Modelling and Performance Analysis of Maximum Achievable Rate over Nakagami-m Fading Uplink Channels

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***Abstract*—It is of great importance and interests for network operators to evaluate the impact of inter-cell co-channel interference on the achievable data rate in cellular networks. In this paper, a closed-form maximum achievable rate over Nakagami-m fading uplink channels based on multicell linear Wyner model is derived. Moreover, the maximum achievable rates in some special cases are investigated. Numerical results show that the maximum achievable rate decreases with the increase of the inter-cell signal interference factor and is also affected by Nakagami-m fading severity parameters and number of users in a cell.**

***Index Terms*—maximum achievable rate; Nakagami-m fading; interference factors.**

I. Introduction

To enhance spectral efficiency, full frequency reuse has been adopted in advanced cellular communication networks, which however generates severe inter-cell co-channel interference and degrades the achievable rate at mobile terminals. Therefore, it is of great importance and interests for network operators to evaluate the impact of inter-cell co-channel interference on the achievable data rate in cellular networks.

Some early studies investigating the uplink capacity with co-channel interference appeared in [1], [2]. In [1], Wyner proposed a linear array cells model, i.e., the Wyner model, to analyze the capacity of cellular networks and defined the concept of inter-cell signal interference factor to evaluate the impact of interference on the uplink capacity of cellular networks. In [2], considering the co-channel interference and wireless channel fading, Shamai et al. used the maximum achievable rate per cell as a metric to evaluate the uplink capacity of cellular networks employing time division multiple access (TDMA), wideband (WB) and fractional intercell time-sharing (ICTS) schemes, respectively. In [3], the authors studied the transmission rates assuming the Rayleigh wireless fading channels, the Wyner model of cellular networks was employed to study the limits of maximum achievable rate per transmitter and the optimal performance in TDMA cellular networks. An analytical co-channel interference model is proposed and exact normalized downlink average capacity is derived in [4] for multicell MIMO cellular networks. Numerous single cell processing techniques have been proposed in the literature for improving the uplink capacity in wireless communication systems [5], [6]. In [5], the accuracy of the Wyner model was studied in both uplink and downlink transmissions and considering both single-cell processing and multi-cell processing. In [6], Bang et al. investigated the gains of multicell zeroforcing beamforming (ZFBF) on the downlink of a Wyner-type network and compared the gap in data rate between ZFBF and single-cell processing (SCP) under mulituser scheduling.

In the aforementioned cellular network capacity studies, only the traditional Rayleigh fading channels were considered and the maximum achievable rate analysis under the more general Nakagami-m fading uplink channels has not been investigated. Motivated by the above observations, in this paper we study the maximum achievable rate per cell for cellular networks with Nakagami-m fading uplink channels considering inter-cell signal interference factors. Moreover, some special cases are investigated in detail in this paper.

The rest of paper is organized as follows. Section II describes the system model. Considering a general case and special cases, a closed-form expression for the maximum achievable rate per cell for cellular networks with Nakagami-m fading uplink channels is derived in Section III. In Section IV, numerical simulations show the impact of inter-cell signal interference factor, number of users in a cell and Nakagami-m fading severity parameter on maximum achievable rate. Finally, Section V concludes this paper.

II. System Model

Let us consider a linear array of M cells with one BS and K users per cell. The radius of each cell is assumed to be R. Users are assumed to be independently and identically

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distributed (i.i.d.) in a cell following a uniform distribution. Further, it is assumed that users within the same cell use different channels to communicate and users belonging to different BSs may use the same channel due to full spatial frequency reuse. Therefore, a BS receives the desired signal from users located within the same cell and interference is caused by users in adjacent cells. The above model is known as the linear Wyner model [1] and is illustrated in Fig.1.

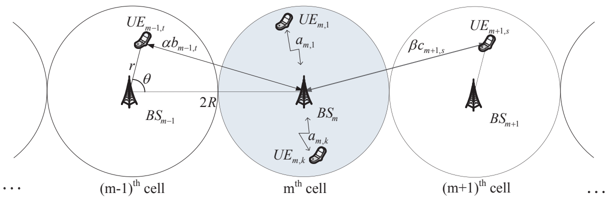

Fig. 1. A general linear Wyner model.

