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An Adaptive Power Allocation Scheme for Performance Improvement of Cooperative SWIPT NOMA Wireless Networks

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Abstract: Future wireless networks demand high spectral efficiency, energy efficiency and reliability. Cooperative non-orthogonal multiple access (NOMA) with simultaneous wireless information and power transfer (SWIPT) is considered as one of the novel techniques to meet this demand. In this work, an adaptive power allocation scheme called SWIPT based adaptive power allocation (SWIPT-APA-NOMA) is proposed for a power domain NOMA network. The proposed scheme considers the receiver sensitivity of the end users while calculating the power allocation coefficients in order to prevent wastage of power allocated to user in outage and by offering priority to any one of the users to use maximum harvested power. A detailed analysis on the bit error rate (BER) performance of the proposed scheme is done and closed form expression is obtained. Simulations have been carried out with various parameters that influence the receiver sensitivity and the results show that the network achieves better outage and BER performance using the proposed scheme. It is found that the proposed scheme leads to a ten-fold decrease in transmit power for the same error performance of a fixed power allocation scheme. Further, it offers 96.06% improvement in the capacity for a cumulative noise figure and fading margin of 10 dB.

Keywords: NOMA, SWIPT, cooperative relaying, adaptive power allocation.

1 Introduction

Future generation mobile communication networks demand high spectral efficiency, massive connectivity, low latency and prolonged battery life. These demands cannot be met by conventional orthogonal multiple access schemes like time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA) or orthogonal frequency division multiple access (OFDMA) as the number of users who can simultaneously access the network is limited by the orthogonality constraint. Therefore, non-orthogonal multiple access (NOMA) is being considered as a candidate multiple access scheme for 5G [Higuchi and Benjebbour (2015); Ding, Liu, Choi et al. (2017); Kizilirmak (2017)]. NOMA permits the sharing of frequency, time and space by multiplexing the signals in power domain or code domain.

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In power domain NOMA (PD-NOMA), users share the same frequency and time resources and are multiplexed with different levels of power. In PD-NOMA, successive interference cancellation (SIC) is the key technique for multi-user interference cancellation with complexity $O(K^3)$, where K is the number of users, which is much less complex than maximum likelihood detection. In code domain NOMA, spreading sequences or code books should be known at the receiver to realize multi-user detection, and the complexity of the message passing algorithm (MPA) based receiver is higher than a SIC-based receiver [Dai, Wang, Yuan et al. (2015)].

NOMA can be combined with cooperative relaying to further enhance network performance [Liu, Ding, Elkashlan et al. (2016); Ding, Peng and Poor (2015); Kim and Lee (2015)]. In cooperative relaying, some of the nodes in the network act as relays to forward the information intended for other users. When the direct link between the source and destination is in a deep fade, the relay may have a good link with both the source and the destination. Thus relaying enhances the reception reliability of the network by providing a form of spatial diversity. Relaying can also extend the coverage area of the network when the signal from the source cannot directly reach the destination because of excessive path loss, or shadowing due to the presence of obstacles. Although amplify-and-forward (AF) relays are simple to implement, they suffer from noise amplification problem. However, a decode-and-forward (DF) relay overcomes this problem. In Lv et al. [Lv, Chen and Ni (2016)], the authors have studied the effect of increasing the number of cooperating users in a cognitive radio inspired NOMA (CR-NOMA) network. It is found that by increasing the number of cooperating secondary users, the outage performance of the secondary network can be greatly improved. The performance of the same network for a Nakagami-m fading channel is studied in Lv et al. [Lv, Ni, Ding et al. (2017)]. Cooperative and non-cooperative multicast NOMA networks are analyzed and compared in Chen et al. [Chen, Wang and Jiao (2017)] and it is shown that cooperative NOMA achieves the best fairness among users than non-cooperative NOMA. In Lee et al. [Lee, Duong, da Costa et al. (2018)], the authors propose a hybrid underlay CR-NOMA network combining OMA/NOMA schemes. They show that user cooperation benefits the cell edge users and those with poor channel conditions. The rate regions for two different relaying strategies in cooperative NOMA are analyzed in Li et al. [Li, Xiao and Rasmussen (2018)]. In Li et al. [Li, Jiang, Zhang et al. (2018)], cooperative NOMA with MIMO beam forming is used to maximize the throughput of the cell edge users. It is shown that there is a significant decrease in outage probability when cooperative MIMO is incorporated into the NOMA network. The performance gain that can be achieved by cooperative relaying is evident from these studies.

The nodes present in the network are mostly battery powered and are energy constrained. To prolong the battery life of the nodes and to improve the energy efficiency of the network, the concept of simultaneous wireless information and power transfer (SWIPT) can be combined with cooperative NOMA so that the future network demands are met. In SWIPT, the nodes in the network are made to harvest electromagnetic energy from ambient RF signals [Gu and Aissa (2015)]. This harvested energy can be used by the node to make its transmissions. Two energy harvesting strategies in use are time switching and power splitting [Hedayati and Kim (2018)]. In the time switching case, the relay alternates between an energy harvesting mode and a transmission mode. During the energy harvesting mode, power is transmitted wirelessly to the nodes by the base station. Throughput optimization for such a network is performed with NOMA SIC constraints and the non-convex optimization problem is solved by joint optimization of time spent for energy harvesting and energy consumption in Lyu et al. [Lyu, Yang and Gui (2018)]. The performance of an energy harvesting receiver using time switching protocol is studied in Ni et al. [Ni and Motani (2017)] and the optimal code rate when the receiver harvests energy from the transmitter and other RF sources is derived. In the power splitting case, a fraction of energy of the received signal is harvested by the relay to power its battery and the remaining fraction is used for information decoding. For a two-user cooperative SWIPT NOMA network, the optimum value of the power splitting coefficient is derived in Ho et al. [Ho, Zhang and Zhou (2013)]. The two user SWIPT NOMA network analyzed in Do et al. [Do and An (2018)] shows that NOMA outperforms OMA only when the channel to the two users is sufficiently different. Time switching requires separate time slots to decode information and to harvest energy. In order to simultaneously perform energy harvesting while information decoding, a power splitting protocol is considered in this work.

In order to reap the advantages of power domain NOMA, proper selection of power allocation coefficients is mandatory. In Yang et al. [Yang, Ding, Fan et al. (2017)], the authors propose three different power allocation schemes for a downlink cooperative SWIPT NOMA network which consists of a source, an energy harvesting relay and two end users. The relay follows DF power splitting protocol. The three power allocation schemes considered are fixed power allocation (SWIPT-F-NOMA), dynamic power allocation with fixed QoS at the weak user (SWIPT-CR-F-NOMA) and dynamic power allocation with variable QoS at the strong user (SWIPT-CR-D-NOMA). All these power allocation schemes were compared in terms of outage performance.

From the literature, it is realized that the power allocation coefficients have been estimated without considering the receiver sensitivity of end users. Hence, a power allocation scheme taking receiver sensitivity into account is proposed in this work. Further, the receiver sensitivity depends not only on the power of noise but also on other several factors such as antenna gain, data/symbol rate, receiver system noise figure and fading margin. This can be mathematically expressed as, $P_{sens} = -174 + 10\log_{10}(B) + NF + FM + I$ where, B, NF, FM and I denote bandwidth, noise figure, fading margin, and interference respectively. As the future generation systems also target towards high data rates, it is also important to evaluate the performances over the bandwidth instead of fixed bandwidth. If the transmission is made without checking the receiver sensitivity, the power may be wasted. Thus, the adaptive power allocation based on the receiver sensitivity may improve the system performance. Hence, the focus of this present work is to evaluate the performance of the proposed power allocation scheme with the consideration of various factors that influence the receiver sensitivity i.e., data rates (bandwidth), noise figure, fading margin and transmit power. The performances of the systems have been studied in terms of outage probability, BER, and average capacity. To the best of our knowledge, this is the first work that considers receiver sensitivity into account to allocate power.

