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Performance Analysis of Relay-Assisted Millimeter-Wave Network in SWIPT-Enabled MIMO-NOMA Systems

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Abstract—This paper addresses the challenge of improving the digitalisation of 5G communications, with multiple-input-multiple-output (MIMO) non-orthogonal multiple access (NOMA) systems employing relaying, by using simultaneous wireless information and power transfer (SWIPT). In the case of a massive number of users, the connections demand a more efficient network. Therefore, we design a novel framework for a relay-assisted SWIPT NOMA system, to analyze the improvement of SWIPT transmission with NOMA. We derive a closed-form expression for a lower range of spectral efficiencies, assess the performance of the designed system through sum rate analysis, and discuss the power splitting ratio dependence of the performance. Finally, the sum rate is calculated to present the capability of this novel scheme.

1. INTRODUCTION

Commercial deployment of the fifth-generation (5G) wireless communications is being accelerated worldwide [1, 2]. The key drivers for this acceleration are the notable improvements compared to fourth-generation (4G) with respect to lower latency and increased spectral and power efficiencies that may benefit deployments in automotive, health care, and manufacturing verticals, to name just a few [2]. Specifically, we aim to understand and upgrade the quality-of-service (QoS) of wireless communications in an industrial setting, where it will be essential to take into account the benefits of 5G wireless networks.

Massive Multiple Input Multiple Output Non-Orthogonal Multiple Access (mMIMO-NOMA) is a technique being explored with further improving 5G capability and performance. Some studies have considered different circumstances [3–6] as compared to the conventional orthogonal multiple access (OMA) schemes [7], with the spectral efficiency noticeably improved when incorporating NOMA [8, 9]. For each massive MIMO radio frequency (RF) beam, more than one user can provide extra assistance of intra-beam superposition coding and successive interference cancellation (SIC) [8], whereas in a conventional MIMO system each beam only serves one user during the same time window. In [3], the NOMA scheme was first applied in beam space MIMO, and low-complexity hybrid-precoding and power allocation was used to maximise the achievable sum rate. In addition, resource allocation was enhanced in [10] for the purpose of maximising the energy efficiency in massive MIMO systems, and simultaneously an optimised algorithm was proposed to obtain a better power allocation.

The relay can be used to forward signals if the Line-of-Sight (LOS) signal is blocked, or if NOMA has additional bandwidth costs. The most popular solution is to employ a half-duplex (HD) relaying technology [11]. To be a more spectral efficient system, the HD relay receives and then transmits in the same frequency band, as has been applied in a 5G network in [11]. Different types of HD

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relaying techniques for decode-and-forward (DF) and amplify-and-forward (AF) relaying have been discussed in [12, 13]. In [14], the performance of HD AF used in a MIMO-NOMA system was investigated considering the outage probability and bit-error-rate. Instead of traditional relaying, the signal refraction by smart materials was studied in [15], and the intelligent surface [16] was used to replace traditional relays, which can also be used in a 5G network and its applications.

Simultaneous wireless information and power transfer (SWIPT) provides a potential solution to address the issue of energy shortage in wireless networks [17], and as such, has attracted increased research interest [18–20]. With SWIPT, both information and energy can be transferred via the same RF signal, which in practice can be achieved by power splitting or time switching [18]. The ability to transfer both power and information through a system can help the edge devices to communicate more efficiently and also prolong the lifetime of devices near the base station [19]. In this way, in cooperative systems it can provide the much-needed flexibility at relays to harvest the energy from a remote source.

In this paper, a novel relay-assisted, SWIPT-enabled, massive MIMO-NOMA system (RSMN) is proposed, where both that relaying and SWIPT are first considered simultaneously in a MIMO-NOMA system. A power splitting relay is used for each relay to realise SWIPT by splitting the received signal into two parts: information decoding (ID) and energy harvesting (EH). Compared with the previously proposed MIMO-NOMA [3] and relay-assisted NOMA systems [14], the capacity and spectral efficiency of our proposed RSMN system is greatly enhanced.

2. SYSTEM MODEL

The RSMN system, in which both information and energy harvesting are enabled and required, is depicted in Figure 1 and is supported by M relays to connect to Ψ users. In this study, the transmitter is equipped with one antenna. As shown in Figure 1, the transmission procedure includes two hops. In the first hop, the requested information is NOMA-encoded and transmitted from the base station to the relays, and simultaneously a part of the channel is separated as a sub-band for energy harvesting. In the second hop, the required information is derived by relays at the end-users' side under AF model. The AF relaying model can significantly enlarge the coverage and improve the QoS for the end-users.

