

Performance Analysis of a NOMA-Based Multi-User IoT Network with SWIPT Protocol

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Abstract

This study investigates the performance of user equipments (UEs) and Internet of Things (IoT) devices in a multi-user (MU) multiple-input single-output (MISO) configuration based non-orthogonal multiple-access (NOMA) system. The proposed model includes a base station surrounded by many users and a number of dispersed IoT devices. In the considered MU IoT network scenario, power allocation coefficients are set to ensure that both the relaying UE and the targeted IoT device experience increased performance. To assist the intended IoT device with weak channel conditions, an optimal user selection method is developed that picks a UE with comparatively better reception, and thereby the selected UE acts as a relay forward node utilizing the simultaneous wireless information and power transfer protocol. The characterization of a key performance metric, i.e., the outage probability is derived by adopting a two-step procedure. First, quadratic forms of signal-to-interference-plus-noise ratio (SINR) at the relaying UE and the signal-to-noise ratio (SNR) and SINR at the intended IoT device are constructed. Then, using the indefinite quadratic form approach, we arrive at closed-form expressions for the outage probability (OP) of the intended IoT device under linearly dependent beamformers. To validate the analytical expressions provided in this study, simulations are performed.

Keywords: MU-MISO-NOMA, User selection, Energy harvesting, SWIPT, Beamformers

Introduction

The increasing proliferation of IoT devices has led to a surge in demand for efficient and reliable wireless communication systems. Traditional orthogonal multiple access (OMA) techniques, which allocate distinct resources to each user, are becoming insufficient to meet the burgeoning connectivity needs. Non-orthogonal multiple access (NOMA) has emerged as a promising solution, enabling multiple users to share the same frequency resources by exploiting differences in their channel conditions.

In this context, this study focuses on a MU-MISO NOMA system, where a base station serves multiple UEs and IoT devices. The key challenge addressed is enhancing the performance of IoT devices, especially those with weak channel conditions. By leveraging the concept of simultaneous wireless information and power transfer (SWIPT) and implementing an optimal user selection method, the system aims to improve the reliability and efficiency of IoT communications.

System Model

The proposed model consists of a base station surrounded by numerous UEs and dispersed IoT devices. The base station employs NOMA to serve multiple users simultaneously. Power allocation coefficients are strategically set to balance the performance between the relaying UEs and the targeted IoT devices.

In scenarios where an IoT device experiences poor channel conditions, an optimal user selection method is applied. This method selects a UE with better reception capabilities to act as a relay forward node. The chosen UE assists the IoT device by forwarding information and energy, thereby enhancing the overall system performance.

Performance Metric - Outage Probability

Outage probability (OP) is a critical performance metric used to evaluate the reliability of the communication system. It measures the probability that the received signal quality falls below a predefined threshold. In this study, the OP for the intended IoT device is derived through a two-step procedure:

Construction of Quadratic Forms

Signal-to-noise ratio (SNR) and SINR at the intended IoT device

Indefinite Quadratic Form Approach:

Using this mathematical approach, closed-form expressions for the OP are derived. This method accounts for the linearly dependent beamformers used in the system.

Optimal User Selection and SWIPT:

To mitigate the effects of weak channel conditions for certain IoT devices, an optimal user selection method is implemented. This method identifies a UE with relatively better channel conditions to act as a relay. The selected UE employs SWIPT to simultaneously transfer information and power to the IoT device, thereby improving its performance.

Simulation and Validation

To validate the analytical expressions derived for the OP, extensive simulations are performed. These simulations consider various network scenarios and parameter settings to ensure the robustness and accuracy of the proposed model. The results confirm that the analytical expressions closely match the simulated outcomes, thereby validating the effectiveness of the proposed MU-MISO NOMA system. Non-orthogonal multiple access (NOMA) provides low latency, high reliability, enormous connectivity, and better spectral efficiency (SE) for bandwidth-hungry Internet of Things (IoT) applications. Besides, NOMA is a promising technique for beyond fifth-generation (B5G) networks as it can cater for scenarios with large numbers of users and IoT devices simultaneously. Users can engage the same resource block, i.e., time and frequency, in this technique, while multiplexing is done in the power domain (Saito et al., 2013). The base station (BS) transmits a composite message signal that is superimposed depending on power allocation (PA) factors and transmitted employing the same time–frequency resources. In NOMA systems, the notion of successive interference cancellation (SIC) is applied at the user equipment (UE). Because of the strong channel conditions, the UE can employ SIC to remove co-channel interference and sequentially decode the intended signal (Kader et al., 2018). The concept of beamforming at the transmission side is utilized for interference mitigation in multi-user (MU) scenario for two network configurations, namely, multiple-input single-output (MISO) and multiple-input multiple-output (MIMO), and often an eigenvalue-based formulation is adopted to obtain the outage probability (OP) expressions (Al-Naffouri et al., 2015). The theoretical