The main contributions of this paper are as follows:

- A novel adaptive power allocation scheme called SWIPT based Adaptive Power Allocation in NOMA (SWIPT-APA-NOMA) is proposed, in which the power allocation coefficients are chosen based on the receiver sensitivity.
- Expressions for the sensitivity values of end users are derived based on their target data rates.
- Also, a detailed analysis on the error performance of the proposed scheme is carried out to obtain closed form expression for BER and the same is verified by simulation.

The organization of this paper is as follows. The system model of a cooperative SWIPT NOMA network is presented in Section 2. In Section 3, expressions for the end user receiver sensitivity are derived and the adaptive power allocation scheme i.e., SWIPT-APA-NOMA is proposed. In Section 4, BER analysis is carried out and closed form expression for BER is derived. Simulation results that validate the performance gain achieved by the proposed SWIPT-APA-NOMA are presented in Section 5 and conclusions are drawn in Section 6.

2 System model

In the proposed system, the network consists of a Source (S), End Users (EU) and a relay (R). In order to improve the spectral efficiency of the network, SWIPT NOMA has been used. The relay follows the DF power splitting protocol. It harvests part of the energy from the received signal for its operation and remaining power for the information decoding processes. In the illustrated model shown in Fig. 1, it is assumed that end users (EU_i, i=1, 2) have extremely weak links with the source S and are always assisted by relay R. This assumption applies to a dense urban environment.

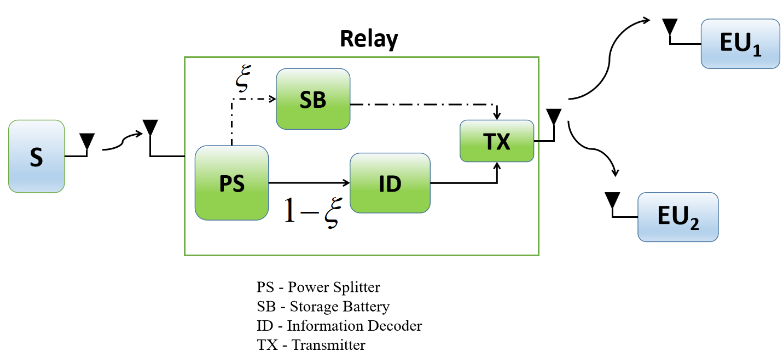


Figure 1: System model of a cooperative SWIPT NOMA network

Let the distances from the source to relay, relay to EU_1 and relay to EU_2 be denoted by d, d_1, and d_2 respectively. In this scenario, d_1 is assumed to be much larger than d_2 and hence, EU_1 is considered as the weak user and EU_2 as the strong user based on their distance. Further, the channel is assumed to be the additive white Gaussian noise (AWGN) channel with $CN(0,\sigma^2)$ and also undergoes Rayleigh flat fading with zero mean and unit variance. The transmission from source to end user occurs in two time slots. In the first time slot, the information pertaining to the end users are transferred to relay using SWIPT-NOMA.

During this slot, relay partly harvests the energy from the received signal for its operation (relaying) and utilizes the remaining power to decode the information. In the second time slot, the relay forwards the decoded information to end users using SWIPT-NOMA.

2.1 Transmission in time slot 1

Let the source S have two separate messages x_1 and x_2 for end users EU_1 and EU_2 respectively and transmits them simultaneously by superposition coding into a single carrier using power domain NOMA with transmit power *P*. Let α_1 and α_2 denote the power allocation coefficients for x_1 and x_2 such that $\alpha_1 + \alpha_2 = 1$ with $\alpha_1 > \alpha_2$. The signal transmitted by the source *s(t)* and the signal received by the relay *r(t)* in the first time slot are given by:

$$s(t) = \sqrt{\alpha_1 P} x_1 + \sqrt{\alpha_2 P} x_2 \tag{1}$$

$$r(t) = (\sqrt{\alpha_1 P} x_1 + \sqrt{\alpha_2 P} x_2) h + w \tag{2}$$

where $h \sim (0, d^{-\upsilon})$ is fading coefficient and given by $fd^{-\upsilon/2}$. The parameters f and υ represent Rayleigh small scale fading coefficient and path loss exponent respectively. The w represents AWGN with zero mean and variance σ^2.

From the received signal, the relay harvests a fraction of energy for relaying the decoded information and the remaining fraction of available signal power is used for information decoding at the relay. The signal available at the relay for decoding is given by,

$$y_D = \sqrt{1-\xi} (\sqrt{\alpha_1 P} x_1 + \sqrt{\alpha_2 P} x_2) h + w \tag{3}$$

where, ξ is the power harvesting coefficient. The received signal is assumed to have high SNR and hence, the energy harvested from AWGN is assumed to be negligible [Yang, Ding, Fan et al. (2017)]. The amount of power harvested by the relay from the received signal is denoted by,

$$P_H = \eta \xi P |h|^2 \tag{4}$$

where, η is the energy harvesting efficiency of the relay node.

As the power allocation coefficient $\alpha_1 > \alpha_2$, the relay detects x_1 first from y_D, considering x_2 as interference. Then, the achievable data rate at the relay in decoding x_1 is

$$R_1^r = \frac{1}{2} \log_2 \left(1 + \frac{(1-\xi)\alpha_1 P |h|^2}{(1-\xi)\alpha_2 P |h|^2 + \sigma^2} \right) \tag{5}$$

After successfully decoding x_1, the relay cancels the estimate of x_1 from y_D and then decodes x_2. The achievable data rate at the relay in decoding x_2 is given by,

$$R_2^r = \frac{1}{2} \log_2 \left(1 + \frac{(1-\xi)\alpha_2 P |h|^2}{\sigma^2} \right) \tag{6}$$

The values of α_1, α_2 and ξ are chosen such that the achievable data rates satisfy the condition, $R_1^r \geq R_1^*$ and $R_2^r \geq R_2^*$ where R_1^* and R_2^* are the target rates fixed for EU_1 and

EU_2 respectively.

