Analyzing System Reliability and Performance in SWIPT Multiuser Cognitive Ratio Systems

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Abstract. This paper studies a Simultaneous Wireless Information and Power design based on two important concepts of energy harvesting and cognitive ratio two key aspects of transfer systems: simultaneous modulation of interference power and output power, and the asymmetric transmit-receive relationship that must exist in the primary user (PU). Building on previous findings about the effects of individual parameters on system behavior, exploring the impact of these combined alterations on interruption probability and system performance. First, the joint manipulation of interference power and output power is under investigation. Our analysis unveils nuanced shifts in interruption probability when both parameters are altered concurrently. By varying these factors within a range, Complex variations in outage probability are observed, underscoring the interplay between interference mitigation and energy availability. Secondly, the deviation of one-to-many communication between sender and receiver in PU integration is under study. This scenario mirrors a real-life situation where a single sender transmits information to multiple receivers. Through simulation and analysis, the effects of this asymmetric relationship on system reliability and interrupt probability are illustrated. This exploration pro-vides insights into the scalability and adaptability of secondary user systems to accommodate different modes of communication. By addressing these two dimensions, this study can contribute to a deeper understanding in real life of the complex interplay between related system parameters and communication dynamics in the secondary and primary users of this system. The findings provide valuable insights for designing and optimizing such systems in the real world, where adaptability and some resilience are critical.

Keywords: Energy harvesting, Cognitive ratio, Time-sharing policy, Outage probability.

1 Introduction

1.1 Energy Harvesting and Cognitive Ratio

Obviously, Ref. [1] reveals the rapid development of wireless communication in recent years and the challenges faced by mobile device battery technology. It

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highlights breakthroughs in wireless communications such as MIMO, capacity to reach coding, millimeter wave communications, and cell networking, enabling wireless access speeds of gigabits. As mobile devices become the dominant Internet access platform, the problem of short battery life and the need for regular charging becomes a barrier to true mobility. These challenges, known as the "last line," include inconvenience, financial losses, threats to health and safety, and environmental concerns due to the production of large numbers of non-recyclable chargers. There have been some researches in related fields [2,3] provides a new direction and vision for related research.

Research interest in the topic of Simultaneous Wireless Information and Energy Transfer (SWIPT) has continued to grow in recent years, and this interdisciplinary appeal and broad application potential have inspired people to pay attention to this topic. The article [4] provides a brief survey of the current situation and describes several practical transceiver architectures that may help with its implementation. It demonstrates the feasibility of the SWIPT form. In [5], delve into the concept of energy harvesting, particularly through RF energy harvesting, which enables wireless devices to convert received RF signals into electricity. This process establishes a sustainable power source derived from the ambient radio environment. This technology has witnessed rapid adoption across various applications such as wireless sensor networks, wireless body networks, and wireless charging systems. Following this, explore a schematic representation of a standard power scavenging module that provides power to a communication transceiver, as detailed in [6]. Investigate the cognitive ratio, as discussed in [7], which represents the convergence of computing power in wireless PDAs and their networks for radio resource management and inter-device communication. A cognitive radio (CR) possesses the capability to smartly identify whether any part of the spectrum is currently in use. It can then opportunistically utilize that spectrum without causing interference to the transmissions of other users [8]. Relevant studies [9] also show that the cognitive ratio can make good use of energy harvesting. It is evident that the energy driving the cognitive ratio system can originate from environmental energy harvesting.

1.2 Motivation and Contribution

Synchronous Wireless Information and Power Transfer (SWIPT) for multi-user cognitive radio (CR) systems is motivated by the urgent need to optimize spectrum usage and provide sustainable energy solutions for wireless networks. SWIPT can transmit data and power to multiple users simultaneously, improving spectral efficiency and extending device life. By integrating cognitive radio's dynamic spectrum access and intelligent resource allocation, SWIPT systems adaptively utilize available spectrum resources while efficiently delivering data and power to users. This fusion of CR and energy harvesting technologies offers a promising solution to spectrum shortages and energy sustainability challenges in wireless networks. The author established a system integrating energy harvesting and cognitive radio, and conducted a preliminary simulation of the system, but in real life, there will be more practical situations to simulate this system. Therefore, in this paper, the author will use MATLAB simulation, on the basis of the original results, to discuss the impact of some specific conditions on the probability of whether the system can continue.