performance comparison between NOMA and conventional orthogonal multiple access (OMA) system was investigated in (Chen et al., 2017), wherein the authors demonstrated that NOMA always outperform conventional OMA system due to optimum resource allocation. The resource management framework for a backscatter-aided cooperative NOMA network with imperfect SIC decoding was discussed by the authors in (Ahmed et al., 2022). Optimization of time allocation and power loading at the BS and cooperative user, as well as the reflection coefficient of the backscatter, all significantly improved the sum rate of the cooperative NOMA system. The authors in (Khan et al., 2022) focused on optimization based framework on backscatter node reflection coefficient and transmit power of BS. Their work also deliberated on the aspects of physical layer security of the NOMA-based backscatter communication system in the presence of eavesdroppers (ED) for low powered IoT network applications. Han and Zhang (2021) evaluated the secrecy OP for an EH NOMA network with several IoT-enabled relaying devices in the presence of an ED, while taking into account random and two-stage relay selection schemes over the Nakagami-m fading channel. According to the authors, increasing the time splitting factor and energy conversion efficiency degraded secrecy performance. Although deploying a MU-MISO-NOMA network has several benefits, there are also many challenges, which motivate the proposed work.

A simultaneous wireless information and power transfer (SWIPT) protocol was used for the characterization of OP, and a fair data rate of cell-edge users was established for a two-user network scenario (Hedayati and Kim, 2018). Ghous et al. (2021) investigated performance of a cell-edge user using a precoder and equalizer architecture in the two-user cooperative MIMO-NOMA system while maintaining data rate fairness and improving outage performance. In (Raeisidehkordi and Bakhshi, 2021), the authors focused on maximizing fairness and power in NOMA networks while complying to the new user priority approach to offer unbiased quality-of-service (QoS) and preserving sufficient power for high priority users. The authors in (Docomo, 2014), investigated a model based on cell-center users as well as cell-edge users using NOMA to improve the SE. Dai et al. (2015) observed degradation in terms of cell-edge users performance and capacity when the data rate for cell-center users increases relative to cell-edge users. An analysis of a two user MISO-NOMA cooperative model was discussed in (Ghous et al., 2020), wherein the authors have focused on the enhancement in the QoS of cell-edge user by introducing the concept of downlink beamformers for optimal PA.

A cooperative NOMA method for selecting the relaying mechanism was described in (Yang et al., 2017), wherein users at the cell-center act as relay and use energy to improve the performance of the cell-edge users and also to decode their information. On the energy-constrained devices, this leads to a shortage of energy. In (Liu et al., 2016), a spectral and energy efficient technique was proposed which fused on node cooperation, NOMA, and SWIPT protocol to overcome this issue. Additionally, in (Ding et al., 2015), MU-MIMO-NOMA was taken into account with an assumption that the channel state information (CSI) was perfect. A training-based NOMA algorithm was examined in (Cheng et al., 2017) for the MU-MIMO with NOMA system in order to generate closed-form expressions of the downlink capacity. The performance of a cell-edge user was evaluated in (Nguyen et al., 2022) under both perfect and imperfect SIC conditions using NOMA-based full-duplex IoT relay systems with SWIPT over the Nakagami-m fading channels, where the authors used selection combining (SC) technique for both direct and non-direct links between the source node and cell-edge user. Furthermore, Nguyen et al. (2022) also proposed an algorithm to enhance system's overall throughput by optimizing the time-switching factor.