At the first hop, the channel is split into two components: information with NOMA encoding and energy for harvesting. In the applied power splitting protocol, the total power in one time slot is 1; β_e defines the period used for energy harvesting (EH); $(1 - \beta_e)$ defines the period for information decoding

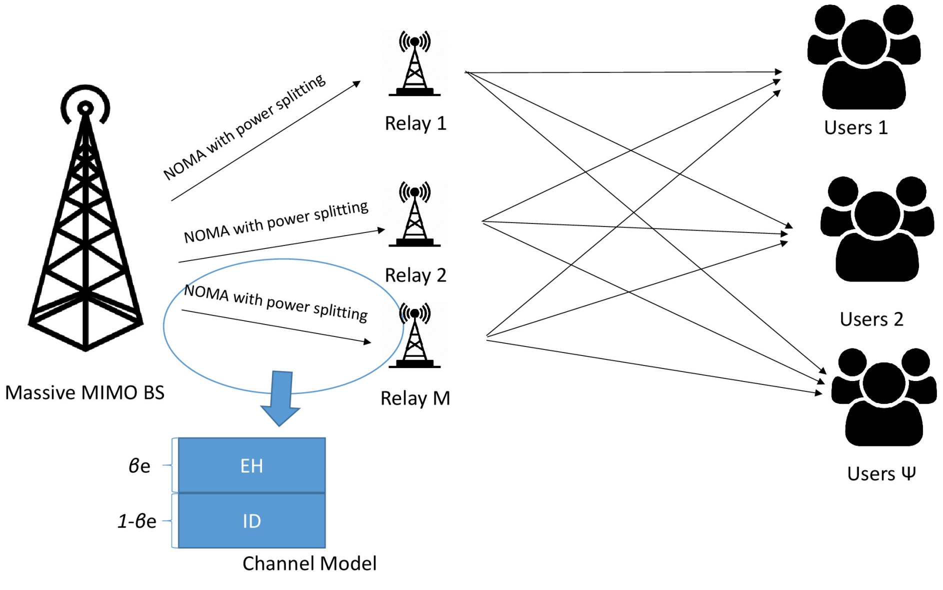

Figure 1. The relay-assisted SWIPT-enabled massive MIMO-NOMA System (RSMN).

(ID) with power splitting protocol. There is $P_{total} = \beta_e + (1 - \beta_e)$. In the second hop, the harvested energy at the relay will be used to deliver the signal to the users.

For each relay, the transmitted information x_m via NOMA encoding at BS to the mth relay can be defined as

$$x_m = \sum_{k=1}^{K_m} \sqrt{P_{m,k}} S_{m,k}, \tag{1}$$

where $S_{m,k}$ is a white Gaussian distributed signal, and $P_{m,k}$ is the energy that the mth relay utilizes to send target information to the kth user, which can be given as

$$P_{m,k} = P_m^{EH} \times q_{m,k}, \tag{2}$$

where P_m^{EH} is the power for the uplink information, and $q_{m,k}$ is the proportion that the kth user consumes in percentage of the mth relay harvested energy.

The received information in all sub-bands at the mth relay can be explained as

$$y_m = \sqrt{\varrho_m} h_m^H x_m + \sum_{j=1, j \neq m}^{M} \sqrt{\varrho_m} h_m^H x_j + N_m, \tag{3}$$

where h_m is the Rayleigh channel fading coefficient for the path from the BS to the mth relay, ϱ_m the typical path loss of the mth user, h_m^H the conjugate transpose of h_m, x_j the transmitted signal, and N_m the complex additive white Gaussian noise (AWGN).

To stipulate better fairness between multiple connections, the typical path loss for a millimeter wave MIMO system can be given as

$$\varrho_m = 20\log_{10}\left(\frac{4\pi d_{break}}{\lambda}\right) + 10\alpha_{\text{pl}}\log_{10}\left(\frac{d_m}{d_{break}}\right) + X, \tag{4}$$

where d_{break} is the distance after breakpoint from the BS to relays, α_{pl} the path loss exponent, d_m the distance between the BS and the mth relay, and $X = \alpha_o d_m$ the shadowing fading usually relevant to the atmospheric attenuation coefficient α_o, which we fix at 0.09 dB/km for average.