2 Model of SWIPT Multiuser Cognitive Ratio System

2.1 Primary Users

The model is shown in Fig. 1. In SWIPT multi-user cognition ratio systems, a "primary user" is a user initially assigned to a specific spectrum band or channel, usually a user with high priority or first possession. It mainly consists of two parts: one is the transmitter that initially wants to send the information, and the other is the receiver to which those messages are intended to be delivered. Increasing the number of transmitters and receivers in the primary user brings some benefits and disadvantages.

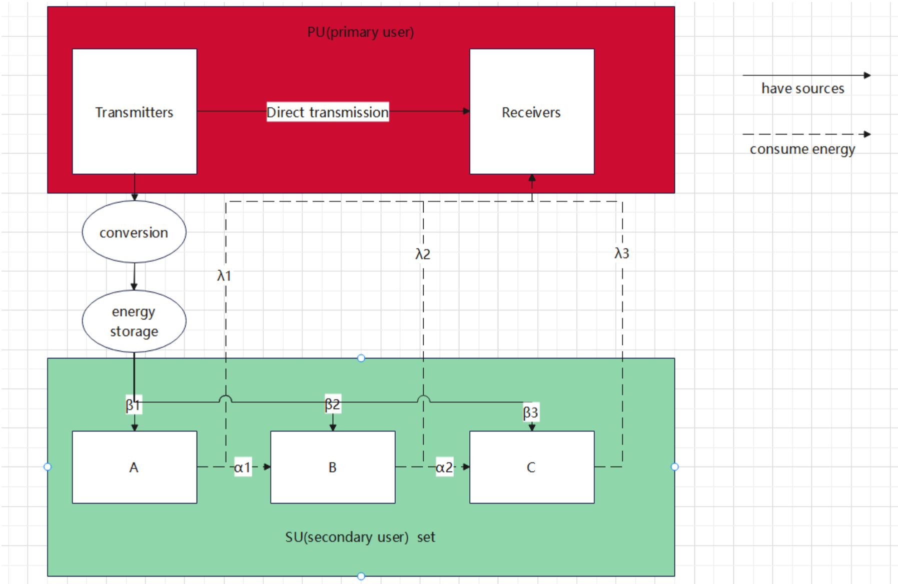

Fig. 1. The ideal model consists of two parts, one is the original Primary users, the other is the Secondary users based on the cognitive ratio design.

Firstly, regarding redundancy and backup, increasing the number of transmitters and receivers can provide redundancy and backup, thereby enhancing the reliability of the system. If a transmitter or receiver fails, other transmitters or receivers can still continue to work, ensuring the continuity and stability of the system.

Secondly, to improve coverage and signal quality, increasing the number of transmitters and receivers can expand the coverage of the system and improve the density and quality of signal coverage. This is especially important for applications that cover a large area or require high signal strength.

Thirdly, to improve system capacity, increasing the number of transmitters and receivers can increase the capacity of the system, allowing more users to be served at the same time, thereby improving the overall performance and throughput of the system.

Regarding its disadvantages, there are roughly the following points.

Firstly, it will lead to competition for spectrum resources: Increasing the number of transmitters and receivers may lead to more competition for spectrum resources, especially when spectrum resources are limited. This can cause spectrum fragmentation and interference problems, affecting the performance and stability of the system.

Secondly, it can be seen that as the number increases, the performance of the entire system is affected by a variety of factors, which may become better or worse. In previous papers, the investigation delved into the variations in system performance with increasing transmitter numbers when transmitters and receivers are paired. In this paper, the aim is to advance by challenging the premise that the quantity of transmitters must match that of receivers, instead opting to align with alternative criteria.

Since it is not clear whether the operational efficiency of the whole system is increased or decreased after increasing the number of transmitters, simulation experiments are required to ascertain the change trend of the outage probability and identify the optimal number of PU transmitters.

2.2 Secondary Users

In the context of energy harvesting on primary user (PU) networks, three distinct components play vital roles, A is Secondary Source (SS), B is Secondary Relay (SR), and C is Secondary Destination (SD).