The signals received by the M BSs may be represented in a vector form as follows:

$$\vec{y} = H\vec{x} + \vec{n} \tag{1}$$

where $\vec{y}$ is a $M \times 1$ column vector representing signals received by the M BSs, $\vec{x}$ is a $MK \times 1$ column vector representing uplink signals sent by K users, H is a $M \times MK$ channel transfer matrix and $\vec{n}$ is a $M \times 1$ column vector denoting the noise received by the M BSs.

Based on the traditional Wyner model, the base station only receives co-channel interference from users in adjacent cells. Therefore, the channel transfer matrix H in (1) can then be written as

$$H = \begin{pmatrix} \vec{a}_1 & \beta\vec{c}_2 & 0 & \cdots & 0 & 0 \\ \alpha\vec{b}_1 & \vec{a}_2 & \beta\vec{c}_3 & 0 & \cdots & 0 \\ 0 & \alpha\vec{b}_2 & \vec{a}_3 & \beta\vec{c}_4 & \ddots & \vdots \\ \vdots & 0 & \alpha\vec{b}_3 & \ddots & \ddots & 0 \\ 0 & \vdots & \ddots & \ddots & \vec{a}_{M-1} & \beta\vec{c}_M \\ 0 & 0 & \cdots & 0 & \alpha\vec{b}_{M-1} & \vec{a}_M \end{pmatrix} \tag{2}$$

where $\vec{a}_m = \{a_{m,1}, a_{m,2}, \cdots, a_{m,k}, \cdots, a_{m,K}\}$, $m \in [1, M]$ and $k \in [1, K]$, is a $1 \times K$ random vector, representing the multi-path and shadowing fading effect experienced by the desired signals from K active users in the m^{th} cell, $\vec{b}_{m-1} = \{b_{m-1,1}, b_{m-1,2}, \cdots, b_{m-1,t}, \cdots, b_{m-1,K}\}$ and $\vec{c}_{m+1} = \{c_{m+1,1}, c_{m+1,2}, \cdots, c_{m+1,s}, \cdots, c_{m+1,K}\}$, t and $s \in [1, K]$, are two $1 \times K$ random vectors representing the multi-path and shadowing fading effect experienced by the interference signals from users in the $(m-1)^{th}$ and $(m+1)^{th}$ cells respectively. It is assumed that $a_{m,k}$, $b_{m-1,t}$ and $c_{m+1,s}$, are random complex variables, and are statistically independent of each other.

The parameter $\alpha \in [0, 1]$ is the *inter-cell signal interference factor*, which represents the path loss of interfering signals from users in the $(m-1)^{th}$ cell to the m^{th} cell [3]. Considering that the interference signals are statistically independent, the inter-cell signal interference factor from users in the $(m+1)^{th}$ cell to the m^{th} cell is $\beta \in [0, 1]$.

Considering the impact of interference and noise in the linear Wyner model, the maximum achievable rate with single cell processing scheme R_{SCP_m} in the m^{th} cell is given by [1]

$$R_{SCP\_m} = E\left\{\log\left(1 + \frac{P_m}{N_m + I_m}\right)\right\} \tag{3}$$

where P_m is the average received signal power, I_m is the average interference power from the $(m-1)^{th}$ and $(m+1)^{th}$ cell, N_m is the average noise power in uplink channel received by BS_m, $E\{\cdot\}$ is an expectation operator. To avoid the near-far effect in cellular networks, the user terminals generally adaptively adjust the transmission power to keep all signal power received by BSs at the same level. Therefore, the received power at the BS is represented by a common value. Based on the simple one-slope path loss model, the received power at BS BS_m is traditionally expressed as [7]

$$P_m = \frac{\mathfrak{K}\bar{P}_{tr}}{K}\sum_{k=1}^{K}(d_0/d_{m,k})^{\lambda}|a_{m,k}|^2 \tag{4}$$