2.2 Transmission in time slot 2

In the second time slot, the relay performs power domain multiplexing of the signals x_1 and x_2 and transmits the resulting signal with the power harvested in the previous time slot. The signal transmitted by the relay is given by $\sqrt{P_H\beta_1}x_1+\sqrt{P_H\beta_2}x_2$, where β_1 and β_2 denote the power allocation coefficients at the relay such that $\beta_1+\beta_2=1$ and $\beta_1>\beta_2$. The signal received at the i^{th} user (i=1, 2) is given by,

$$y_i=(\sqrt{P_H\beta_1}x_1+\sqrt{P_H\beta_2}x_2)h_i+w \tag{7}$$

where $h_i\sim(0,d_i^{-\upsilon})$ is the channel coefficient between the relay and EU_i, (i=1,2). $h_i=f_id_i^{-\upsilon/2}$, f_i is the Rayleigh fading coefficient for i^{th} user and, d_i is the distance between the relay and the i^{th} user. EU_1 directly decodes x_1 from y_1 considering the x_2 term as interference. The achievable data rate at EU_1 in decoding x_1 is,

$$R_1^N=\frac{1}{2}\log_2\left(1+\frac{\beta_1P_H\,|\,h_1\,|^2}{\beta_2P_H\,|\,h_1\,|^2+\sigma^2}\right) \tag{8}$$

Since EU_2 is the strong user and is allocated less power than EU_1, it must first decode x_1 from the received signal y_2. The achievable data rate at EU_2 in decoding x_1 is,

$$R_{1(2)}^N=\frac{1}{2}\log_2\left(1+\frac{\beta_1P_H\,|\,h_2\,|^2}{\beta_2P_H\,|\,h_2\,|^2+\sigma^2}\right) \tag{9}$$

After estimating x_1 from y_2, EU_2 performs SIC and decodes x_2 from the remaining signal. The achievable data rate at EU_2 in decoding x_2 is,

$$R_2^N=\frac{1}{2}\log_2\left(1+\frac{\beta_2P_H\,|\,h_2\,|^2}{\sigma^2}\right) \tag{10}$$

Because of large scale path loss, the energy harvested by the relay is very small in practice. In order to economically utilize the harvested energy, β_1 and β_2 must be optimized to minimize the relay transmit power. The power allocation algorithms presented in the literature Lv et al. [Lv, Chen and Ni (2016); Lv, Ni, Ding et al. (2017); Yang, Ding, Fan et al. (2017)] are not energy efficient because of the following reasons. In the absence of knowledge of receiver sensitivity, the relay transmits the entire harvested power to satisfy the target rate of end users. Further, the target rate achievement is also not guaranteed. This leads to a wastage of power by the transmission. In this proposed work, SWIPT-APA-NOMA, an adaptive algorithm computes β_1 and β_2 based on the received signal strength and end user sensitivity. This helps to optimize energy consumption at the relay. In addition, it improves outage performance and BER of any one user while maintaining that of the other user. Computation of β_1 and β_2 using the proposed adaptive algorithm is described below.

3 Proposed scheme

In the system model existing in literature, the transmission takes place in the second time slot whenever the power harvested at the relay is greater than zero. However, if the power harvested at the relay is less than the receiver sensitivity of the end users, the information transmitted by the relay with the harvested power cannot be detected by them. Hence, this transmission power is wasted. Instead, this wasted transmission power can be saved and exploited to improve the performance of one of the users by following an appropriate adaptive power allocation scheme. For adaptive power allocation at relay two cases considered here are, (i) giving priority to the weak user and (ii) giving priority to the strong user. In the following sections, the receiver sensitivity equations of the two users are derived and hence, an adaptive power allocation scheme namely, SWIPT-APA-NOMA is proposed at the relay.

3.1 Receiver sensitivity

Sensitivity is defined as the minimum required power for detection of a signal at the receiver. If the received signal power falls below the sensitivity level, the receiver declares outage. Let R_1^*, R_2^* denote the target data rates and $\varepsilon_1, \varepsilon_2$ denote the target SNRs at EU_1 and EU_2 respectively and, $\varepsilon_i = 2^{2R_i^*} - 1$, i=1,2. The relay initially calculates β_1 and β_2 using any of the power allocation schemes available in literature. With these power allocation coefficients, the achievable SNR at EU_1 to decode x_1, SNRs at EU_2 to decode x_1 and x_2 can be obtained from Eqs. (8)-(10) as Eqs. (11)-(13) respectively,

$$SNR_{rx1} = \frac{\beta_1 P_H |h_1|^2}{\beta_2 P_H |h_1|^2 + \sigma^2} \tag{11}$$

$$SNR_{rx1(2)} = \frac{\beta_1 P_H |h_2|^2}{\beta_2 P_H |h_2|^2 + \sigma^2} \tag{12}$$

$$SNR_{rx2} = \frac{\beta_2 P_H |h_2|^2}{\sigma^2} \tag{13}$$

For the users to be in coverage, it is required that $SNR_{rx1} \geq \varepsilon_1$, $SNR_{rx1(2)} \geq \varepsilon_1$ and $SNR_{rx2} \geq \varepsilon_2$. Let $P_{rx,i} = P_H |h_i|^2$ denote the received signal power at EU_i, i =1, 2. The minimum received signal power required for users to be in coverage is derived by setting both SNR_{rx1} and $SNR_{rx1(2)}$ to ε_1 and SNR_{rx2} to ε_2. The sensitivities to decode x_1 at EU_1 and EU_2 and x_2 at EU_2 are,

$$P_{sens,1} = P_{sens,1(2)} = \frac{\sigma^2 \varepsilon_1}{\beta_1 - \varepsilon_1 \beta_2} \tag{14}$$

$$P_{sens,2} = \frac{\varepsilon_2 \sigma^2}{\beta_2} \tag{15}$$

If $P_{rx,1}$ becomes less than $P_{sens,1}$, EU_1 is declared in outage. In the same way, if $P_{rx,2}$

becomes less than $\max\{P_{sens,1(2)}, P_{sens,2}\}$, EU_2 is declared in outage.

In the proposed scheme, initially any one of the baseline approaches is used by the relay to calculate β_1 and β_2. For example, the relay may fix $\beta_1 = 0.75$ and $\beta_2 = 0.25$. Then, the receiver sensitivities P_{sens1}, $P_{sens,1(2)}$ and $P_{sens,2}$ are computed using Eqs. (14) and (15). With the knowledge of Channel State Information (CSI), $P_{rx,i}$, i=1,2 is compared with $P_{sens,i}$, i=1,2 to know if the harvested power is sufficient to satisfy the target rates of the end users. Based on these results, the proposed scheme computes β_1 and β_2 as described in the next section.

3.2 SWIPT-APA-NOMA scheme

The system model assumes that perfect CSI is available to the relay [Parida and Das (2014); Li and Li (2018)]. The performance has been analyzed with three possible outage conditions namely, Case (1): Both the users are in coverage, Case (2): Anyone user either a weak or a strong user in outage denoted Cases (2a) and (2b) respectively and Case (3): Both the users are in outage.

The proposed scheme assigns priority to the users to get the entire power used if users are in outage. Based on user priority, allocation of harvested power to each user by the proposed SWIPT-APA-NOMA scheme is done as follows:

Case (1): During the existence of good channel gain between the source and relay, the relay harvested power satisfies the sensitivity requirement of both the end users i.e., powers available at end user receivers are greater than the sensitivity levels given by both Eqs. (14) and (15). This ensures that both end users are not in outage. In this case, the relay allocates the same fraction of power as calculated by the reference power allocation scheme.

Case (2): During the existence of moderate channel gain between the source and relay, the harvested power may satisfy the sensitivity requirement of only one user. In this case, transmission to the user whose sensitivity is not met leads to wastage of power because the user will surely be in outage. In this scenario, the proposed scheme redefines the power allocation coefficients in such a way that the relay allocates the entire harvested power to the user who meets the sensitivity requirement, and zero power to the other user. Now, the user who is allocated the entire power gets a higher achievable data rate, keeping the outage condition of the other unaltered.

Case (3): In another scenario, the sensitivity requirement of both the users may not be satisfied, i.e., both EU_1 and EU_2 could be in outage. This may occur due to (i) the existence of weak channel gain between the source and relay which leads to poor harvested power and (ii) poor links from the relay to end users. In this case, the power allocation coefficients calculated as per the baseline scheme will not favor any of the users. Hence, allocating the entire power to one user may help that user to come out of outage. The proposed scheme selects the user to whom the entire power is to be allotted based on the priority given to the users. This would lead to a reduced outage probability of the prioritized user while maintaining the outage performance of the other user. In this work, the priority given to the weak user and the strong user are denoted by Cases 3(a) and 3(b) respectively.