The Secondary Source (SS) serves as an energy-constrained secondary user device tasked with generating and transmitting information. However, owing to its energy limitations, the SS relies on harvesting energy from the primary user's wireless signal to sustain its transmission activities. It functions as the originator of data transmission to the Secondary Destination (SD), making effective energy harvesting essential for its operation.

Situated between the SS and the SD, the Secondary Relay (SR) acts as another energy-constrained secondary user device. It facilitates communication by relaying information between the SS and the SD, particularly in scenarios where direct connectivity is hindered by deep fading or other obstacles. Similar to the SS, the SR also harnesses energy from the primary user's wireless signal to support its relay function, thereby contributing to the overall energy dynamics of the system.

On the receiving end, the Secondary Destination (SD) represents a fully powered secondary user device responsible for receiving transmitted information from the SS. In addition to its primary role in data reception, the SD, like the SS and SR, has the capability to harvest energy from the primary user's wireless signal. This energy harvesting feature ensures that the SD remains operational and capable of receiving data even in energy-constrained environments.

Collectively, these components form integral parts of the energy harvesting process within PU networks, where energy-constrained secondary user devices collaborate to sustain communication activities by leveraging energy from the primary user's wireless signals.

2.3 Operating Principle

Table 1 shows the general idea of the operation of the model. Consider a transition process with a total duration of T, which can be subdivided into four distinct stages T1, T2, T3, and T4, each occurring sequentially over the entire time frame T.

Table 1. System runtime allocation.

	A	B	C
T1	Harvest energy	Harvest energy	Harvest energy
T2	Transmit information to B	Receive information from A	
T3		Transmit information to C	Receive information from B
T4	Transmit information to PU receivers	Transmit information to PU receivers	Transmit information to PU receivers

The total duration T is the sum of the stages:

$$T = T1 + T2 + T3 + T4 \tag{1}$$

These stages follow a specific order, with T1 ending first, followed by T2, then T3, and finally T4.

In initial phase T1, all the entities involved, namely A, B, and C, have the ability to receive wireless information from the primary user (PU) transmitter. In addition, this period is conducive to energy harvesting activities.

Transitioning to the second stage T2, wireless information is transmitted from entity A to entity b. At the same time, energy harvesting processes can also be carried out to support and facilitate this data transmission.

In the subsequent phase T3, entity B replicates the behavior of entity A in T2, transmitting wireless information to entity c. Similar to previous phases, energy harvesting mechanisms can be used during T3 to power this communication process.

Finally, in the summary phase T4, Entity C consolidates all the wireless information collected throughout the process. In addition, any energy collected through the collection process is used directly to power the designated PU receiver.

Finally, regarding the energy and power in this process. The formula from the reference paper can be employed for this purpose. The model comprises an independent PU transmitter and an independent PU receiver, and get A, B, C energy and power, take n (0<n<1) as energy conversion, take P as the energy collected by A, B, and C in the energy harvesting process:

$$E_a = n \times P \times T_1 \times \beta_1 \tag{2}$$

$$E_b = n \times P \times T_1 \times \beta_2 \quad (3)$$

$$E_c = n \times P \times T_1 \times \beta_3 \quad (4)$$

There is A P1, and in order to ensure that the interference power to PU does not exceed PI, the transmit power of A and B is constrained. Therefore, the transmit power at A and B are given by

$$P_a = \min\left(\frac{E_a}{T_2}, \frac{P_1}{\lambda_1}\right) \quad (5)$$

$$P_b = \min\left(\frac{E_b}{T_3}, \frac{P_1}{\lambda_2}\right) \quad (6)$$

Here, these two values will be used to determine whether an outage has occurred.

3 Simulation and Result Analysis

3.1 Simulate the Preparation

The Threshold Signal-to-Noise Ratio (TSNR) is the lowest signal-to-noise ratio threshold at which the receiving end can correctly decode and recognize information in a communication system. Signal-to-noise ratio refers to the ratio of signal to noise, which is used to measure the intensity of the signal and the degree of interference from noise.

In digital communication, the signal is subjected to various interferences and distortions during transmission, with noise being the most significant interference source. When the signal-to-noise ratio is low, the noise affects the signal more than the signal itself, causing the receiver to be unable to decode and recognize the information correctly. Therefore, the threshold SNR is the lowest SNR required by the receiving end to ensure correct decoding and recognition.

