IoT-RELAYING INFORMATION TRANSFER WITH MASSIVE MIMO

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Abstract

This paper studies the performance of a IoT-relaying node transmission with massive multiple-input multiple-output (MIMO) system network. The system is a simple schematic setup which includes one user, one IoT-relaying node and one base station (BS). The user and IoT-relaying node have a single antenna while the BS is equipped with a hundred and/or even a thousand of antennas array. The transmission protocol is performed based on a very simple amplify-and-forward (AF) relaying scheme. To decode the transmitted signal from the user, the BS applies maximum-ratio (MR) combining technique (the combined channel of the links from the user to BS and the IoT-relaying node to the BS) under assumption of perfect channel station (CSI). The exact closed-form of the throughput and the results for the signal-to-interference-plus-noise ratio (when the number of relay antennas goes to large) are analyzed.

Keywords: Amplify and forward, CSI, IoT-Relaying, massive MIMO

1. Introduction

The Internet-of-thing (IoT) is currently investigating which add the massive multiple-input multiple-output (MIMO) to boost the system rate where the users are very weak channel direct links to the destination. In the work of (Nguyen, Nguyen, Vu, da Costa, & Ho, 2020), a system with IoT-based coordinated direct and relay transmission adopting non-orthogonal multiple access, where an information source directly communicates with a strong user while a weak user needs the help of an IoT master node. MIMO is a modelized transmission protocol where a base station with a very large antenna array simultaneously serves a group of users (tens or hundreds of users) (Hassan & Fernando, 2017; Marzetta, 2015; Ngo, 2015). The study on the channel hardening and favorable properties when the number of antennas is scaled up, massive MIMO can achieve a huge system performance base on a very simple linear processing technique such as maximum-ratio, zero-forcing, and minimum mean-square error (MMSE) processing (Marzetta, 2015; Yang, Liang, Song, Xu, & Jin, 2018).

Recently, the application of massive MIMO technology to relaying networks has attracted a lot of research interest since it can reap all benefits of both technologies. In particular, the design of massive MIMO system is promised key technology for fifth and sixth generation (5G and 6G) wireless communication were showed in (Ibrahim et al., 2023; Mohammadi, Vu, Ngo, & Matthaiou, 2023; Ngo, Interdonato, Larsson, Caire, & Andrews, 2024). The work of (Ho, Ngo, Matthaiou, & Duong, 2017a) derived the ergodic rate with maximum-ratio (MR) processing and showed that the energy efficiency scales with the number of relay antennas. Moreover, (Ho, Ngo, Matthaiou, & Duong, 2017b) analyzed the achievable rate of a multi-way massive MIMO relay network with zero-forcing processing at the relay under assumption that the relay has perfect channel state (CSI) to detect all bearing-data from all users. This work also analyzed the system performance, as well as, to compare the achievable rate with zero-forcing (ZF) and maximum-ratio processing (MRC). It is shown that by using massive antenna arrays at the relay station, the interference can be reduced significantly and hence improve the system network performance drastically. All above works examine a system where multiple users communicate with each other with the help of a relay equipped with massive antenna arrays. A system in (Wang et al., 2024) where the base station (BS) equipped with massive antenna arrays transmits signals to the users in the downlink with the help of relays was proposed and illustrated. In this paper, the channel state information (CSI) needs to be estimated at the BS and the relay. In addition, the direct links from the BS to the users are unavailable. Furthermore, the work of (Muharar, Yunida, & Nasaruddin, 2024) studied the uplink and downlink transmission of a multiuser massive MIMO which issue is resolved by performing the analysis in the large system regime, where the number of users and the number of antennas at the relay go unbounded with a constant ratio under assumption of no imperfect CSI at the relay and the direct link from users to the BS were not considered in this paper (Kudathanthirige & Baduge, 2017).