Once the priority is set, there are three different options for the relay to allocate power depending on the outage conditions of the end users as discussed above. The proposed adaptive power allocation scheme deployed in SWIPT-NOMA has been explored in the flow chart given in Fig. 2 for the different outage conditions discussed above.

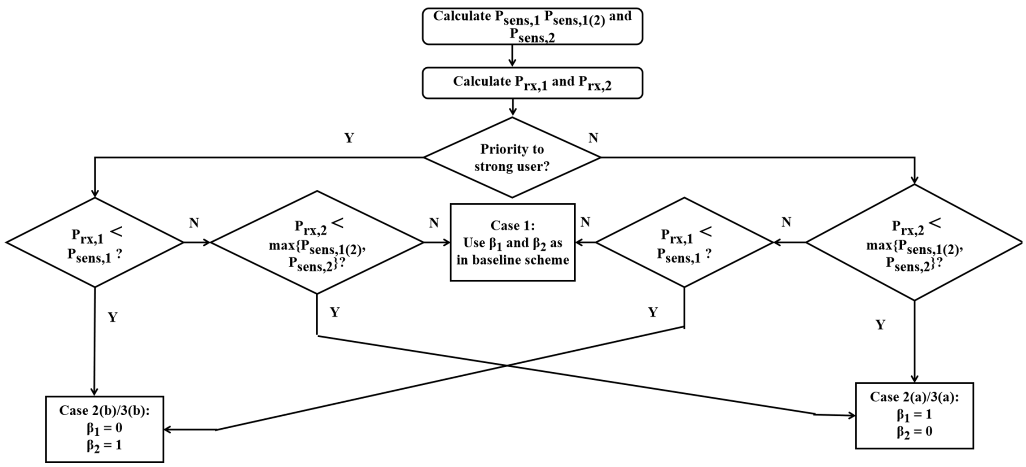


Figure 2: Flow chart depicting the proposed SWIPT-APA-NOMA scheme

The proposed scheme starts by assigning priority to either strong or weak user. The outage conditions of users are checked in the order from the non-prioritized user. Then, the power allocation coefficients are selected in different cases as described below.

Power allocation coefficients as in baseline scheme: When there are good channel conditions available for the users, both users are in coverage i.e., Case (1). The relay uses the power allocation coefficients β_1, β_2 as calculated by the baseline scheme depending on the consideration. In this case, the outage probability for the weak user (P_o^1) and the strong user (P_o^2) are given by, $\Pr\left(P_H |h_1|^2 < P_{sens,1}\right)$ and $\Pr\left(P_H |h_2|^2 < \max\{P_{sens,1(2)}, P_{sens,2}\}\right)$ respectively.

Allocation of entire harvested power to one user: The relay allocates the entire harvested power to one user by setting $\beta_1 = 1, \beta_2 = 0$ or $\beta_1 = 0, \beta_2 = 1$ based on the outage conditions of users and priority given.

The values $\beta_1 = 1, \beta_2 = 0$ are computed i.e., allocation of full harvest power to the weak user is done in two scenarios:

Scenario (i): The weak user is in coverage and the strong user is in outage irrespective of priority denoted by Case (2a). Allocation of the entire harvested power to the weak user $\beta_1 = 1, \beta_2 = 0$ will increase its achievable rate without changing the outage condition of both users. The resultant outage probabilities of the weak user (P_o^1) and the strong user (P_o^2) will be equal to $\Pr\left(P_H |h_1|^2 < \varepsilon_1 \sigma^2\right)$ and $\Pr\left(P_H |h_2|^2 < \max\{P_{sens,1(2)}, P_{sens,2}\}\right)$ respectively.

Scenario (ii): Priority is given to the weak user and both users are in outage as denoted by Case 3(a). Although priority is given to the weak user, the reduction in its outage probability achieved by $\beta_1 = 1, \beta_2 = 0$ is expected to be insignificant because of the following two reasons: Firstly, the weak user is allotted the entire harvested power only when the strong user is in outage. The probability of strong user going into outage is less compared to that of weak user. Secondly, for the weak user, original power shared itself is high and the additional power due to the priority may not significantly improve its received power.

In this case, the resultant outage probability of the weak user is given by,

$$P_{o,w}^{1} = \Pr(\text{weak user is in outage with } \beta_1 = 1, \beta_2 = 0 \,/\, \text{strong user is in outage})$$

$$P_{o,w}^{1} = \Pr\left(P_H |h_1|^2 < \varepsilon_1\sigma^2 \,/\, P_H |h_2|^2 < \max\{P_{sens,1(2)}, P_{sens,2}\}\right) \tag{16}$$

For the strong user, the resultant outage probability is given by,

$$P_{o,w}^{2} = \Pr\left(P_H |h_2|^2 < \max\{P_{sens,1(2)}, P_{sens,2}\}\right) \tag{17}$$

Similarly the values $\beta_1 = 0, \beta_2 = 1$ are computed i.e., allocation of full harvested power to the strong user is done in other two scenarios:

Scenario (iii): The Strong user is in coverage and the weak user is in outage irrespective of priority as denoted by Case (2b). Since the weak user is already in outage, setting $\beta_1 = 0, \beta_2 = 1$ maintains its outage condition while providing an increased data rate to the strong user. It should be noted that the additional power provided to the strong user does not alter its outage conditions because it was already in coverage before allocating the whole harvested power to it. Then, the resultant outage probabilities (P_o^1), $(P_o^2)$are $\Pr\left(P_H |h_1|^2 < P_{sens,1}\right)$ and $\Pr\left(P_H |h_2|^2 < \varepsilon_2\sigma^2\right)$ respectively.

Scenario (iv) : Priority is given to the strong user when both are in outage as denoted by Case (3b). When the strong user signal is allocated with whole harvested power, the absence of interfering weak user signal makes EU_2 achieve improved SNR. This leads to a significant improvement in its outage performance. Further, the weak user is expected to maintain the same outage performance as before. Therefore, the resultant outage probability of the strong user is given by,

$$P_{o,s}^{2} = \Pr(\text{strong user is in outage with } \beta_1 = 0, \beta_2 = 1 / \text{weak user is in outage}).$$

$$P_{o,s}^{2} = \Pr\left(P_H |h_2|^2 < \varepsilon_2\sigma^2 \,/\, P_H |h_1|^2 < P_{sens,1}\right) \tag{18}$$

For the weak user, the resultant outage probability is same as in Case (1) and given by,

$$P_{o,s}^{1} = \Pr\left(P_H |h_1|^2 < P_{sens,1}\right) \tag{19}$$

It should be noted that the effect of prioritizing a user results in a reduction in its outage probability while maintaining that of the other user with a possibility of an increased achievable rate when the prioritized user is not in outage.