By setting an appropriate threshold SNR, the reliability and performance of the communication system can be improved. When the SNR is higher than the threshold value, the receiver can accurately recover the original information. When the SNR is lower than the threshold, the receiving end cannot decode the information correctly, resulting in transmission errors.

It can be learned from [10] on how to judge outage. This probability will serve as the criterion for evaluating the efficiency of the entire system because the lower the probability, the less likely the system is to fail to pass messages. Here, set the parameters as follows: the percentage of energy collected by a node is 0.8; the energy collection time ratio T1=0.5T; Fixed interference power is 10dB, then calculate its decimal value 10^(15/10); Set the transmit power to 0dB, whose decimal value is 10^(0/10); The threshold signal-to-noise ratio (dB) is -10dB; Monte Carlo simulation is a computational method based on probability statistics that solves problems through random sampling and statistical analysis. In Monte Carlo simulation, an approximate solution to the problem can be obtained by repeating the experiment many times. Set this value to 100000. Then set the coordinates of the simulation of the node, coordinates of A are [0 0], coordinates of B are [0.5 0], coordinates of C are [1 0], the center of the transmitter and receiver is set to [0.5 1], [1 0.5], suppose M is the number of transmitters, and N is the number of receivers.

First, simulate the probability transformation trend of outage when the output power and interference power increase simultaneously, and the transmitter and receiver still maintain a one-to-one corresponding quantity ratio. Then change the number ratio of transmitter and receiver, simulate the actual situation, where there is a transmitter corresponding to multiple receivers in the system.

3.2 Diagram and Description of Simulation Results

Through the simulation results in Fig. 2 and Fig. 3, it can be observed that when the output power and interference power are increased by the same decibels, the outage probability of the entire system basically remains unchanged.

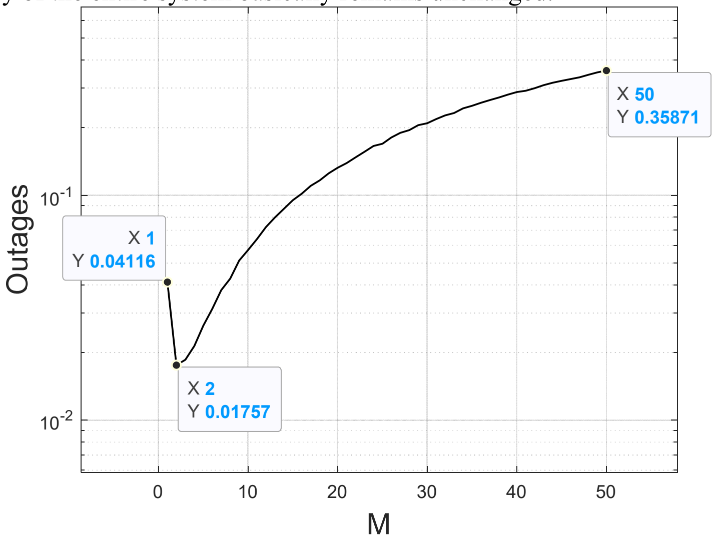

Fig. 2. Interference power is 10dB, transmit power is 0dB.

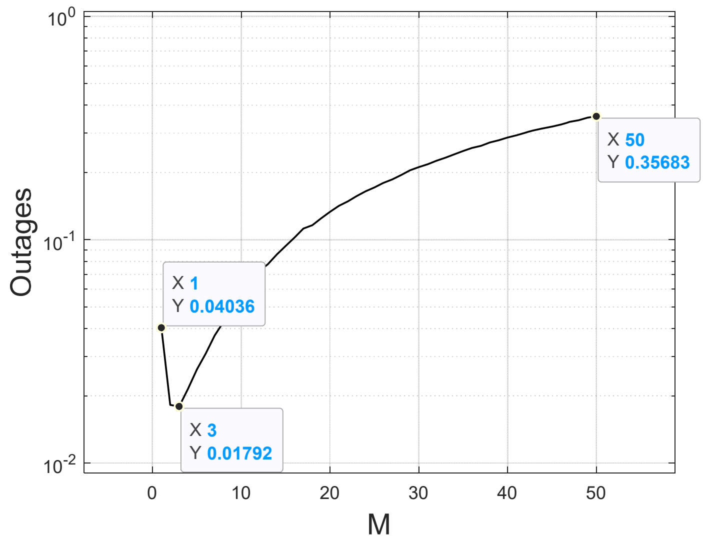

Fig. 3. Interference power is 20dB, transmit power is 10dB.