where $\bar{P}_{tr}$ is the average transmission power of users in a cell, $d_{m,k}$ is a distance between the transmitter and the receiver, d_0 is a reference distance and $\bar{P}_{tr}$ is the received power at d_0, λ is an attenuation coefficient and $\mathfrak{K}$ is an propagation coefficient, $\mathfrak{K} = -31.54dB$ when $d_0 = 1$ meter. The average interference power from users in the $(m-1)^{th}$ and $(m+1)^{th}$ cells to the BS in the m^{th} cell can be written as

$$\begin{aligned} I_m = &\frac{\mathfrak{K}\bar{P}_{tr}}{K}\sum_{t=1}^{K}\left(d_0/d_{m-1,t}\right)^{\lambda}|b_{m-1,t}|^2 \\ &+\frac{\mathfrak{K}\bar{P}_{tr}}{K}\sum_{s=1}^{K}\left(d_0/d_{m+1,s}\right)^{\lambda}|c_{m+1,s}|^2 \end{aligned} \tag{5}$$

The noise is assumed as a zero mean, i.i.d. Gaussian process. For the sake of simplicity, the average noise power in uplink channel is normalized to a unit power in this paper. Then, based on the assumption that the inter-cell signal interference factor is a constant, the R_{SCP_m} can be rewritten as

$$R_{SCP\_m} = E\left\{\log\left(1 + \frac{\frac{\bar{P}_{tr}}{K}\sum\limits_{k=1}^{K}|a_{m,k}|^2}{1 + {I_m}'}\right)\right\} \tag{6}$$

with

$${I_m}' = \frac{\bar{P}_{tr}}{K}\overline{\alpha^2}\sum_{t=1}^{K}|b_{m-1,t}|^2 + \frac{\bar{P}_{tr}}{K}\overline{\beta^2}\sum_{s=1}^{K}|c_{m+1,s}|^2,$$

where $\overline{\alpha^2}$ and $\overline{\beta^2}$ are denoted as the average inter-cell power interference factors from the $(m-1)^{th}$ and $(m+1)^{th}$ cells.

III. Maximum Achievable Rate over Nakagami-m Fading Uplink Channels

A. Maximum Achievable Rate over Nakagami-m Fading Uplink Channels

To facilitate the derivation of the maximum achievable rate, three random variables are defined: $S = \sum_{k=1}^{K} |a_{m,k}|^2$, $T_L = \sum_{t=1}^{K} |b_{m-1,t}|^2$ and $T_R = \sum_{t=1}^{K} |c_{m+1,s}|^2$. The maximum achievable rate in (6) can be rewritten in the form of the three random variables as

$$\begin{aligned} R_{SCP\_m} &= E\left\{\log\left(K + \bar{P}_{tr}\left(S + \overline{\alpha^2}T_L + \overline{\beta^2}T_R\right)\right)\right\} \\ &-E\left\{\log\left(K + \bar{P}_{tr}\left(\overline{\alpha^2}T_L + \overline{\beta^2}T_R\right)\right)\right\} \end{aligned} \tag{7}$$

considering the inter-cell power interference factor depends on the location of users, $\overline{\alpha^2}$ and $\overline{\beta^2}$ are the average inter-cell power interference factors from the $(m-1)^{th}$ and $(m+1)^{th}$ cells, respectively.

In the system model in Fig. 1, the general Nakagami-m fading uplink channels are considered [8]. Moreover, every signal including the interference signal is assumed to be independent and is subject to independent Nakagami-m fading. In this case, the PDF of Z^2, which represents the signal power in wireless uplink channels, can be approximated by a Gamma distribution [7]

$$f_{Z^2}(x) = \frac{\left(\frac{m}{\Omega}\right)^m}{\Gamma(m)} x^{m-1} e^{\left(-\frac{mx}{\Omega}\right)} \tag{8}$$

which can be simply denoted as $Z^2 \sim \Gamma(m, \Omega/m)$, where m is a fading severity parameter and Ω is a received signal power at the corresponding BS.