If priority is given to the weak user, the overall outage probability of the weak user with adaptive power allocation can be expressed as given by,

$$P^1_{out,w} = \Pr\left(P_H |h_1|^2 < \varepsilon_1 \sigma^2 / P_H |h_2|^2 < \max\{P_{sens,1(2)}, P_{sens,2}\}\right) + \Pr\left(P_H |h_1|^2 < P_{sens,1} / P_H |h_2|^2 > \max\{P_{sens,1(2)}, P_{sens,2}\}\right) \tag{20}$$

Overall outage probability of the strong user can be expressed as,

$$P^2_{out,w} = \Pr\left(P_H |h_2|^2 < \max\{P_{sens,1(2)}, P_{sens,2}\}\right) \tag{21}$$

If priority is given to the strong user, the overall outage probability of the strong user with adaptive power allocation can be expressed as given by,

$$P^2_{out,w} = \Pr\left(P_H |h_2|^2 < \varepsilon_2 \sigma^2 / P_H |h_1|^2 < P_{sens,1}\right) + \Pr\left(P_H |h_2|^2 < \max\{P_{sens,1(2)}, P_{sens,2}\} / P_H |h_1|^2 > P_{sens,1},\right) \tag{22}$$

Overall outage probability of the weak user can be expressed as,

$$P^1_{out,s} = \Pr\left(P_H |h_1|^2 < P_{sens,1}\right) \tag{23}$$

As stated earlier and confirmed by simulations, the significant improvement is achieved only when priority is given to the strong user. Hence, the improvement in bit error performance is proceeded for the priority given to the strong user case in the next section.

4 BER analysis of SWIPT-APA-NOMA scheme

It has been observed in Section 3.2 that prioritizing the strong user offers a significant improvement in its outage performance and thereby, it will improve its error performance. In this section, the average BER of the proposed SWIPT-APA-NOMA for the priority given to strong user has been derived as,

$$BER_s = \left(1 - P_{out,w}\right)\overline{BER_{s,1}} + P_{out,w}\overline{BER_{s,2}} \tag{24}$$

where, $\overline{BER_{s,1}}$ and $\overline{BER_{s,2}}$ are the average BERs when transmission happens to both users while the weak user is in coverage and only to the strong user while the weak user is in outage respectively, $P_{out,w}$ is the outage probability of weak user with fixed power allocation. The first term of Eq. (24) involves β_1 and β_2 values as determined by fixed power allocation. The second term uses $\beta_1 = 0$ and $\beta_2 = 1$, i.e., whole power is allocated only for the strong user while the weak user is in outage.

For an average harvested power $P_{H,av}$ by the relay, the outage probability of the weak user is $\Pr\left(\dfrac{\beta_1 P_{H,av} |h_1|^2}{\beta_2 P_{H,av} |h_1|^2 + \sigma^2} < \varepsilon_1\right)$, which can be rewritten as,

$$P_{out,w} = \Pr\left(|h_1|^2 < \frac{\varepsilon_1 \sigma^2}{P_{H,av}(\beta_1 - \varepsilon_1 \beta_2)} \right) \tag{25}$$

Since, $|h_1|$ is Rayleigh distributed, $g = |h_1|^2$ follows exponential distribution. The pdf of g is given by,

$$f_G(g) = d_1^{\upsilon} \exp\left(-g d_1^{\upsilon}\right), \; g \geq 0 \tag{26}$$

Using Eq. (26), the expression for outage probability $P_{out,w}$ is derived as,

$$P_{out,w} = \int_0^T f_G(g)\, dg = 1 - \exp\left(\frac{-\varepsilon_1 \sigma^2 d_1^{\upsilon}}{P_{H,av}(\beta_1 - \varepsilon_1 \beta_2)} \right) \tag{27}$$

where, $T = \frac{\varepsilon_1 \sigma^2}{P_{H,av}(\beta_1 - \varepsilon_1 \beta_2)}$. For the channel SNR γ and the selected values of β_1 and β_2, the conditional $BER_{s,1}$ and $BER_{s,2}$ for fixed power allocation employing BPSK are derived using Q-function [Kara and Kaya (2018)],

$$BER_{s,i} = Q\left(\sqrt{\gamma_c}\right) - \frac{1}{2} Q\left(\sqrt{\gamma_d}\right) + \frac{1}{2} Q\left(\sqrt{\gamma_e}\right) + \frac{1}{2} Q\left(\sqrt{\gamma_f}\right) - \frac{1}{2} Q\left(\sqrt{\gamma_g}\right), \; i = 1, 2 \tag{28}$$

The Q-function and other parameters used inside the Q-function in Eq. (28) are defined as,

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(\frac{-u^2}{2} \right) du \tag{29}$$

$$\gamma_c = \frac{P_{H,av} \beta_2 d_2^{-\upsilon}}{\sigma^2 / 2} \tag{30}$$

$$\gamma_d = \frac{P_{H,av} \left(\sqrt{\beta_1} + \sqrt{\beta_2} \right)^2 d_2^{-\upsilon}}{\sigma^2 / 2} \tag{31}$$

$$\gamma_e = \frac{P_{H,av} \left(2\sqrt{\beta_1} + \sqrt{\beta_2} \right)^2 d_2^{-\upsilon}}{\sigma^2 / 2} \tag{32}$$

$$\gamma_f = \frac{P_{H,av} \left(\sqrt{\beta_1} - \sqrt{\beta_2} \right)^2 d_2^{-\upsilon}}{\sigma^2 / 2} \tag{33}$$

$$\gamma_g = \frac{P_{H,av} \left(2\sqrt{\beta_1} - \sqrt{\beta_2} \right)^2 d_2^{-\upsilon}}{\sigma^2 / 2} \tag{34}$$

The average BERs $\overline{BER_{s,i}}$, i=1, 2 on coverage and outage defined earlier are derived from the $\overline{BER_{s,1}}$ and $\overline{BER_{s,2}}$ as,

$$\overline{BER_{s,i}} = \int_0^\infty f_\gamma(\gamma)d\gamma, \qquad i=1, 2 \tag{35}$$

where, $f_\gamma(\gamma)$ is the pdf of instantaneous SNR (γ) in a Rayleigh fading channel. With the help of Eq. (5.6) of Simon et al. [Simon and Alouini (2004)], the above integral is evaluated as,

$$\begin{aligned}\overline{BER_{s,i}} = {} & 0.5\left(1-\sqrt{\frac{\gamma_c}{2+\gamma_c}}\right)-0.25\left(1-\sqrt{\frac{\gamma_d}{2+\gamma_d}}\right)+0.25\left(1-\sqrt{\frac{\gamma_e}{2+\gamma_e}}\right)\\ & +0.25\left(1-\sqrt{\frac{\gamma_f}{2+\gamma_f}}\right)-0.25\left(1-\sqrt{\frac{\gamma_g}{2+\gamma_g}}\right)\end{aligned} \tag{36}$$

For the selected values of β_1 and β_2, the average BER of the proposed SWIPT-APA-NOMA for the priority given to the strong user is obtained by substituting Eqs. (27) and (36) in Eq. (24).