Due to the extensive connectivity and information sharing in massive IoT network systems, the authors in (Duan et al., 2020) investigated a cooperative full-duplex device-to-device (D2D) system with partial decode-and-forward (P-DF) and NOMA with and without ED presence by using maximum ratio combining (MRC) technique. The complexity of SIC processor desires a minimum received power gap between various IoT nodes over the same frequency block for effective operation. In the transmit PA to the IoT nodes, some practical constraints arise due to limited resources. Therefore, to maximize the SE of the IoT networks under power domain NOMA, the authors in (Khan et al., 2020) proposed an optimization based solution for frequency and PA. The SE-improved cooperative device-to-device (D2D) NOMA system was taken into consideration in (Ji et al., 2020), where the effects of weak channels and various decoding techniques were studied in depth. Kilzi et al. (2021) developed an effective combination of the Kuhn-Munkres channel assignment technique with the proposed PA techniques to achieve the best sum-throughput for full-duplex IoT systems underlying cellular networks with mutual SIC NOMA. Liu et al. (2020) used throughput-aware and fairness-aware NOMA-based scheduling strategies, to demonstrate the performance trade-off between throughput and fairness while considering an adaptive PA algorithm to enhance network fairness in wireless powered IoT networks. Rauniyar et al. (2020) presented a bidirectional relaying (BR) NOMA-SWIPT system and evaluated its performance under both perfect and imperfect SIC conditions with the goal of improving SE and energy efficiency (EE) for wireless IoT relay networks requiring low data rates. Simulation results showed that proposed system outperformed the two-way relaying (TWR) OMA SWIPT. In (Zhang et al., 2021), the effectiveness of massive MIMO-NOMA based cell-free IoT network was investigated considering spatially correlated Rician fading channels into account. The downlink SE and EE expressions were derived while for the effects of intercluster interference, intracluster pilot contamination, and imperfect SIC with minimum mean-squared error (MMSE), element wise-MMSE, and least square estimations, respectively. The authors concluded that the system's overall performance in terms of SE and EE was enhanced by having more number of access points (APs), antenna array, and Rician factors. Nguyen et al. (2020) investigated the merits of employing NOMA for IoT-based coordinated direct and relay transmission (CDRT) to enhance the SE. In terms of ergodic sum capacity, the developed system performed exceptionally well; but, during cooperative transmission, the scheme had an outage at the strong user. The authors in (Vu et al., 2022) presented a short-packet communications (SPCs) with NOMA for CDRT IoT networks in order to improve spectrum utilization and system performance under imperfect SIC circumstances and co-channel interference. Vu et al. (2022) also obtained optimal system throughput rate by simultaneously optimizing power allocation co-efficients (PACs) and channel coding ratios, and moreover, the suggested system with short messages outperformed the long-messages terms of latency and reliability.

The authors in (Xu et al., 2020) proposed a cooperative NOMA IoT network where the intended users were provided with cooperative buffers, and the goal of selecting a direct or relaying transmission mode depending on the CSI and the cooperative buffer state. Rajak et al. (2022) examined an energy-efficient massive MIMO-NOMA assisted IoT network with an aim to provide seamless data transfer and reliable connectivity in B5G communications while considering the imperfect CSI and actual power consumption at the transmission end. To increase the sum data rate of the NOMA based MIMO system, the authors in (Yilmaz et al., 2021) proposed a user-set selection mechanism along with an optimal PA scheme for uplink transmissions in IoT networks. To meet the demands of growing IoT applications, the scheme utilized the wireless

physical layer network coding (PNC) to communicate information between the selected IoT pairs with the goal to increase SE and reduced latency. By jointly optimizing the offloading decision making, local computation resource allocation, access control, user clustering, sub-carrier assignment, and transmit power control the authors in (Du et al., 2020) focused on energy and system capacity maximization in a NOMA mobile edge computing (MEC) based IoT system while relying on graph theory and low-complexity heuristic algorithm. A power beacon (PB) assisted wireless powered NOMA based IoT system was presented in (Vu and Kim, 2021), where all the transmitters were capable of harvesting energy from a PB for transmitting their signals to the intended device. To improve the system performance, two algorithms were developed to minimize the OP of users by optimizing time-splitting factors and to improve sum throughput by concurrently optimizing PA and time-splitting factors (Vu and Kim, 2021). In (Vu et al., 2021), the authors considered an IoT network operating under SIC imperfections in a cooperative NOMA enabled SWIPT protocol, wherein a unitary source harvests energy from the multi-antenna PB in order to serve a couple of IoT devices with the assistance of several energy-limited relay nodes. Furthermore, the authors developed a deep learning method for maximizing the system's sum-rate and EE with low computation complexity albeit high accuracy. In (Karem et al., 2022), NOMA and unmanned aerial vehicle (UAV) were integrated to establish a high-capacity, multi-application IoT uplink network. The resource allocation approach was used in the frequency and time domains, respectively, to increase system throughput while reducing IoT application latency. The proposed technique in (Karem et al., 2022) is highly useful for IoT networks demanding ultra-reliable low-latency communication (URLLC).