Additionally, SWIPT is applied to achieve better energy efficiency by using the harvested energy to support signal transfer from relays to users. The fixed gain for the case of operation at the mth relay can be expressed as

$$u_m = \sqrt{\frac{Q_m}{E[|\sqrt{\varrho_m} h_m^H x_m + N_m|^2]}}, \tag{5}$$

where $Q_m = \frac{\sum_{m=1}^{M} P_m^{EH}}{M}$ is the average power with a constant value.

The forwarded signal used for information decoding with the NOMA encoding method can be expressed as

$$Y_m = u_m \sqrt{(1 - \beta_e)} y_m. \tag{6}$$

Using the power splitting factor for the mth relay, the harvested energy can be explained as in [21], where the power for the uplink information is

$$P_m^{EH} = \frac{\eta_m \beta_e |h_m^H|^2 \sum_{k=1}^{K} P_{m,k}}{\varrho_m}, \tag{7}$$

where $P_{m,k} = P_m^{EH} \times q_{m,k}$, η_m is the power transfer efficiency of the mth relay.

In this scenario, at the second hop the received signal at the kth user's spot can be written as

$$y_{m,n} = v_{m,n}\left(\sum_{j=1}^{M} \sqrt{\alpha_{j,m,n}} g_{j,m,n} Y_m + N_{m,n}\right). \tag{8}$$

Similarly, $\alpha_{j,m,n}$ is the path loss related to the channel from the mth relay to the nth user; $g_{j,m,n}$ is the Rayleigh channel fading coefficient for the path from the mth relay to the fnth user; $N_{m,n}$ is the receiving noise; $v_{m,n} = \frac{g_{m,m,n}^*}{|g_{m,m,n}|}$ is the compensation of the channel phase.

3. THE SUM RATE AND SPECTRAL EFFICIENCY ANALYSIS

In this section, the system spectral efficiency performance is addressed. To achieve a closed-form expression, random theory with analysis procedures is applied to the energy distributed to the kth user from the mth relay. Subsequently, the signal-to-interference ratio (SIR) is addressed to obtain the final function for the system's capacity. Finally, the closed-form expression of the spectral efficiency is derived by attaining all users' capacities within the sub-band using (1), (5), (6)–(8).

$$\begin{aligned} y_{m,n} \ = \ & v_{m,n}\sqrt{\alpha_{m,m,n}\varrho_m} g_{m,m,n}\sqrt{\frac{Q_m}{E[|\sqrt{\varrho_m}h_m^H x_m+N_m|^2]}}\sqrt{(1-\beta_e)}h_m^H\sqrt{P_{m,n}}S_{m,n} \\ & +v_{m,n}\sqrt{\alpha_{m,m,n}\varrho_m} g_{m,m,n}\sqrt{\frac{Q_m(1-\beta_\mathrm{e})}{E[|\sqrt{\varrho_m}h_m^H x_m+N_m|^2]}}h_m^H\sum_{\mathrm{i=1,i\neq n}}^{\psi}\sqrt{\mathrm{P_{m,i}}}\mathrm{S_{m,i}} \\ & +v_{m,n}\sum_{j=1}^{M}\sum_{i=1}^{K_j} g_{j,m,n}\sqrt{\frac{Q_m\alpha_{j,m,n}\varrho_j}{E[|\sqrt{\varrho_j}h_j^H x_j+N_j|^2]}}\sqrt{(1-\beta_e)}h_j^H\sqrt{P_{j,i}}S_{j,i} \\ & +v_{m,n}\sum_{j=1}^{M}\sqrt{\alpha_{j,m,n}}g_{j,m,n}\sqrt{\frac{Q_m}{E[|\sqrt{\varrho_j}h_j^H x_j+N_j|^2]}}\sqrt{(1-\beta_e)}N_j+N_{m,n}, \end{aligned} \tag{9}$$

where $\alpha_{j,m,n}$ is the path loss between relay and users, specifically, and it is ensured that $\psi > n$. The end-to-end signal-to-noise ratio (SNR) can be derived as (10), and the SIR for the received signals at the users' sides is represented by (11).