The contributions of this work are we analysis the simple the transmission protocol where the system includes one user wants to transmit its bearing signal to the Massive MIMO base station with the help of IoT-relaying node. The system also takes into account the direct link for data acquisition. From the system analysis, we propose the exact closed-form expression for the achieve rate by employing the maximum-ratio processing at the base station. In the first schedule, the user sends its bearing data to the IoT-relaying node and the base station (via the direct link) at the same time-frequency band. In the second step the IoT-relaying node forward the scaled version of the user’s data to the base station. From the closed-form expression for the achievable rate, we compare various scenarios of the Signal-to-Noise Ratio (SNR) when the number of base station antenna changing. Furthermore, we also tress the system structure is very useful in realistic to improve the signal throughput of the user at the cell boundaries or the users who have very weak direct channel to the base station.

Notation: Vectors are represented via upper and lower-case boldface letters. The Hermitian transpose, Frobenius norm of vector **a**, variance and expectation operator are denoted by $\mathbf{a}^H$, $\|\mathbf{a}\|_F$, $Var\{.\}$, and $\mathbf{E}\{.\}$, respectively.

2. System Model

We consider an IoT-relaying transformation system with massive MIMO network as shown in Fig. 1, which includes one user, one IoT-relay node and one base station (BS). The user and IoT-relay node have one antenna, while the BS is equipped with M antennas. In this system, the user wants to transfer its information to the BS via the help of single antenna IoT-relaying node. We assume the system operates in half-duplex mode with a simple amplify and forward (AF) protocol; IoT-relaying node and the BS have perfect channel state information (CSI). More precisely, the user first sends its signal to the IoT-relaying node and the BS in the same time-frequency band. Then, the IoT-relaying node amplify the received signal and forward it to the BS. Finally, the BS uses the maximum-ratio combining (MRC) technique to combine the received signal from the user (via the direct link) and the signal transmitted from IoT-relaying node.

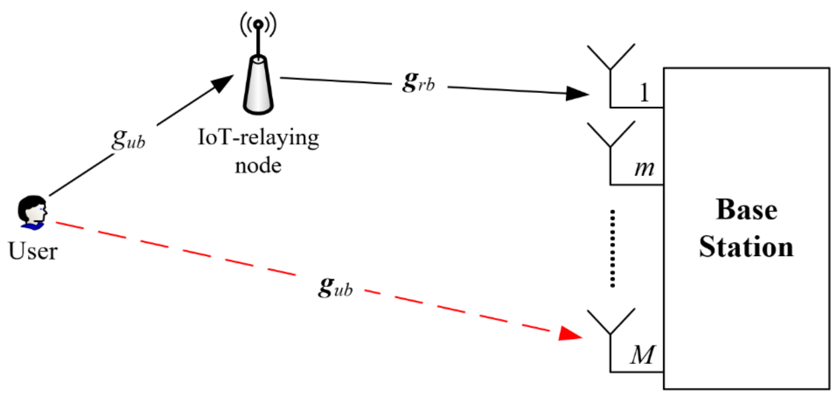

Figure 1. Schematic of AF IoT-relaying information transfer with massive MIMO network.

Let $g_{ur} = \sqrt{\beta_{ur}} h_{ur}$ is the channel coefficient between the user and IoT-relaying node, $\mathbf{g}_{ub} = \sqrt{\beta_{ub}} \mathbf{h}_{ub}$ is the channel from the user to the BS with $(M \times 1)$ channel matrix and $g_{rb} = \sqrt{\beta_{rb}} h_{rb}$ be the channel between IoT-relaying node and the BS, where $h_{ur} \sim CN(0,1)$, $\mathbf{h}_{ub} \sim CN(0, \mathbf{I}_M)$, $h_{rb} \sim CN(0,1)$ represent the small-scale fading and β_{ur}, β_{ub}, β_{rb} models the large-scale fading.

a. Signal Transmission Protocol

1) The First Phase: In this phase, the user simultaneously transmits its signal to the IoT-relaying node and the BS. Let $x = \sqrt{\rho} s$ is the transmitted data from the user, where $\mathbf{E}\left\{ |s|^2 \right\} = 1$, be the signal transmitted from the user, P_u is normalized the power of the user. Then, the (1×1) and $(M \times 1)$ signals received at the IoT-relaying node and the BS are, respectively, given by

$$y_r^{(1)} = g_{ur} x + w_r^{(1)} = \sqrt{P_u} g_{ur} s + w_r^{(1)}. \tag{1}$$

$$\mathbf{y}_b^{(1)} = \mathbf{g}_{ub} x + \mathbf{w}_b^{(1)} = \sqrt{P_u} \mathbf{g}_{ub} s + \mathbf{w}_b^{(1)}. \tag{2}$$

where $w_r^{(1)} \sim CN(0,1)$ and $\mathbf{w}_b^{(1)} \sim CN(0, \mathbf{I}_M)$ are the vector noise Additive White Gaussian Noise (AWGN) at the IoT-relaying node and the BS, respectively.