Using (8), the Nakagami-m fading effect of desired signal in the m^{th} cell and interference signal in the $(m-1)^{th}$ and $(m+1)^{th}$ cells, represented by $|a_{m,k}|^2$, $|b_{m-1,t}|^2$ and $|c_{m+1,s}|^2$ can be expressed by Gamma distributions: $|a_{m,k}|^2 \sim \Gamma(m_1, \Omega/m_1)$, $|b_{m-1,t}|^2 \sim \Gamma(m_2, \Omega/m_2)$, and $|c_{m+1,s}|^2 \sim \Gamma(m_3, \Omega/m_3)$, respectively. $|a_{m,k}|^2$, $|b_{m-1,t}|^2$ and $|c_{m+1,s}|^2$ are assumed independent. Parameters m_1, m_2 and m_3 are fading severity parameters in the m^{th}, $(m-1)^{th}$ and $(m+1)^{th}$ cells, respectively. The Nakagami-m fading severity parameters are assumed as the same for all users in a cell. Based on the moment matching approximation approach, the maximum achievable rate with Nakagami-m fading uplink channels can be derived as

$$\begin{aligned} R_{SCP\_m} &= \int_0^\infty \log\left(K + \bar{P}_{tr}x\right) \frac{x^{\kappa-1}e^{-\frac{x}{\Theta}}}{\Theta^\kappa \Gamma(\kappa)} dx \\ &-\frac{1}{\varepsilon}\int_0^\infty \log\left(K + \bar{P}_{tr}x\right) x^{Km_2+Km_3-1} e^{-m_3 x/\overline{\beta^2}\Omega} H dx \end{aligned} \tag{9}$$

with

$$\varepsilon = \left(\frac{\overline{\alpha^2}\Omega}{m_2}\right)^{Km_2} \left(\frac{\overline{\beta^2}\Omega}{m_3}\right)^{Km_3} \Gamma\left(Km_2 + Km_3\right),$$

$$H = {}_1F_1\left[Km_2; Km_2 + Km_3; \left(\frac{m_3}{\overline{\beta^2}\Omega} - \frac{m_2}{\overline{\alpha^2}\Omega}\right)x\right],$$

$$\kappa = \frac{K\left(1 + \overline{\alpha^2} + \overline{\beta^2}\right)^2}{\left(\frac{1}{m_1} + \frac{\overline{\alpha^4}}{m_2} + \frac{\overline{\beta^4}}{m_3}\right)},$$

$$\Theta = \frac{\Omega\left(\frac{1}{m_1} + \frac{\overline{\alpha^4}}{m_2} + \frac{\overline{\beta^4}}{m_3}\right)}{1 + \overline{\alpha^2} + \overline{\beta^2}},$$

where ${}_1F_1(\cdot\,;\ \cdot\,;\ \cdot)$ is a confluent hypergeometric function.

B. Maximum Achievable Rate in Special Cases

1) Receiving interference from one side: When the base station in the m^{th} cell only receives co-channel interferences from users in the $(m-1)^{th}$ cell, $\overline{\beta^2} = 0$ holds. Based on Meijer's G-functions [9], the closed-form maximum achievable rate with interference from one side can be rewritten as

$$\begin{aligned} R_{SCP\_m} &= \varepsilon_o \left(\frac{\overline{P_t}}{K}\right)^{-Km_1-Km_2} G_1 \\ &+\varepsilon_o \log K \left(\frac{m_2}{\overline{\alpha^2}\Omega}\right)^{-Km_1-Km_2} G_2 \\ &-\frac{1}{\Gamma(Km_2)} G_{3,2}^{1,3}\left(\begin{matrix} 1-Km_2, 1, 1 \\ 1, 0 \end{matrix} \middle| \frac{\overline{P_t}\overline{\alpha^2}\Omega}{Km_2}\right) - \log K \end{aligned} \tag{10}$$

with

$$\varepsilon_o = \left(\frac{m_1}{\Omega}\right)^{Km_1} \left(\frac{m_2}{\overline{\alpha^2}\Omega}\right)^{Km_2} \frac{1}{\Gamma(Km_1),}$$