The key performance indicators (KPIs) were characterized using a tractable mathematical technique, and the cumulative density function (CDF) in the Normal random variables was evaluated using indefinite quadratic form (IQF) approach (Al-Naffouri and Hassibi, 2009). This method involves first expressing any inequalities that appear in CDF equations as a unit step function, and then replacing those expressions with their Fourier transform equivalents. Do et al. (2017) proposed three distinct antenna selection approaches. The analysis included transmit antenna selection under SWIPT protocol. In (Zhao et al., 2019), the pilot contamination issue in a massive MIMO system based on time division duplexing (TDD) was studied, the optimal pilot assignment approach of normalized mean square error (NMSE) for upper and lower bounds were proposed.

Although cooperative MISO/MIMO NOMA systems using the SWIPT protocol have been studied in the literature with two users located in a straight line, no research to the best of our knowledge has been conducted to investigate the OP minimization problem in a realistic downlink MU-MISO-NOMA cooperative IoT network scenario using a user selection technique based on distances to select best UE for relaying. We have proposed a model where multiple users and a IoT device are deployed in a realistic scenario while two different user selection strategies are also developed for selection the best UE to act as an EH relay.

Contributions

In this research, a realistic model of the cooperative downlink MU-MISO-NOMA IoT network is taken into consideration, in which an optimal near UE is selected from a group of users based on the proposed user selection algorithm. The selected UE acts as an energy harvesting (EH) relay for the intended IoT device located far from the BS or in a low-coverage zone. The selected near UE

transmits the data to the desired IoT device by the harvested energy using a power splitting technique. Following are the primary contributions of the proposed work.

We develop a downlink MU-MISO-NOMA based IoT system in which users deployment is more realistic as compared to prior work which considered two users located in a straight line. Specifically, we have utilized trigonometric identities to calculate relative distances between the nodes when not in a straight line.

We propose a system model that includes analysis on linearly dependent beamformers and formulate the SINR and SNR equations of both direct and indirect (relaying) transmission that characterizes the OP using IQF approach, while assuming statistical CSI availability at the transmit side. This is achieved by employing modern IQF methodology on the concerned system model.

We develop a user selection algorithm in which UE with least outage is selected as an EH relay to assist intended IoT device. Using this strategy, the reduction in OP of the given IoT device is showcased.

Organization

The remaining part of the paper is organized as follows. Section 2 presents the system model of cooperative downlink MU-MISO-NOMA IoT network and key SINR/SNR formulations. Section 3 gives the closed-form expressions of the OP. User selection strategies are discussed in Section 4. In Section 5, simulations and validations of the proposed user selection strategy and the system model are presented, while Section 6 concludes the paper.

System model

The proposed model presents a downlink MU-MISO-NOMA IoT network transmission as shown in where N transmit antennas are located at the BS. For brevity and without loss of generality, we have numbered UEs and IoT devices (Ds) in The multiple UEs are denoted by UE-1 – UE-5 and the IoT devices are denoted by D1 – D8. Furthermore, each UE is outfitted with a single antenna that can both broadcast and receive data whereas IoT devices are designed to receive the message signal from the BS or from the relaying UE only. It is assumed that the device to target is d th IoT device having poor channel condition, compared with the rest. As a result, to ensure the intended IoT device's QoS requirements, any of the UE will be chosen using the user selection method presented in this work which will act as an EH relay to the IoT device. The channel used in the proposed model is based on wireless links for u th UE, all other UEs except u th UE and the IoT device, respectively. The exponential random variable $|h_{ud}|^2$ is the channel gain between u th UE acting as a relay and the d th IoT device. The notations used in this paper are listed in Table 1.