2) The Second Phase: In this phase, the IoT-relaying node first amplifies its received signal $y_r^{(1)}$ at the IoT-relaying node in the first phase as $x_r = \sqrt{\alpha_r} y_r^{(1)}$, where α_r is the normalization factor which is selected to satisfy the power constraint at the IoT-relaying node by

$$\mathbf{E}\left\{ |x_r|^2 \right\} = P_r. \tag{3}$$

We obtain,

$$\alpha_r = \frac{P_r}{P_u \mathbf{E}\left\{ \|g_{ur}\|^2 \right\} + \mathbf{E}\left\{ \|w_r^{(1)}\|^2 \right\}} = \frac{P_r}{P_u \beta_{ur} + 1}. \tag{4}$$

With the transmit signal $x_r = \sqrt{\alpha_r} y_r^{(1)}$, the BS receive the signal transmitted from the IoT-relaying in the second phase as follow

$$\begin{aligned} \mathbf{y}_b^{(2)} &= \mathbf{g}_{rb} x_r + \mathbf{w}_b^{(2)} = \mathbf{g}_{rb} \sqrt{\alpha_r} y_r^{(1)} + \mathbf{w}_b^{(2)} = \mathbf{g}_{rb} \sqrt{\alpha_r} \left(\sqrt{P_u} g_{ur} s + w_r^{(1)} \right) + \mathbf{w}_b^{(2)} \\ &= \sqrt{P_u \alpha_r} \mathbf{g}_{rb} g_{ur} s + \sqrt{\alpha_r} \mathbf{g}_{rb} w_r^{(1)} + \mathbf{w}_b^{(2)}. \end{aligned} \tag{5}$$

where $\mathbf{w}_b^{(2)} \sim CN(0, \mathbf{I}_M)$ is AWGN vector at the BS.

Now, the BS receives $\mathbf{y}_b^{(1)} \in \mathrm{C}^{M \times 1}$ from the user in the first phase, and $\mathbf{y}_b^{(2)} \in \mathrm{C}^{M \times 1}$ from the relay in the second phase as follows

$$\begin{aligned} \mathbf{y}_b = \begin{bmatrix} \mathbf{y}_b^{(1)} \\ \mathbf{y}_b^{(2)} \end{bmatrix} &= \begin{bmatrix} \sqrt{P_u} \mathbf{g}_{ub} s + \mathbf{w}_b^{(1)} \\ \sqrt{P_u \alpha_r} \mathbf{g}_{rb} g_{ur} s + \sqrt{\alpha_r} \mathbf{g}_{rb} w_r^{(1)} + \mathbf{w}_b^{(2)} \end{bmatrix} \\ &= \begin{bmatrix} \sqrt{P_u} \mathbf{g}_{ub} \\ \sqrt{P_u \alpha_r} \mathbf{g}_{rb} g_{ur} \end{bmatrix} s + \begin{bmatrix} \mathbf{w}_b^{(1)} \\ \sqrt{\alpha_r} \mathbf{g}_{rb} w_r^{(1)} + \mathbf{w}_b^{(2)} \end{bmatrix} \\ &= \mathbf{g} s + \mathbf{w}. \end{aligned} \tag{6}$$

where

$$\mathbf{g} = \begin{bmatrix} \sqrt{P_u}\mathbf{g}_{ub} \\ \sqrt{P_u\alpha_r}\mathbf{g}_{rb}g_{ur} \end{bmatrix}, \quad \mathbf{w} = \begin{bmatrix} \mathbf{w}_b^{(1)} \\ \sqrt{\alpha_r}\mathbf{g}_{rb}w_r^{(1)} + \mathbf{w}_b^{(2)} \end{bmatrix}. \tag{7}$$