$$G_1 = G_{2,2:0,1:1,2}^{2,1:1,0:1,1}\left(\begin{matrix} {}^{-Km_1-Km_2, 1-Km_1-Km_2}_{-Km_1-Km_2, -Km_1-Km_2} \Big| {}^{-}_{0} \Big| \\ {}^{1-Km_1}_{0, 1-Km_1-Km_2} \Big| \\ \frac{m_2 K}{\overline{\alpha^2}\Omega\overline{P_t}}, \frac{K\left(\frac{m_1}{\Omega} - \frac{m_2}{\overline{\alpha^2}\Omega}\right)}{\overline{P_t}} \end{matrix}\right),$$

$$G_2 = G_{2,2}^{1,2}\left(\begin{matrix} 1-Km_1-Km_2, 1-Km_1 \\ 0, 1-Km_1-Km_2 \end{matrix} \middle| \\ \left(\frac{m_1}{\Omega} - \frac{m_2}{\overline{\alpha^2}\Omega}\right)\frac{\overline{\alpha^2}\Omega}{m_2}\right).$$

2) Receiving same interference from two sides: It is assumed that the base station in the m^{th} cell receives the same interference from the $(m-1)^{th}$ and $(m+1)^{th}$ cells, i.e., $\overline{\alpha^2} = \overline{\beta^2}$ and $m_2 = m_3$.

Based on Meijer's G-functions, the closed-form maximum achievable rate with same interference from two sides is derived as

$$
\begin{aligned}
&R_{SCP\_m} \\
&= \left(\frac{m_1}{\Omega}\right)^{Km_1}\left(\frac{m_2}{\overline{\alpha^2}\Omega}\right)^{2Km_2}\frac{1}{\Gamma\left(Km_1\right)}\left(\frac{\overline{P_t}}{K}\right)^{-Km_1-2Km_2} G_3 \\
&+\left(\frac{m_1\overline{\alpha^2}}{m_2}\right)^{Km_1}\frac{\log K}{\Gamma\left(Km_1\right)}G_4-\frac{1}{\Gamma\left(2Km_2\right)}G_5-\log K
\end{aligned}
\tag{11}
$$

with

$$
G_3 = G^{2,1:1,0:1,1}_{2,2:0,1:1,2}\left(\begin{array}{l} {}^{-Km_1-2Km_2,1-Km_1-2Km_2}_{-Km_1-2Km_2,-Km_1-2Km_2}\Big| \, {}^{-}_{0} \, \Big| \\ {}^{1-Km_1}_{0,1-Km_1-2Km_2}\Big| \\ \dfrac{Km_2}{\overline{\alpha^2}\Omega\overline{P_t}}, \dfrac{K\left(\overline{\alpha^2}m_1-m_2\right)}{\overline{\alpha^2}\Omega\overline{P_t}} \end{array}\right),
$$

$$
G_4 = G^{1,2}_{2,2}\left(\begin{array}{c} 1-Km_1-2Km_2, 1-Km_1 \\ 0, 1-Km_1-2Km_2 \\ \dfrac{\overline{\alpha^2}m_1-m_2}{m_2} \end{array}\right),
$$

$$
G_5 = G^{1,3}_{3,2}\left(\begin{array}{c} 1-2Km_2,1,1 \\ 1,0 \end{array}\middle| \frac{\overline{\alpha^2}\Omega\overline{P_t}}{Km_2}\right).
$$

3) Ignoring interference: When the average inter-cell power interference factors in (9) are configured as $\overline{\alpha^2} = \overline{\beta^2} = 0$, interference from adjacent cells is ignored. Based on Meijer's G-functions, the closed-form maximum achievable rate without interference can be expressed as

$$
R_{SCP\_\max} = \frac{1}{\Gamma\left(Km_1\right)}G^{1,3}_{3,2}\left(\begin{array}{c} 1-Km_1,1,1 \\ 1,0 \end{array}\middle| \frac{\overline{P_t}\Omega}{Km_1}\right).
\tag{12}
$$

IV. Numerical Analysis

Based on the maximum achievable rate over Nakagami-m fading uplink channels obtained in the last section, some numerical performance evaluations are performed. The following parameters are used in the numerical evaluation: the received signal power Ω at a BS is normalized as 1, the average user transmission power is configured $\bar{P}_{tr} = 10$dB.