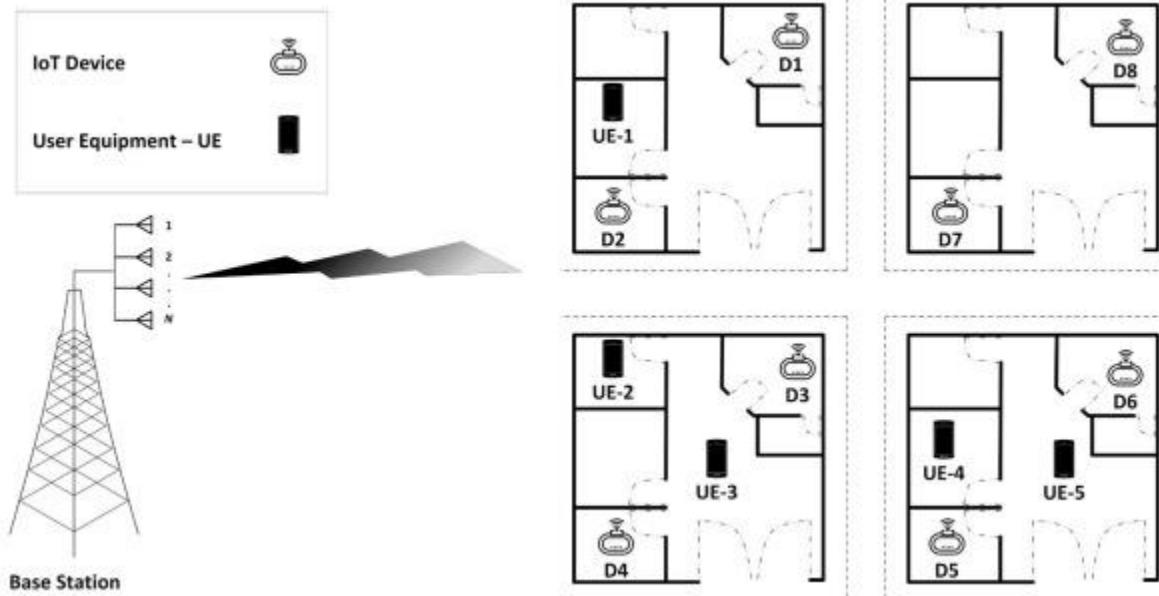


Table 1. List of notations.