3.1. Spectral Efficiency

To derive the closed-form expression of the spectral efficiency, we will employ the SNR given by (10). Generally, the spectral efficiency of the (m, k)th user in the multiple-relays assisted massive MIMO-NOMA system can be described as

$$R_{m,n}=\frac{1}{2}E[\log_2(1+\gamma_{m,n})]\times\frac{1}{2}\log_2\left(1+\frac{\Phi_{m,n,0}}{\Phi_{m,n,1}+\Phi_{m,n,2}+\Phi_{m,n,3}+\Phi_{m,n,4}+(N_{m,n})^2}\right). \tag{12}$$

In this paper, the emphasis is on the performance diversification when relays are added to a MIMO system. In this case, both $|g_{m,m,n}|^2$ and $|h_{m,m,n}|^2$ have a scaled $X^2()$ distribution by a factor of $\frac{1}{2}$. Additionally, $E[|g_{m,m,n}|] = E[|h_{m,m,n}|] = 0.8862$ can be obtained. Moreover, h_m is a constant, and $h_m = h_m^H$, thus $u_m = \sqrt{\frac{Q_m}{E[\varrho_m\sum_{k=1}^{\Psi}P_{m,k}]+1}}$.

As defined below, $\gamma_{m,n}$ in (10) is composed of four different parts. The desired signal is rewritten as

$$\Phi_{m,n,0}=\frac{E[|g_{m,m,n}|^2]E[|h_m|]^2\varrho_m\alpha_{m,m,n}P_{m,n}Q_m(1-\beta_e)}{\varrho_m P_m^{EH}+1}. \tag{13}$$

The power of the signal leakage is then given as

$$\Phi_{m,n,1}=\frac{\varrho_m\alpha_{m,m,n}P_{m,n}Q_m(1-\beta_e)}{(\varrho_m P_m^{EH}+1)}(1-E[|g_{m,m,n}|^2]E[|h_m|]^2). \tag{14}$$

Similarly, from three inter-relay interferences, one can achieve

$$\Phi_{m,n,2} \ = \ \frac{\varrho_m\alpha_{m,m,n}Q_m(1-\beta_e)\sum_{i=1}^{n-1}P_{m,i}E[|g_{m,m,n}|^2]E[|h_m^H|^2]}{\varrho_m P_m^{EH}+1}, \tag{15}$$

$$\Phi_{m,n,3} \ = \ \sum_{j=1}^{M}\frac{(1-\beta_e)\varrho_j\alpha_{j,m,n}Q_m}{\varrho_j P_j+1}, \tag{16}$$

$$\Phi_{m,n,4} \ = \ \sum_{j=1}^{M}\frac{(1-\beta_e)\alpha_{j,m,n}Q_m}{\varrho_j P_j+1}, \tag{17}$$

Substituting Equations (13), (14), (15), (16), and (17) into (12), the spectral efficiency can be computed as

$$\begin{aligned} R_{m,n} &= \frac{1}{2}\log_2\left(1+\frac{\frac{E[|g_{m,m,n}|^2]E[|h_m|]^2\varrho_m\alpha_{m,m,n}P_{m,n}u_m^2(1-\beta_e)}{(\varrho_m P_m^{EH}+1)\Gamma^2(N_t-(M-1))}}{\Phi_{m,n,1}+\Phi_{m,n,2}+\Phi_{m,n,3}+\Phi_{m,n,4}+1}\right) \\ &= \frac{1}{2}\log_2\left(1+\frac{\frac{E[|g_{m,m,n}|^2]E[|h_m|]^2\varrho_m\alpha_{m,m,n}P_{m,n}u_m^2(1-\beta_e)}{(\varrho_m P_m^{EH}+1)\Gamma^2(N_t-(M-1))}}{\ell}\right). \end{aligned} \tag{18}$$

where $\ell = \frac{\varrho_m\alpha_{m,m,n}P_{m,n}Q_m(1-\beta_e)}{(\varrho_m P_m^{EH}+1)}(1-E[|g_{m,m,n}|^2]E[|h_m|]^2)+\frac{\varrho_m\alpha_{m,m,n}Q_m(1-\beta_e)\sum_{i=1}^{n-1}P_{m,i}E[|g_{m,m,n}|^2]E[|h_m^H|^2]}{\varrho_m P_m^{EH}+1}+\sum_{j=1}^{M}\frac{\varrho_j\alpha_{j,m,n}Q_m}{\varrho_j P_j+1}+\sum_{j=1}^{M}\frac{\alpha_{j,m,n}Q_m}{\varrho_j P_j+1}+1$, and the sum rate is written as

$$S_{rate} = \sum_{m=1}^{M}\sum_{n=1}^{K} R_{m,n}. \tag{19}$$

4. NUMERICAL RESULTS

The analytical results are presented in this section. Furthermore, the sum rate performance of the RMNS system is investigated. Table 1 summarises the analytical parameters that are used. For simplicity, as a typical 5G signal strength, the input power for the base station was set to 100 mW, resulting in the possible activation of up to three antennas under these circumstances with limited power supply. Based on the parameters of the equipment in the workshop, for simplification, the energy used to transmit a signal over each path from a relay to user is fixed at an equal rate. Moreover, from the base station to each relay, there is an equal division of harvested energy in this simulation.