A. Receiving Interference From One Side

Supposing that the number of users in a cell $K = 1$ and the Nakagami-m fading severity parameter $m_2 = 1$ in the $(m-1)^{th}$ cell, the maximum achievable rate per cell for different channel conditions is shown in Fig. 2.

Given that the Nakagami-m fading severity parameter is configured as $m_1 = m_2 = 2$, Fig. 3 illustrates the maximum achievable rate per cell as a function of the number of users in a cell.

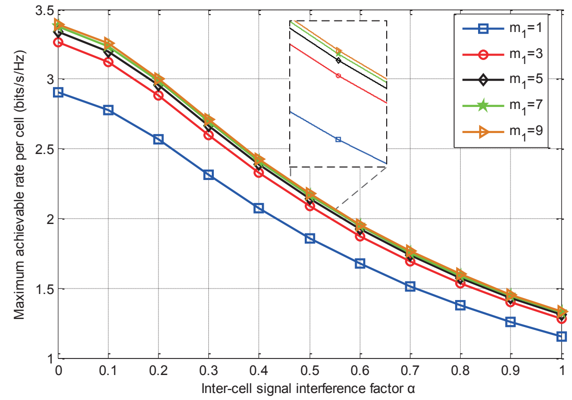

Fig. 2. Maximum achievable rate per cell with respect to the inter-cell signal interference factor and the signal fading severity parameter

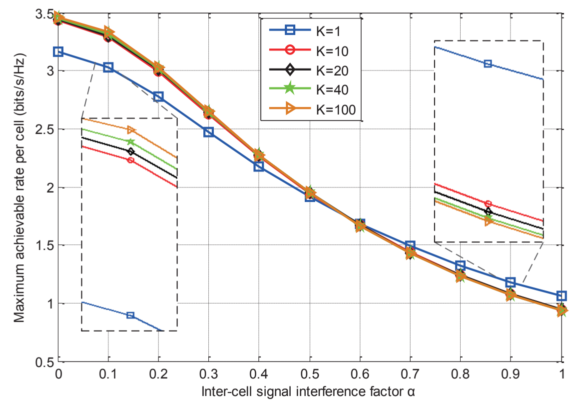

Fig. 3. Maximum achievable rate per cell with respect to the inter-cell signal interference factor and the user number in a cell

B. Receiving Same Interference From Two Sides

Supposing that the number of users in a cell $K = 1$ and the Nakagami-m fading severity parameter $m_2 = m_3 = 1$ in the $(m-1)^{th}$ and $(m+1)^{th}$ cells, the maximum achievable rate per cell for different channel conditions is shown in Fig. 4.

Given that the Nakagami-m fading severity parameter is configured as $m_1 = m_2 = m_3 = 1$, Fig. 5 illustrates the maximum achievable rate per cell as a function of the number of users in a cell.

C. Ignoring Interference

When the interference from adjacent cells is ignored, the maximum achievable rate per cell for different channel conditions and different numbers of users is shown in Fig. 6.

V. Discussions and Conclusions

From Fig. 2, Fig. 3, Fig. 4 and Fig. 5, it can be seen that the maximum achievable rate per cell decreases with the increase of the inter-cell signal interference factor.