Direct broadcast transmission to all nodes

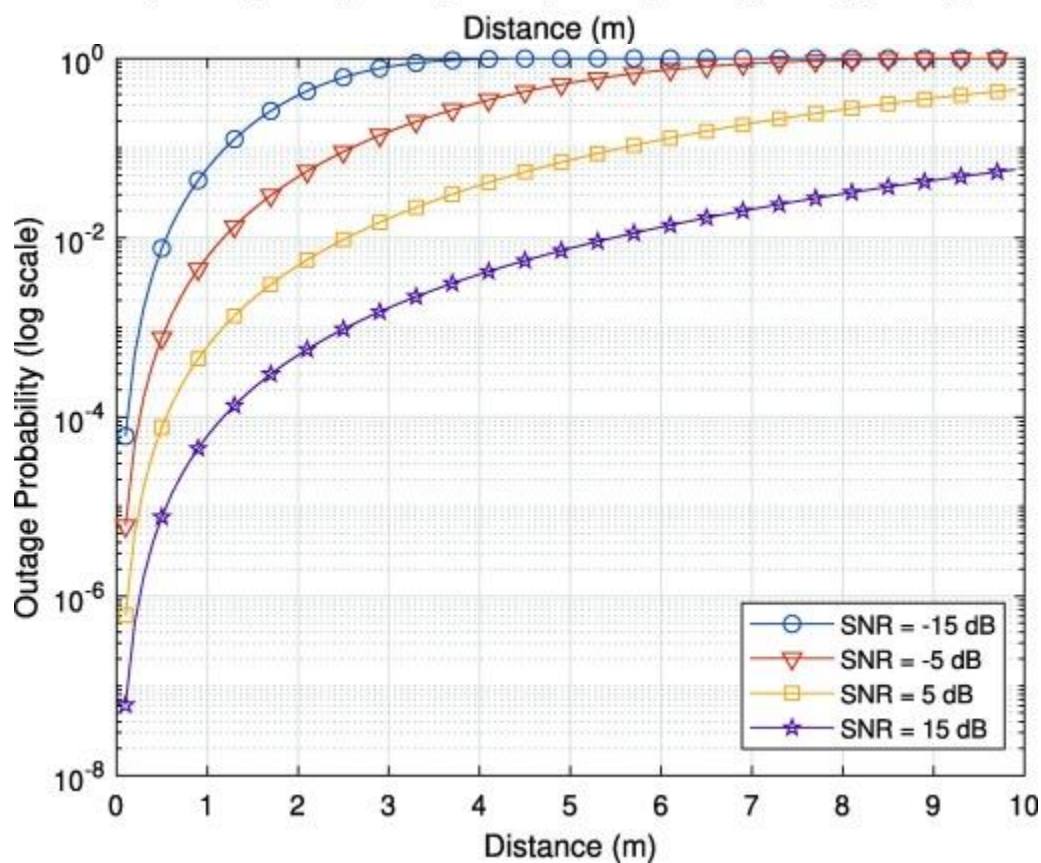
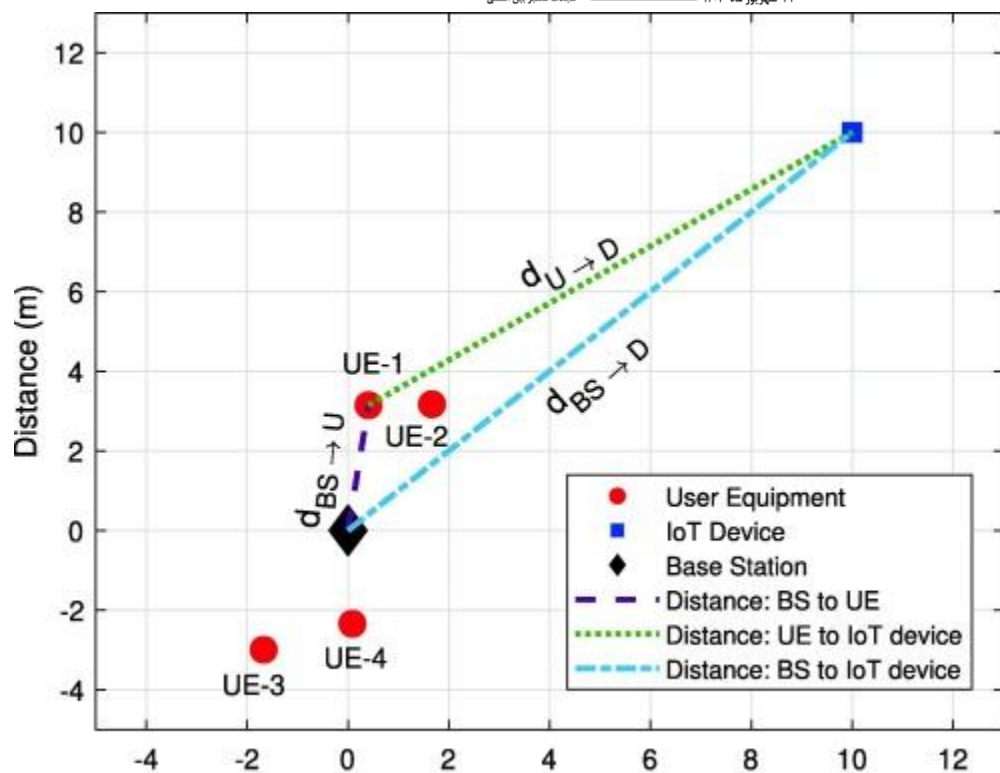
In the first stage, multiple BS antennas are used for downlink transmissions. A composite message is transmitted from all the N antennas of BS to all the UEs and IoT devices with different PACs satisfying the NOMA condition.