b. Data Detection

From the received signal vector in (6), the BS will detect the desired signal s from the user. To do this, MRC technique is implemented, the combination signal after using MRC scheme is denoted as followed:

$$\begin{aligned} \tilde{y}_b &= \mathbf{g}^H\mathbf{y}_b = \mathbf{g}^H\mathbf{g}s + \mathbf{g}^H\mathbf{w} = \mathbf{E}\{\mathbf{g}^H\mathbf{g}\}s + \left(\mathbf{g}^H\mathbf{g} - \mathbf{E}\{\mathbf{g}^H\mathbf{g}\}\right)s + \mathbf{g}^H\mathbf{w} \\ &= \mathbf{E}\{\mathbf{g}^H\mathbf{g}\}s + \tilde{\mathbf{w}}. \end{aligned} \tag{8}$$

where $\tilde{\mathbf{w}} = \left(\mathbf{g}^H\mathbf{g} - \mathbf{E}\{\mathbf{g}^H\mathbf{g}\}\right)s + \mathbf{g}^H\mathbf{w}$.

3. Achievable rate Analysis

In this section, we analyze a closed-form expression for the system throughput of the system network in (8). We can see that, the achievable rate in (8) as follow:

$$\begin{aligned} R &= \log_2\left(1 + \frac{\left|\mathbf{E}\{\mathbf{g}^H\mathbf{g}\}\right|^2}{\mathbf{E}\left|\mathbf{g}^H\mathbf{g} - \mathbf{E}\{\mathbf{g}^H\mathbf{g}\}\right|^2 + \mathbf{E}\left\{\left|\mathbf{g}^H\mathbf{w}\right|^2\right\}}\right) \\ &= \log_2\left(1 + \frac{\left|\mathbf{E}\{\mathbf{g}^H\mathbf{g}\}\right|^2}{Var\left(\mathbf{g}^H\mathbf{g}\right) + \mathbf{E}\left\{\left|\mathbf{g}^H\mathbf{w}\right|^2\right\}}\right). \end{aligned} \tag{9}$$

To derive the achievable rate in closed-form, we need to compute $\mathbf{E}\{\mathbf{g}^H\mathbf{g}\}$, $Var\left(\mathbf{g}^H\mathbf{g}\right)$ and $\mathrm{E}\left\{\left|\mathbf{g}^H\mathbf{w}\right|^2\right\}$.

We first we calculate:

1) Compute $\left|\mathbf{E}\{\mathbf{g}^H\mathbf{g}\}\right|^2$

We have:

$$\begin{aligned} \mathbf{E}\{\mathbf{g}^H\mathbf{g}\} &= \mathbf{E}\left\{\left[\sqrt{P_u}\mathbf{g}_{ub}^H \quad \sqrt{P_u\alpha_r}\mathbf{g}_{rb}^H g_{ur}\right]\begin{bmatrix} \sqrt{P_u}\mathbf{g}_{ub} \\ \sqrt{P_u\alpha_r}\mathbf{g}_{rb}g_{ur} \end{bmatrix}\right\} \\ &= \mathbf{E}\left\{P_u\|\mathbf{g}_{ub}\|^2 + P_u\alpha_r\|\mathbf{g}_{rb}\|^2|g_{ur}|^2\right\} = P_u\mathbf{E}\left\{\|\mathbf{g}_{ub}\|^2\right\} + P_u\alpha_r\mathbf{E}\left\{\|\mathbf{g}_{rb}\|^2|g_{ur}|^2\right\} \\ &= MP_u\left(\beta_{ub} + \alpha_r\beta_{rb}\beta_{ur}\right). \end{aligned} \tag{10}$$

Therefore,

$$\left|\mathbf{E}\{\mathbf{g}^H\mathbf{g}\}\right|^2 = M^2P_u^2\left(\beta_{ub} + \alpha_r\beta_{rb}\beta_{ur}\right)^2. \tag{11}$$