Then, the simulation continues, and the two powers are further increased simultaneously as shown in Fig. 4 and Fig. 5. It was found that the experimental results remained consistent with the previous ones despite the increased values.

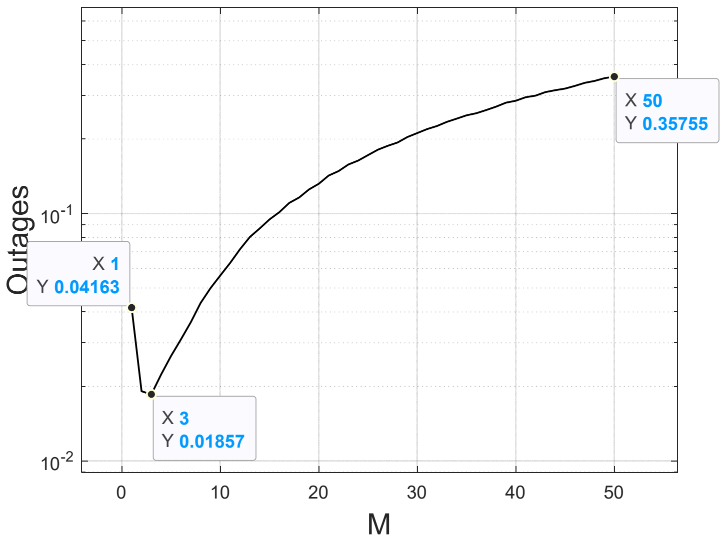

Fig. 4. Interference power is 30dB, transmit power is 20dB.

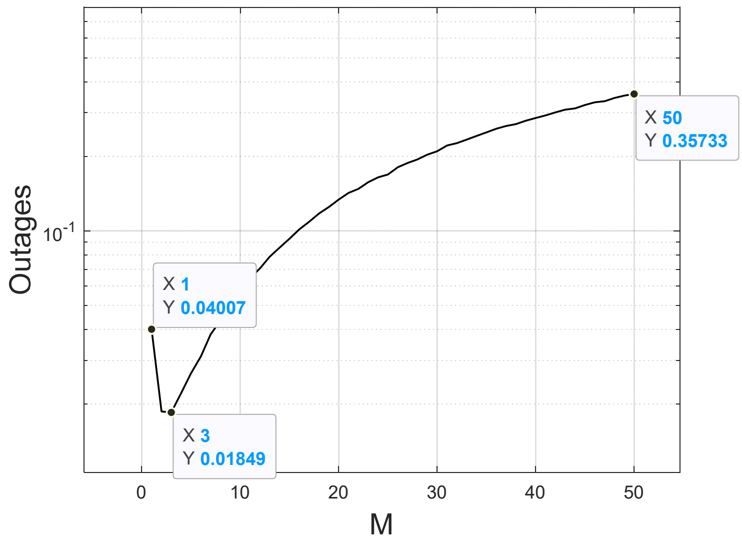

Fig. 5. Interference power is 40dB, transmit power is 30dB.

However, when the output power and interference power are increased at different decibels, as depicted in Fig. 6 and 7, the performance of the entire system is significantly affected, leading to a sharp rise in its overall outage probability to 1. The characteristic where the probability of outage decreases initially and then increases with the increase in transmitter number is lost.