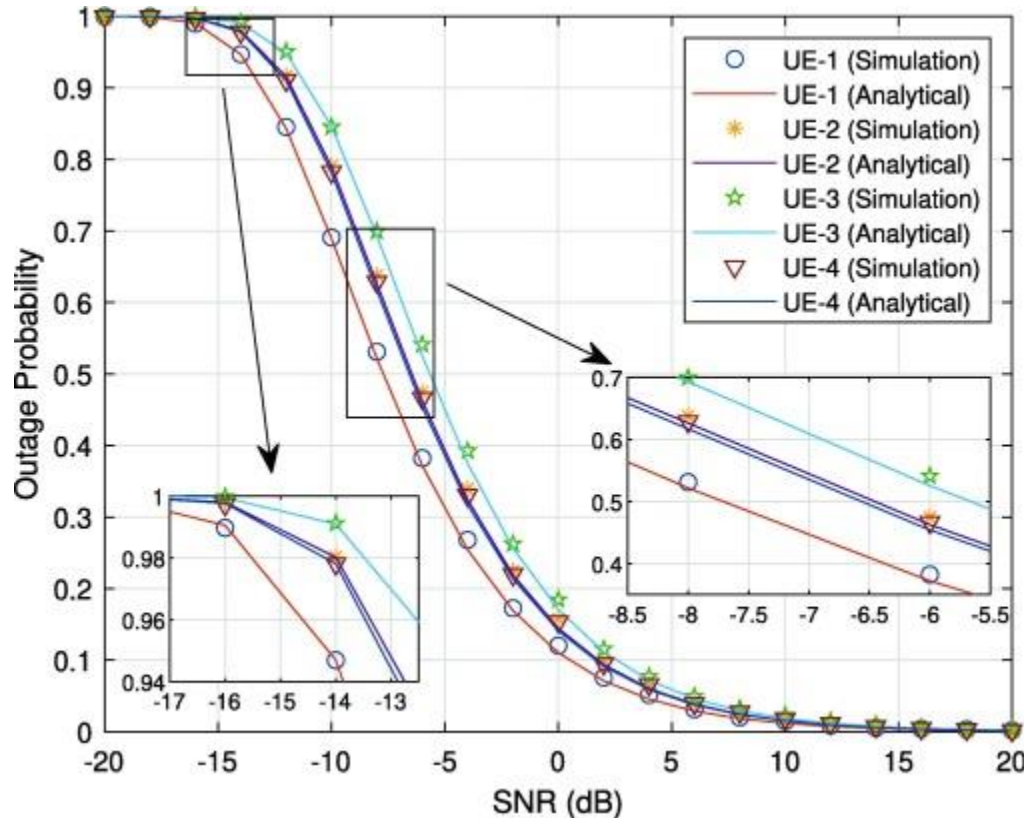
UE and IoT device based cooperative relaying transmission

In the second stage, message of the d th IoT device is relayed from u th UE to d th IoT device through cooperative relaying transmission. The harvested energy during the first stage is used for relaying this message. The expression for the transmitted power of relaying UE is given

User selection strategies

The proposed model has multiple UEs, alongside IoT devices, where one of the UE is to be selected as an EH relay. Because UEs are mobile and their position might change, the need for a user selection approach arises. We first consider a method in which a UE is selected based on distances with the premise that if the intended IoT device is positioned anywhere at the right side of imaginary plane with respect to the BS, the UEs located at the left side of the BS are not considered for selection and vice versa. The relaying path becomes longer than the direct path for signal transmission if the UE and the intended IoT device are located on opposite sides of the imaginary