2) Compute $Var\left(\mathbf{g}^H\mathbf{g}\right)$

We have:

$$Var\left(\mathbf{g}^H\mathbf{g}\right)=\mathbf{E}\left\{\left|\mathbf{g}^H\mathbf{g}\right|^2\right\}-\left|\mathbf{E}\left\{\mathbf{g}^H\mathbf{g}\right\}\right|^2=\mathbf{E}\left\{\left|\mathbf{g}^H\mathbf{g}\right|^2\right\}-M^2P_u^2\left(\beta_{ub}+\alpha_r\beta_{rb}\beta_{ur}\right)^2. \quad (12)$$

From (11), we now compute

$$\begin{aligned}\mathbf{E}\left\{\left|\mathbf{g}^H\mathbf{g}\right|^2\right\}&=\mathbf{E}\left\{\left|\left[\sqrt{P_u}\mathbf{g}_{ub}^H \quad \sqrt{P_u\alpha_r}\,g_{ur}^H\mathbf{g}_{rb}^H\right]\begin{bmatrix}\sqrt{P_u}\mathbf{g}_{ub}\\ \sqrt{P_u\alpha_r}\mathbf{g}_{rb}g_{ur}\end{bmatrix}\right|^2\right\}\\
&=\mathbf{E}\left\{\left|P_u\left\|\mathbf{g}_{ub}\right\|^2+P_u\alpha_r\left\|\mathbf{g}_{rb}\right\|^2\left|g_{ur}\right|^2\right|^2\right\}\\
&=\mathbf{E}\left\{P_u^2\left\|\mathbf{g}_{ub}\right\|^4+2P_u^2\alpha_r\left\|\mathbf{g}_{ub}\right\|^2\left\|\mathbf{g}_{rb}\right\|^2\left|g_{ur}\right|^2+P_u^2\alpha_r^2\left\|\mathbf{g}_{rb}\right\|^4\left|g_{ur}\right|^4\right\}\\
&=P_u^2\mathbf{E}\left\{\left\|\mathbf{g}_{ub}\right\|^4\right\}+2P_u^2\alpha_r\mathbf{E}\left\{\left\|\mathbf{g}_{ub}\right\|^2\left\|\mathbf{g}_{rb}\right\|^2\left|g_{ur}\right|^2\right\}+P_u^2\alpha_r^2\mathbf{E}\left\{\left\|\mathbf{g}_{rb}\right\|^4\left|g_{ur}\right|^4\right\}.\end{aligned} \quad (13)$$

By using Lemma 2.10 in (Tulino & Verdú, 2004), (13) can be obtained as

$$\mathbf{E}\left\{\left|\mathbf{g}^H\mathbf{g}\right|^2\right\}=M(M+1)P_u^2\beta_{ub}^2+2M^2P_u^2\alpha_r\beta_{ub}\beta_{rb}\beta_{ur}^2+2P_u^2\alpha_r^2M(M+1)\beta_{rb}^2\beta_{ur}^2. \quad (14)$$

Therefore, by substituting (14) into (13) we achieve

$$\begin{aligned}Var\left(\left\|\mathbf{g}\right\|^2\right)&=\left(M(M+1)P_u^2\beta_{ub}^2+2M^2P_u^2\alpha_r\beta_{ub}\beta_{rb}\beta_{ur}^2+2P_u^2\alpha_r^2M(M+1)\beta_{rb}^2\beta_{ur}^2\right)\\
&\quad-M^2P_u^2\left(\beta_{ub}+\alpha_r\beta_{rb}\beta_{ur}\right)^2.\end{aligned} \quad (15)$$