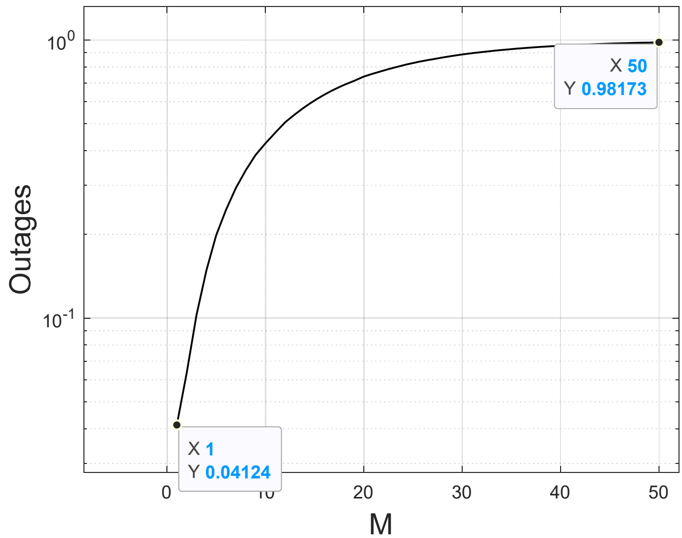

Fig. 6. Interference power is 40dB, transmit power is 40dB.

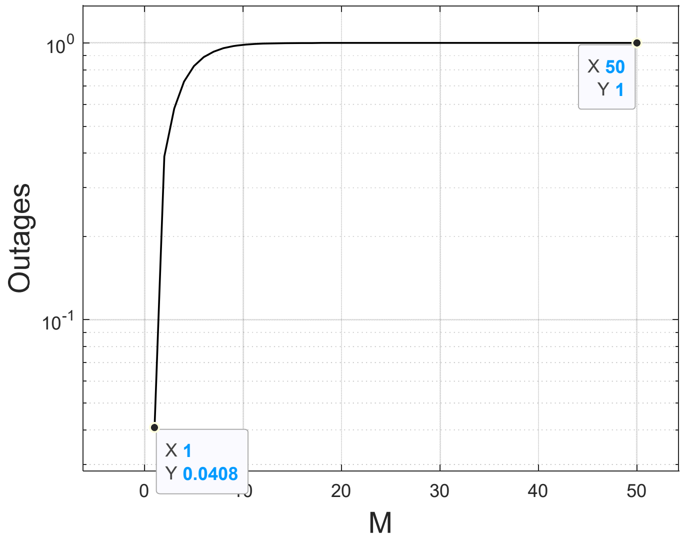

Fig. 7. Interference power is 30dB, transmit power is 40dB.

Through the simulation results Figs. 8-10, it can be found that as the number of receivers becomes more and more than the number of transmitters, the optimal number of transmitters will appear in advance, and the Outage concept corresponding to this point and the number of transmitters after it will increase as a whole. However, the Outage probability of each point before the optimal number point is not affected.

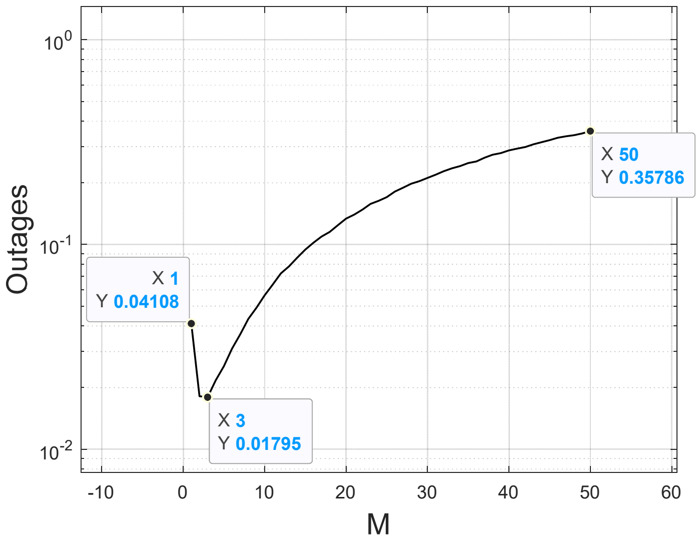

Fig. 8. The number of transmitters is equal to the number of receivers.