5 Results and discussions

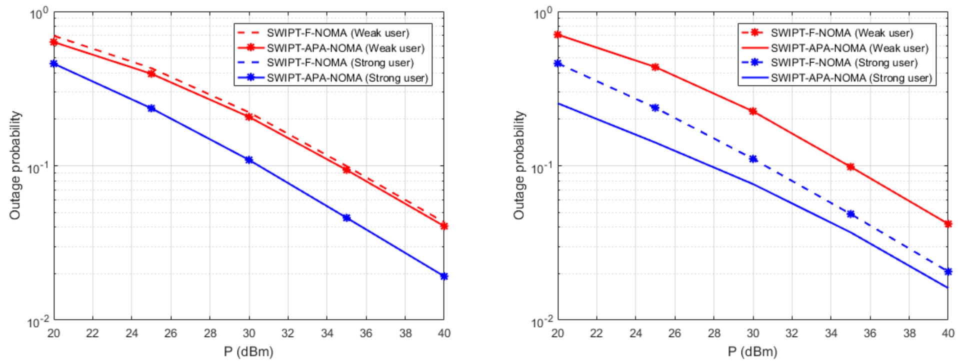
In this section, the outage probability, capacity and BER performances of the proposed SWIPT-APA-NOMA algorithm have been evaluated using Monte Carlo simulations and compared with the performances offered by existing SWIPT-F-NOMA and SWIPT-CR-D-NOMA which have similar target of the present work. As a first case, the outage performance of the proposed SWIPT-APA-NOMA introduced in SWIPT-F-NOMA system has been studied for (i) priority given to weak or strong user, (ii) different target rates and (iii) different power allocation factor (β). Next, the outage performance of the proposed SWIPT-APA-NOMA scheme has also been studied with SWIPT-CR-D-NOMA system. The effects of bandwidth, noise figure and fading margin on the outage, peak data rate and capacity have also been studied. The bit error performance of the proposed SWIPT-APA-NOMA has been evaluated in the last part of this section. The values of simulation parameters that are common in all studies have been chosen as given in Tab. 1.

Table 1: Simulation parameters

Parameter	Value
Source to relay distance (d)	10 m
Relay to EU_1 distance (d_1)	25 m
Relay to EU_2 distance (d_2)	10 m
Carrier frequency	915 MHz
Noise power	-114 dBm
Path loss exponent (υ)	4

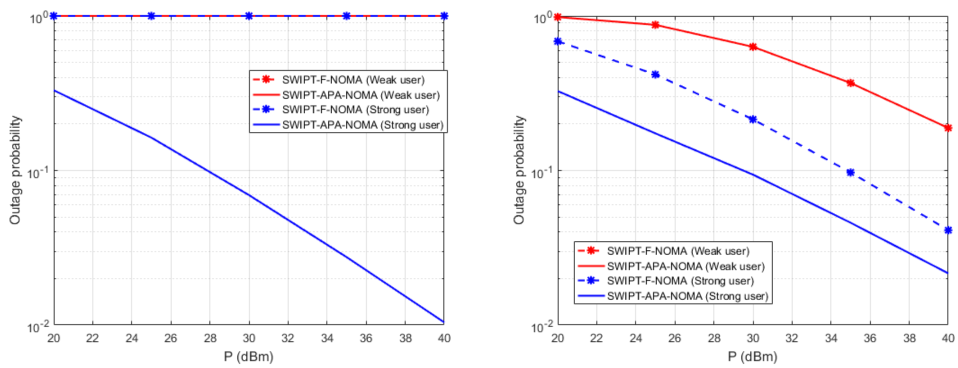
The outage performance of the proposed SWIPT-APA-NOMA along with SWIPT-F-NOMA has been studied from Fig. 3. The outage performance with priority given to weak and strong users has been obtained as in Figs. 3(a) and 3(b) respectively for the target data rates $R_1^* = 0.5$ bps/Hz and $R_2^* = 1.5$ bps/Hz chosen. In this simulation, the values of β_1 and β_2 for SWIPT-F-NOMA are chosen as 0.75 and 0.25 respectively. From Figs. 3(a) and 3(b), it can be observed that the outage probability improvement offered to the weak user when it is given priority, is marginal but, there is a significant improvement for the prioritized strong user. Improvement in outage is due the allocation of additional power to the strong user while the weak user is in outage, which significantly improves the SNR of the strong user but, it is not true in the case of the weak user. It is observed from Fig. 3(b) that the improvement in the outage performance of the strong user reduces in higher SNR region which is similar to the case where priority is given to the weak user. It is also observed that the priority given to one user does not alter the outage probability of the other user. It concludes that (i) significant improvement in outage performance is realized only when the strong user is prioritized and (ii) the proposed algorithm improves the outage performance significantly at low SNRs.

For a given β_1 and β_2 and priority given to the strong user, the effect for increased target rates is studied further. The Fig. 3(c) shows the outage probability evaluated for 0.5 bps/Hz increase in target rates of the users from its earlier values in the selected scenario. It is clear that the outage probability of SWIPT-F-NOMA degrades with an increase in the target rates and both users undergo outage for the chosen target rates. Here, the power allocated to both users may not guarantee the minimum required SNR to any of the users and hence results in degradation. The deployment of the proposed SWIPT-APA-NOMA in those systems boosts the SNR of the strong user due to its additional power allocation. As it is observed in Fig. 3(c), the boosted SNR saves the strong user from undergoing outage.



(a) Priority to weak user (b) Priority to strong user

$R_1^* = 0.5$ bps/Hz, $R_2^* = 1.5$ bps/Hz, $\beta_1 = 0.75, \beta_2 = 0.25$



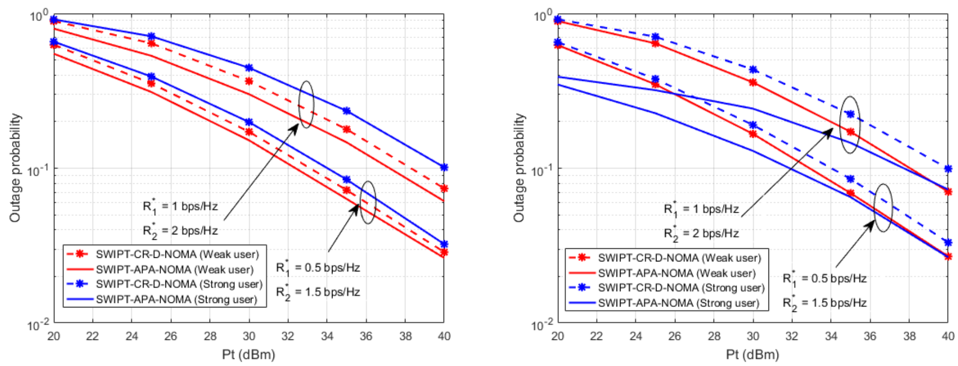
(c) $\beta_1 = 0.75, \beta_2 = 0.25$ (d) $\beta_1 = 0.8, \beta_2 = 0.2$

$R_1^* = 1$ bps/Hz, $R_2^* = 2$ bps/Hz, Priority to strong user

Figure 3: Outage performance comparison of SWIPT-APA-NOMA and SWIPT-F-NOMA over transmit power

For the greedy target rates of $R_1^* = 1$ bps/Hz and $R_2^* = 2$ bps/Hz, the effect of β_1 and β_2 in the proposed method has been studied with Figs. 3(c) and 3(d). The Fig. 3(c) shows that the non-optimal values of β_1 and β_2 lead both users to undergo outage for SWIPT-F-NOMA. This is because, the condition $\beta_1 > \varepsilon_1 \beta_2$ is violated [Yang, Ding, Fan et al. (2017)]. But, even a smaller change in power allocation coefficients by 0.05 i.e., $\beta_1 = 0.8$ and $\beta_2 = 0.2$ yields a drastic improvement in the outage performance for SWIPT-F-NOMA as seen in Fig. 3(d). Thus, it can be concluded that the proper choice of target rate and power allocation coefficients are crucial for SWIPT-F-NOMA. It is also realized from the figure that the use of the proposed SWIPT-APA-NOMA algorithm further improves the outage probability. The above results confirmed that the deployment of proposed SWIPT-APA-NOMA with priority given to strong user enhances the outage performance of SWIPT-F-NOMA for all feasible target rates.