Several insights can be gained from the sum rate performance numerical results shown in Figure 2. Firstly, a growing number of relays always leads to a declining sum rate performance for any power splitting ratio. Secondly, a higher power splitting ratio can result in a better sum rate performance. This is due to the increasing number of relays in the NOMA system, which are subject to interference from other users, thus affecting the sum rate performance.

To verify the efficacy of SWIPT and the effects of the power splitting ratio on the non-regenerative massive MIMO-NOMA relay system, the sum rate performance for ten relays and ten users is compared

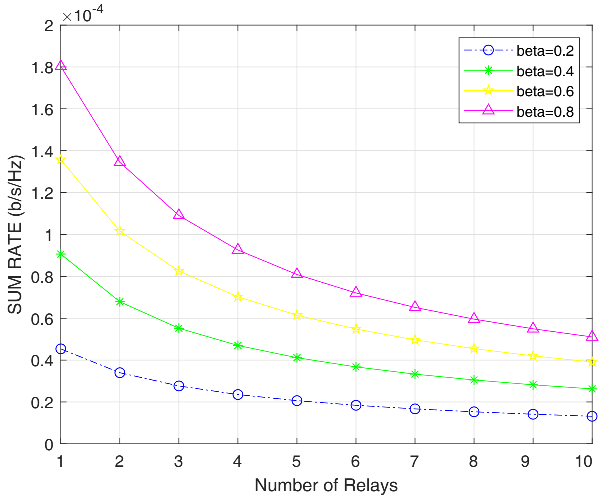

Figure 2. RSMN sum rate performance for 10 users with the power splitting ratio fixed at 0.2, 0.4, 0.6, and 0.8.

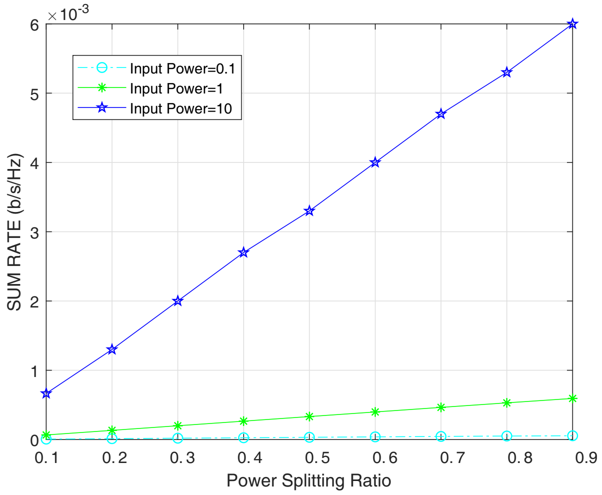

Figure 3. The analytical result of changing power splitting ratio with 10 relays and 10 users.

in Figure 3, with the energy efficiency set at 0.4. The results show that the sum-rate scales linearly with power splitting ratio.

Additionally, by increasing the input power with other constant factors, a higher spectral efficiency and sum rate can be achieved, which further evidences the ability of SWIPT.

Table 1. System parameters used in calculation.

Relays, M	Users, Ψ	Path loss exponent	Number of antennas	Power splitting ratio	Bandwidth
10	10	2	1	$0 \sim 1$	28.5 GHz

5. CONCLUSION

The novel relay-assisted SWIPT-enabled massive MIMO-NOMA system proposed here can enhance the system performance and save the power of 5G technology. The RSMN method is adopted to harvest energy from the received signal. The spectral efficiency is addressed by closed-form expressions with diversification parameters. The numerical results show that a variety of sum rates can be quickly achieved by altering the number of relays. Moreover, the results highlight that a higher energy harvest ratio provides a better sum rate for the system model, with SWIPT providing extra power to users for their energy consumption. Based on these results, a promising next step could be the investigation of this RSMN system using a MIMO system with multiple antennas [22, 23].

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