3) Compute $\mathrm{E}\left\{\left|\mathbf{g}^H\mathbf{w}\right|^2\right\}$

We have

$$\begin{aligned}\mathrm{E}\left\{\left|\mathbf{g}^H\mathbf{w}\right|^2\right\}&=\mathbf{E}\left\{\left|\left[\sqrt{P_u}\mathbf{g}_{ub}^H \quad \sqrt{P_u\alpha_r}\,g_{ur}^H\mathbf{g}_{rb}^H\right]\begin{bmatrix}\mathbf{w}_b^{(1)}\\ \sqrt{\alpha_r}\mathbf{g}_{rb}w_r^{(1)}+\mathbf{w}_b^{(2)}\end{bmatrix}\right|^2\right\}\\
&=\mathbf{E}\left\{\left|\sqrt{P_u}\mathbf{g}_{ub}^H\mathbf{w}_b^{(1)}+\sqrt{P_u\alpha_r}\,g_{ur}^H\mathbf{g}_{rb}^H\left(\sqrt{\alpha_r}\mathbf{g}_{rb}w_r^{(1)}+\mathbf{w}_b^{(2)}\right)\right|^2\right\}\\
&=\mathbf{E}\left\{\left|\sqrt{P_u}\mathbf{g}_{ub}^H\mathbf{w}_b^{(1)}+\sqrt{P_u}\alpha_r g_{ur}^H\mathbf{g}_{rb}^H\mathbf{g}_{rb}w_r^{(1)}+\sqrt{P_u\alpha_r}\,g_{ur}^H\mathbf{g}_{rb}^H\mathbf{w}_b^{(2)}\right|^2\right\}\\
&=P_u\mathbf{E}\left\{\left\|\mathbf{g}_{ub}\right\|^2\right\}+P_u\alpha_r^2\mathbf{E}\left\{\left\|\mathbf{g}_{rb}\right\|^4\left|g_{ur}\right|^2\right\}+P_u\alpha_r\mathbf{E}\left\{\left\|\mathbf{g}_{rb}\right\|^2\left|g_{ur}\right|^4\right\}.\end{aligned} \quad (16)$$

From (17), the closed-form of $\mathrm{E}\left\{\left|\mathbf{g}^H\mathbf{w}\right|^2\right\}$ is

$$\mathrm{E}\left\{\left|\mathbf{g}^H\mathbf{w}\right|^2\right\}=MP_u\beta_{ub}+M(M+1)P_u\alpha_r^2\beta_{rb}^2\beta_{ur}+MP_u\alpha_r\beta_{rb}\beta_{ur}^2. \quad (17)$$

4. Numerical Results

In this section, we choose the parameter setting as follows $\beta_{ur}=\beta_{ub}=\beta_{rb}=1$ for all simulations. The system operations under the perfect channel state information and amplified and forward.

we first illustrate numerical results to validate the correctness of our analytical results. Figure 2 compares the performance of the IoT-relaying node transmission with massive MIMO network with different power transmission of the user (the IoT-relaying node power transmission is fixed). It is clear from the Fig 2 that our analytical results match perfectly with simulations results. It means that, the accuracy of our analytical examination. Note that, the achievable rate increases when the number of antennas at the BS increases. Besides that, the spectral performance of the system schematic is also growth when the power of the user increase.

