. He is a full Professor and Doctoral Supervisor at NJUPT. His research interests span the broad area of wireless networks, cooperative communications and signal processing of communications. He has fulfilled multiple National Natural Science Foundations of China.

Hongbo Zhu was born in Yangzhou, Jiangsu Province, China, in 1956. He is currently a Professor in Jiangsu Key Laboratory of Wireless Communications, Nanjing University of Posts and Telecommunications. He is the Vice Chairman of SG3 of ITU Radio Communication Bureau (ITU-R). He has authored and co-authored over 200 technical papers published in various journals and conferences. His research interests include wireless communication theory and radio propagation in wireless communications.

Yan Liang received the B.S. degree in Communications Engineering, M.S. and Ph.D. degrees in Communication and Information Systems from Nanjing University of Science & Technology in 2001, 2004 and 2013, respectively. From 2004–2008, she was with Lucent Technology as a research engineer. Since 2013, she has been a lecture in the College of Telecommunications and Information Engineering at Nanjing University of Posts and Telecommunications (NUPT), China. Her research interests include broadband wireless communication and communication signal processing.