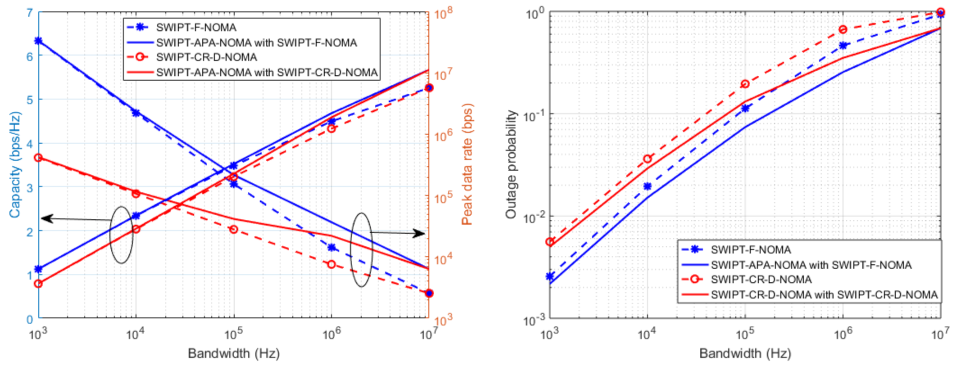
The outage probabilities for different values of target data rate for SWIPT-APA-NOMA with SWIPT-CR-D-NOMA as baseline scheme are plotted in Fig. 4. While comparing with Figs. 3(c) and 4, the SWIPT-CR-D-NOMA keeps the users away from outage even at increased target rates. The introduction of the proposed SWIPT-APA-NOMA in SWIPT-CR-D-NOMA and its impact in outage performance with priority given to the weak user and the strong user is analyzed from Figs. 4(a) and 4(b) respectively.



(a) Priority to weak user (b) Priority to strong user

Figure 4: Outage performance comparison with SWIPT-CR-D-NOMA over transmit power

As seen in the previous case, the network shows only a marginal improvement in outage performance for the selected target rates when priority is given to the weak user. Further, the improvement provided by SWIPT-APA-NOMA becomes higher when the target rates are increased but, still the improvement is insignificant. This is because, when the target data rate of the strong user increases, the outage probability also increases leading to more opportunities for the weak user to be allocated the entire power. It is observed from Fig. 4(b), the proposed scheme achieves a significant improvement in outage performance at low SNR when the priority is given to the strong user but, the improvement in outage probability reduces as the SNR increases. It should be noted that the strong user achieves about 2.2 fold improvements in outage probability by the proposed technique to SWIPT-CR-D-NOMA for the simulated target data rates of $R_1^* = 1$ bps/Hz and $R_2^* = 2$ bps/Hz and 1.8 fold improvement in outage probability for target data rates of $R_1^* = 0.5$ bps/Hz and $R_2^* = 1.5$ bps/Hz. This depicts that when the target data rate increases, the performance gain achieved by SWIPT-APA-NOMA becomes more significant as improvement in SNR available to the strong user brings it away from outage. Also, the Fig. 4(b) confirms that the weak user does not suffer from degradation in outage performance because of the effectiveness of the proposed SWIPT-APA-NOMA scheme.



(a) Capacity and peak data rate (b) Outage performance

Figure 5: Performance comparison over signal bandwidth

Next, the effect of bandwidth on the outage performance, capacity and peak data rate are plotted. Since prioritizing the strong user gives significant performance improvement, all these results are obtained as shown in Fig. 5 by prioritizing the strong user. Fig. 5(a) shows that the peak data rate of the proposed SWIPT-APA-NOMA is greater than that of the schemes considered as reference here. The input noise power increases proportionally to bandwidth and as a result, the system undergoes outage more often, leading to full power allocation to strong user. This offers significant performance improvement to the strong user in the proposed scheme as the bandwidth increases. But this data rate improvement is achieved at the cost of reduced spectral efficiency for all the power allocation schemes considered. This is because, the noise power increases as the bandwidth increases which in turn reduces the capacity. Similarly, for the fixed target rate, the outage probability increases with bandwidth for both schemes as shown in Fig. 5(b). It can be observed from Fig. 5, that the proposed SWIPT-APA-NOMA outperforms both the reference power allocation schemes in terms of outage probability, peak data rate and capacity.

The margins provided to noise and fading offers similar effects and their impact on capacity has been studied with their cumulative change. To study the performance, transmit power of 20 dBm and bandwidth of 1 MHz is considered. The target rates of strong and weak users are chosen as 0.5 bps/Hz and 1.5 bps/Hz respectively. The capacity and percentage of improvement have been estimated over the cumulative change in noise figure and fading margin and are tabulated as in Tab. 2. Increase in the noise figure or fading margin of receivers increases the outage probability of weak user. This increases the chances of entire power being allocated to the strong user. Hence, the capacity of strong user increases with the noise figure/fading margin of receivers. It can be observed from Tab. 2 that the proposed system offers improvement in performance while the noise figure and/or fading margin of receiver increases. It can be noted that the proposed SWIPT-APA-NOMA offers a maximum improvement of 96.06% in capacity in a system operated with SWIPT-CR-D-NOMA at a margin of 10 dB for the considered transmit power, bandwidth and target rates.

Table 2: Effect of noise figure and fading margin

$\Delta(NF+FM)$ (dB)	Capacity (bps/Hz)				% improvement in capacity	
	SWIPT-F-NOMA	SWIPT-APA-NOMA with SWIPT-F-NOMA	SWIPT-CR-D-NOMA	SWIPT-APA-NOMA with SWIPT-CR-D-NOMA	SWIPT-APA-NOMA with SWIPT-F-NOMA	SWIPT-APA-NOMA with SWIPT-CR-D-NOMA
0	1.61	2.1886	1.22	1.883	**35.8**	**54.3**
3	1.61	2.3183	1.22	2.0896	**43.9**	**71.2**
6	1.61	2.4124	1.22	2.2163	**49.8**	**81.6**
10	1.61	2.4495	1.22	2.392	**52.1**	**96.06**

The BER performance of SWIPT-F-NOMA is studied before and after introducing SWIPT-APA-NOMA. For this study, to meet the condition $\beta_1 > \varepsilon_1\beta_2$ and the selected target rates of $R_1^* = 1$ bps/Hz and $R_2^* = 2$ bps/Hz, the power allocation factors and modulation schemes have been chosen as $\beta_1 = 0.8$ and BPSK modulation respectively for both users. The BER performance of the strong user obtained over transmit power is shown in Fig. 6.

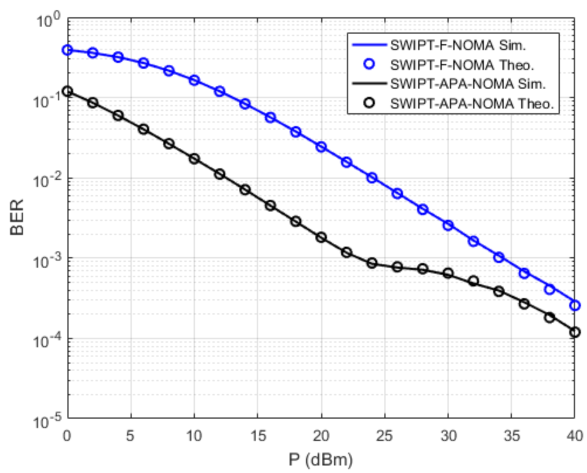


Figure 6: BER performance $(\beta_1 = 0.8, \beta_2 = 0.2)$

The overlapping of curves in Fig. 6 confirms the analytical expression Eq. (24) of BER derived in this work. It can be observed from Fig. 6 that the introduction of proposed SWIPT-APA-NOMA improves the BER performance of the user with priority. This reduction in BER is achieved by the improvement obtained in SNR by additional power allocation to the prioritized strong user. It can be measured that the proposed scheme provides an SNR improvement of about 10 dB over the SWIPT-F-NOMA at a BER of 10^{-3}. Further, the reduction in BER of the strong user by the proposed scheme is more significant at the low SNR region. But, it approaches the performance of baseline scheme at high SNR regions. This is because the weak user is not always in outage at high SNR regions as can be observed from Fig. 3(d). This leads to a decrease in the additional power available to strong user as the weak user gets into coverage.