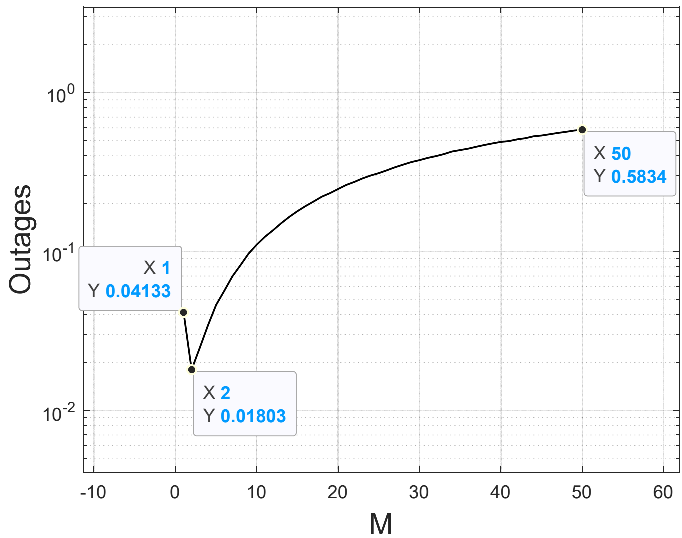

Fig. 9. There are twice as many receivers as transmitters.

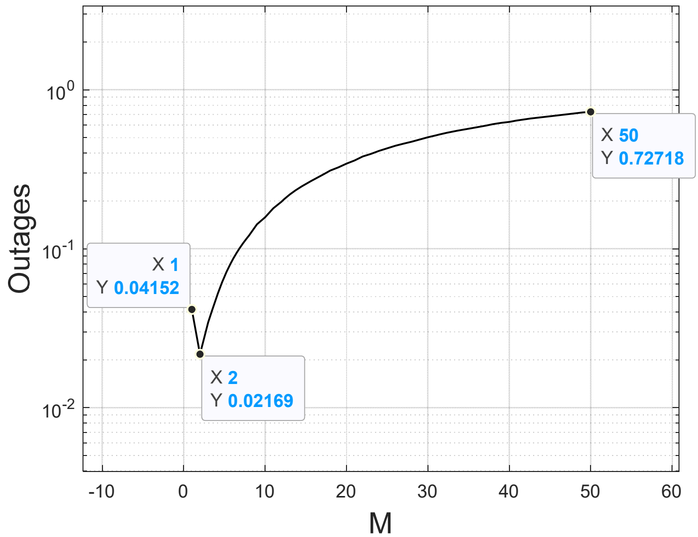

Fig. 10. There are three times as many receivers as transmitters.

4 Conclusion

The simulation results reveal critical insights into the impact of variations in output power and interference power on system outage probability. When these powers are increased at the same decibels, the overall outage probability remains relatively stable. However, divergent expansions result in a significant deterioration in system performance, leading to a sharp increase in outage probability to 1. Furthermore, the traditional characteristic of outage probability initially decreasing and then increasing with transmitter number is disrupted. Increasing the number of receivers can be seen as a disguised expansion of the overall system pressure, but does not allow the associated advantages to be exploited.

Moreover, the study identifies an intriguing phenomenon where an optimal number of transmitters emerges earlier as the number of receivers exceeds transmitters. Beyond this optimal point, the outage probability escalates alongside the increasing transmitter count, while the outage probability before this point remains unaffected.

These findings underscore the delicate balance between output power, interference power, and the number of transmitters and receivers in a system. Achieving optimal system performance requires careful management of these parameters to mitigate interference and maintain reliable communication.

Furthermore, energy-efficient communication is crucial. Devoting efforts to the development of energy-efficient communication protocols and transmission strategies in this SWIPT system can extend the battery life of wireless devices and reduce overall power consumption. Energy-efficient design is essential to extend the life of battery-powered devices and promote sustainable communication systems.

Additionally, enhancing security and privacy is imperative. Addressing security and privacy issues in this SWIPT system involves developing robust encryption algorithms, authentication mechanisms, and privacy protection protocols. Enhanced security measures are necessary to protect sensitive data and ensure the integrity and confidentiality of wireless transmissions.

Finally, conducting more experimental verification is essential. To validate the simulation results, actual experiments need to be conducted in a real-world communication setting. Empirical investigations provide practical insights and verify the effectiveness of the proposed method under real operating conditions. This empirical validation process helps bridge the gap between theoretical simulations and real-world applicability, thereby enhancing the reliability and credibility of research results.

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