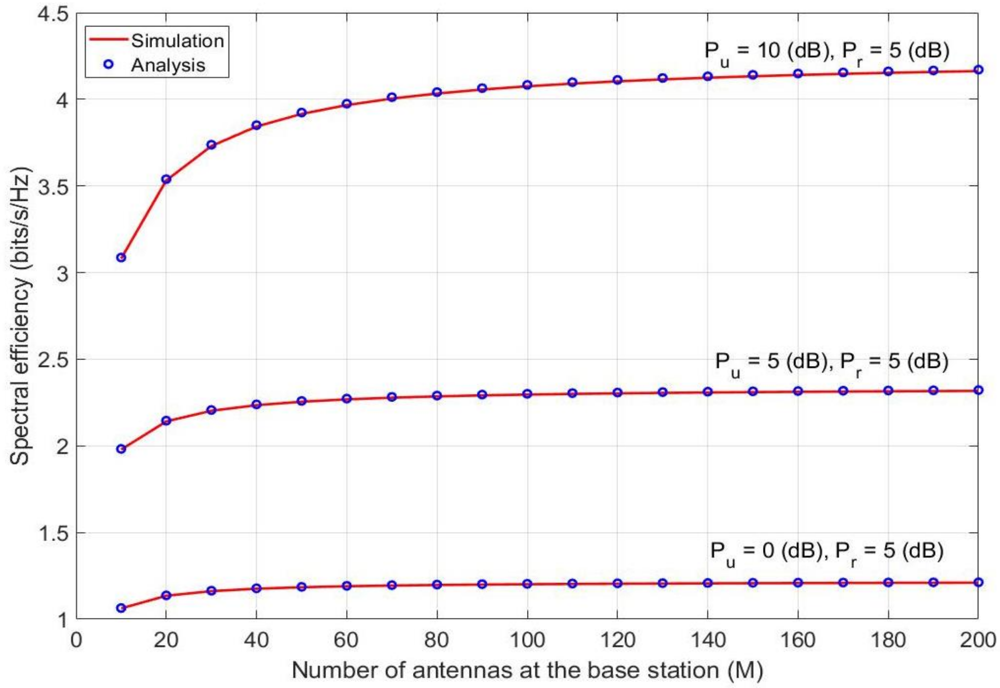

Figure 2. System throughput of the IoT-relaying node with massive MIMO structure versus *M* when SNR (dB) is variation.

Finally, we examine the effect of SNR with different $M(50, 100, 150)$ on the system performance as show in Figure 3. It is clearly that, when the SNR increases the system throughput increases. We also can see that with large antenna array at the BS, the performance of the system is very high rate compared to that the one for small number of antennas.

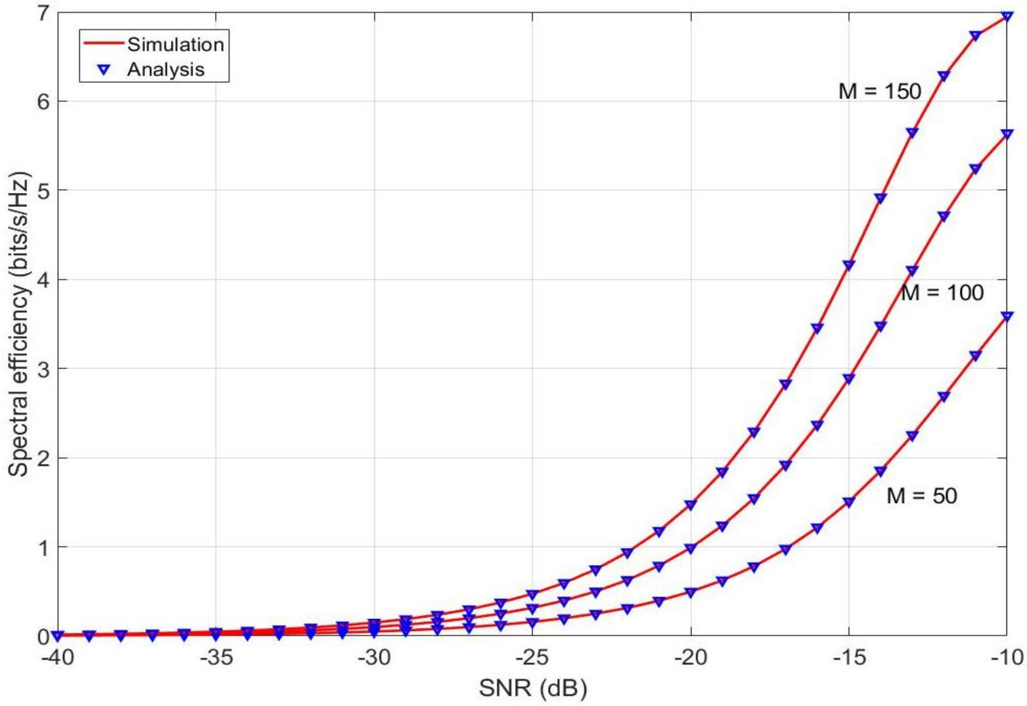

Figure 3. Achievable rate of the IoT-relaying node with massive MIMO network system versus SNR (dB) when *M* is difference.

5. Conclusion

We have illustrated the performance of the IoT-relaying node information transfer with the help of IoT-relaying where a system schematic considers a single-antenna user, a single-antenna IoT-relaying node and a hundred/thousand of antenna base station. We have investigated that by assisting the IoT-relaying node and massive MIMO antennas base station we can increase the system performance throughput. The system will be realistic manner when the users have weak channel direct links to transfer their signal to the destination. For the next step of our research is we will investigate the system performance with multiple users manner and imperfect channel state information.

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