From Fig. 2, Fig. 4 and Fig. 6, it can be seen that the maximum achievable rate per cell increases with the increase

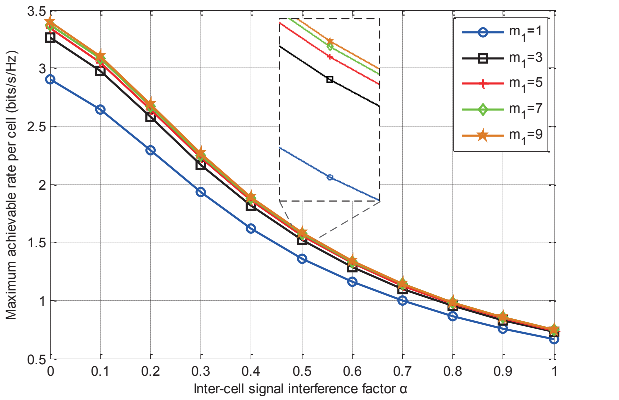

Fig. 4. Maximum achievable rate per cell with respect to the inter-cell signal interference factor and the signal fading severity parameter

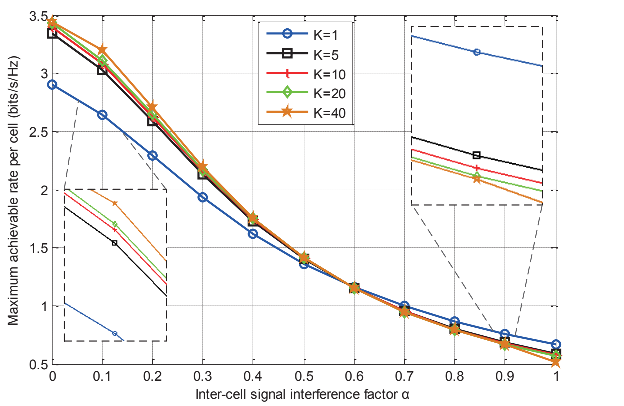

Fig. 5. Maximum achievable rate per cell with respect to the inter-cell signal interference factor and the user number in a cell

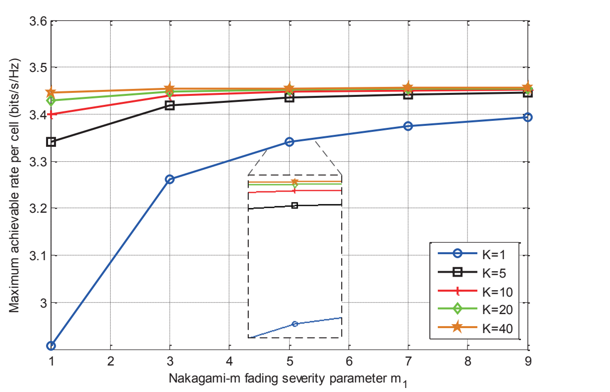

Fig. 6. Maximum achievable rate per cell with respect to the Nakagami-m fading severity parameter m_1 and the user number in a cell

of the Nakagami-m fading severity parameter m_1 in the m^{th} cell when the inter-cell signal interference factor is fixed or there is no inter-cell interference. Because the expectation of desired signals power increases with the increase of Nakagami-m fading severity parameter m_1 in the m^{th} cell. Consider the Eq. (6), the maximum achievable rate per cell will increase when the expectation of desired signals power increases.

From Fig. 3, Fig. 5 and Fig. 6, it can be seen that the maximum achievable rate per cell increases with the increase of the user number in a cell when the inter-cell signal interference factor is less than a common value or there is no inter-cell interference. This result indicates that tthe maximum achievable rate is mainly affected by the benefit of increasing the multi-user diversity in the low interference case or the none interference case. When the inter-cell signal interference factor is large than a common value, the maximum achievable rate per cell decreases with the increase of the user number in a cell. Consider the Eq. (6), the interference power increase with the increase of the number of users per cell. This result implies that the maximum achievable rate is mainly affected by the interference in the high interference case. This result is consistent with the result in interference limited cellular networks [10].

In this paper, we have derived a closed-form maximum achievable rate for cellular networks with Nakagami-m fading uplink channels. Furthermore, some special cases are analyzed. Numerical results show that the maximum achievable rate decreases with the increase of the inter-cell signal interference factor and is also affected by Nakagami-m fading severity parameters and number of users in a cell. The results of the maximum achievable rate can be used to evaluate the impact of inter-cell co-channel interference on the achievable data rate in cellular networks for network operators designing cellular networks. We will further explore the impact of cooperative communications on the maximum achievable rate in the future.

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