6 Conclusion

In this work, a novel power allocation scheme namely, SWIPT-APA-NOMA is proposed for the improvement in outage and error performance. In the proposed work, the power allocation is decided based not only on the target rate and user signal to noise ratio but also on the sensitivity of receivers and priority of the user. The influence of factors that decide the receiver sensitivity like bandwidth, noise figure, fading margin on system performance are also studied. It is concluded that when priority is given to the strong user, the proposed scheme offers a significant improvement in outage and error performances than when priority is given to the weak user. Further, the given priority to one user does not affect the performance of the other user. The simulation results are compared with that of baseline schemes and confirmed with regard to the improvements offered by the proposed scheme. The BER performance of the strong user with priority shows that the transmission power can be reduced by more than 10 dB for the same BER at low power regions. The strong agreement between the simulated BER with theoretical estimation also confirms the validity of the analytical expression derived in this work.

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Appendix

The expression for BER at EU_2 has been derived in this section. The constellation of the resultant NOMA signal with BPSK modulation for the average harvested power and selected power allocation coefficients will appear as shown in Fig. 7.

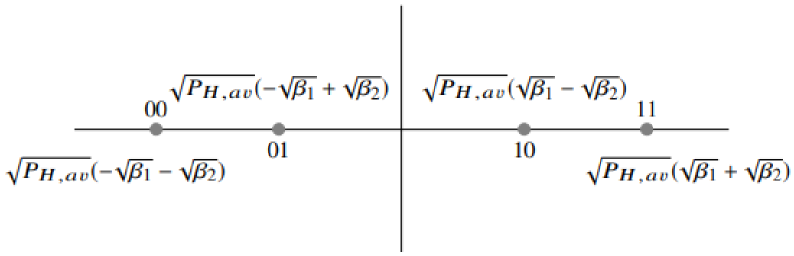
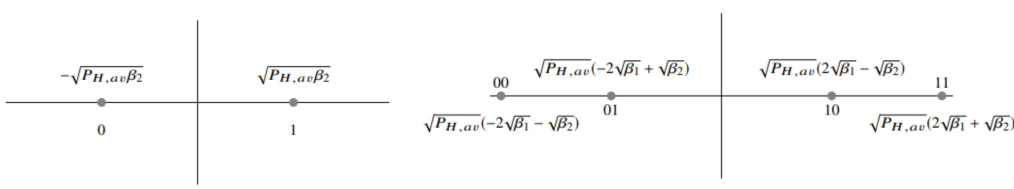


Figure 7: NOMA BPSK constellation

Since $\beta_1 > \beta_2$, the information x_1 of EU_1 is decoded first before decoding the information x_2 of EU_2. Considering the error in the detection of x_1, the conditional BER of EU_2 provided by the channel condition can be written as,

$$BER_{s,i} = \Pr(x_2 \text{ error}/x_1 \text{ correct})\Pr(x_1 \text{ correct}) + \Pr(x_2 \text{ error}/x_1 \text{ error})\Pr(x_1 \text{ error}),\ i=1, 2 \quad (37)$$

The 'i' is selected as discussed in section 4. The constellation of the signal after SIC when x_1 is decoded correctly and with error at EU_2 becomes as shown in Figs. 8(a) and 8(b) respectively. The probabilities $\Pr(x_2 \text{ error}/x_1 \text{ correct})$ and $\Pr(x_2 \text{ error}/x_1 \text{ error})$ are derived using them.



(a) x_1 decoded correctly (b) x_1 decoded with error

Figure 8: Constellation

Let T_1 and T_2 denote the first and second terms of Eq. (37) respectively and they can be simplified as follows.

$$\begin{aligned}
T_1 &= \Pr(x_2 \text{ error}/x_1 \text{ correct})\Pr(x_1 \text{ correct}) \\
&= \frac{1}{2}\Pr\left(n < \sqrt{P_{H,av}}\left(\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2\right) \times \Pr\left(n > \sqrt{P_{H,av}\beta_2}\,h_2 / n < \sqrt{P_{H,av}}\left(\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2\right) \\
&\quad + \frac{1}{2}\Pr\left(n < \sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right) \times \Pr\left(n < -\sqrt{P_{H,av}\beta_2}\,h_2 / n < \sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right) \\
&= \frac{1}{2}\Pr\left(\sqrt{P_{H,av}\beta_2}\,h_2 < n < \sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right) + \frac{1}{2}\Pr\left(n < -\sqrt{P_{H,av}\beta_2}\,h_2\right) \\
&= \Pr\left(n > -\sqrt{P_{H,av}\beta_2}\,h_2\right) - \Pr\left(n > \sqrt{P_{H,av}}\left(\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2\right)
\end{aligned}$$

$$=Q\left(\frac{\sqrt{P_{H,av}\beta_2}h_2}{\sqrt{\sigma^2/2}}\right)-\frac{1}{2}Q\left(\frac{\sqrt{P_{H,av}}\left(\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2}{\sqrt{\sigma^2/2}}\right)$$

$$T_1=Q\left(\sqrt{\gamma_c}\right)-\frac{1}{2}Q\left(\sqrt{\gamma_d}\right) \tag{38}$$

$$T_2=\Pr\left(x_2 \text{ error}/x_1 \text{ error}\right)\Pr\left(x_1 \text{ error}\right)$$

$$=\frac{1}{2}\Pr\left(n>\sqrt{P_{H,av}}\left(\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2\right)$$

$$\times\Pr\left(n>\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2/n>\sqrt{P_{H,av}}\left(\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2\right)$$

$$+\frac{1}{2}\Pr\left(n>\sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right)$$

$$\times\Pr\left(n<\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2/n>\sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right)$$

$$=\frac{1}{2}\Pr\left(n>\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2\right)$$

$$+\frac{1}{2}\Pr\left(\sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2<n<\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right)$$

$$=\frac{1}{2}\Pr\left(n>\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2\right)+\frac{1}{2}\Pr\left(n>\sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right)$$

$$-\frac{1}{2}\Pr\left(n>\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2\right)$$

$$=Q\left(\frac{\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}+\sqrt{\beta_2}\right)h_2}{\sqrt{\sigma^2/2}}\right)+\frac{1}{2}Q\left(\frac{\sqrt{P_{H,av}}\left(\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2}{\sqrt{\sigma^2/2}}\right)$$

$$-\frac{1}{2}Q\left(\frac{\sqrt{P_{H,av}}\left(2\sqrt{\beta_1}-\sqrt{\beta_2}\right)h_2}{\sqrt{\sigma^2/2}}\right)$$

$$T_2=\frac{1}{2}Q\left(\sqrt{\gamma_e}\right)+\frac{1}{2}Q\left(\sqrt{\gamma_f}\right)-\frac{1}{2}Q\left(\sqrt{\gamma_g}\right) \tag{39}$$

Substituting Eqs. (38) and (39) in Eq. (37), the average BER based on outage is estimated.