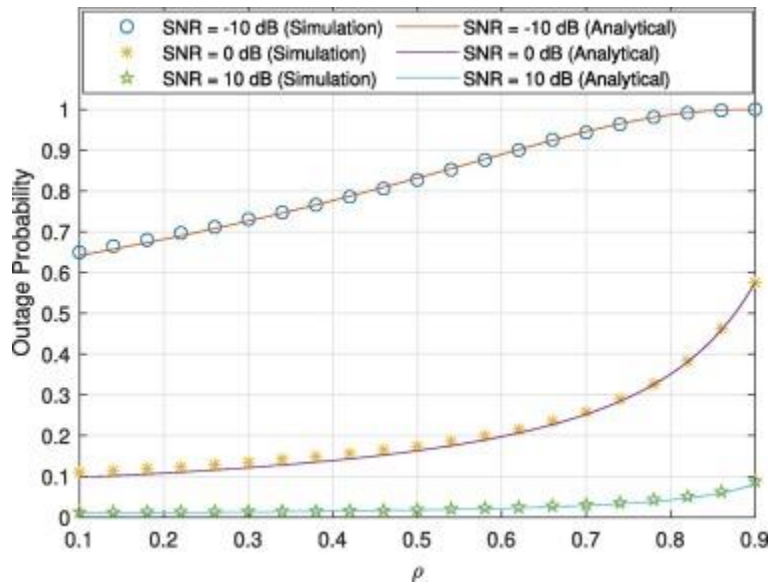
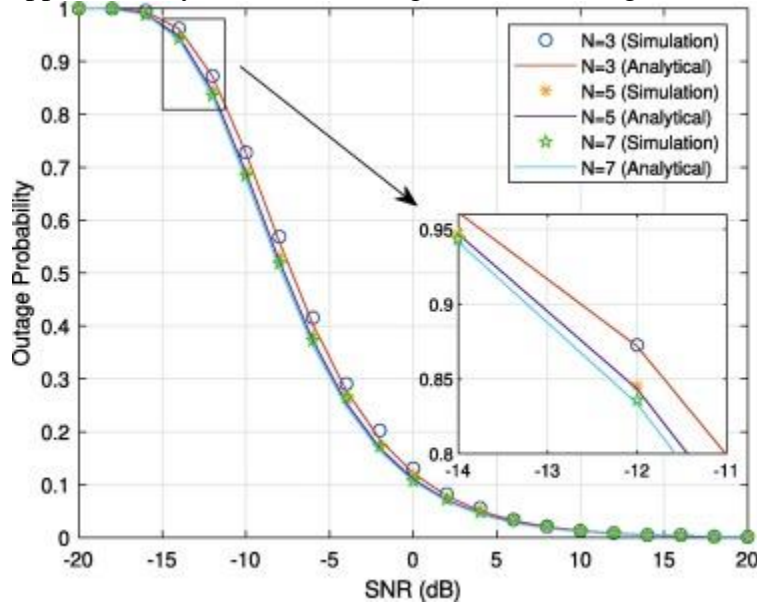
Results and discussions

In this section, closed-form expressions derived in the proposed work are validated. It is assumed that the correlation matrices and beamformer vectors are known. Based on widely accepted assumptions as in (Do et al., 2017, Ghous et al., 2020), we consider that the path-loss exponent is set to be 3 for all wireless links.

Parameters	Values
Bandwidth	1 MHz
Energy conversion efficiency factor for information decoding	0.7
Path-loss exponent $\epsilon(\epsilon)$	3
Noise power density of antennas	-100 dBm/Hz
Noise power density for information processing	-90 dBm/Hz
Target data rates of uth UE = dth IoT device	0.2 bits/s/Hz

Validation of OP based user selection strategy

Considering MU IoT network scenario in a more realistic hierarchy, the OP of d th IoT device is presented. considering each UE as an EH relay for N to be 5. It illustrates that the UE with the least outage for d th IoT device over the whole SNR range is the one performing well in the proposed method. The OP curves may differ because of the position of UEs and their respective correlation matrices. Similarly, it can be clearly observed that for low SNR the OP is higher than for the higher SNR values. From here, it is observed that the UE with least OP, i.e., UE-1 is the most suitable to be selected for relaying purpose as its probability of going into outage is minimum compared with the others. More specifically, at SNR of -5 dB there is a reduction of OP by approximately 35%. Hence, Algorithm 2 is designed based on the analysis performed in



Conclusion

A framework for the characterization of OP for downlink MU-MISO-NOMA IoT network is presented in this paper. The exact closed-form expression is achieved by using the IQF approach for linearly dependent beamformers. The analytical results closely match the simulation results with an average error ranging to a factor of 10⁻⁴. It has been demonstrated that the most suitable UE to act as a relay is the UE experiencing least outage for dth IoT device using the OP based user selection approach. Similarly, introducing multiple antenna elements at the BS for transmission in downlink scenario has a considerable impact on the OP. It has also been observed that multiple antenna elements at the BS results in decreased OP on average by approximately 10% for dth IoT device and vice versa. This work may be extended to downlink MU-MISO-NOMA cooperative IoT networks by conducting optimal analysis on independent beamformers and PACs with instantaneous CSI to select the best relaying user and improve overall system performance.

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