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Outage Performance of Asymmetrical Cognitive Simultaneous Wireless Information and Power Transfer Networks Based on Non-Orthogonal Multiple Access with an Incremental Cooperation Relay and Hardware Impairments

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Abstract: This work aims to investigate an asymmetrical NOMA transmission network based on cognitive radio, where both the source and relay nodes of the secondary user are energy limited, and the energy could be harvested from the transmission signal of the power beacon. Considering some particular hardware impairments and asymmetry in the NOMA transmission, the closed-form expressions of outage probability for relay and destination nodes were derived using incremental relay methods. Furthermore, built on the expressions of the outage probability, the throughput performance was analyzed. Finally, the correctness of our theoretical analysis was verified using simulations.

Keywords: energy harvesting; hardware impairments; NOMA; performance analysis

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1. Introduction

Recently, with the increasing number of mobile services and the rapid growth of mobile data traffic [1–3], the already low utilization of spectrum resources has become even more scarce, and cognitive radio (CR) has been recognized as a promising technique for alleviating spectrum resource shortages. The significance of CR for future networks was described in [4]. Non-orthogonal multiple access (NOMA) has been considered as a promising technique for the next generation of wireless networks. A new opportunistic adaptive NOMA transmission strategy was designed in [5]. The base station (BS) opportunistically used the NOMA to serve a pair consisting of a near user and a far user among multiple near users and far users. Two transmission modes were proposed for the system: a direct transmission mode and a cooperative mode. Meanwhile, in order to increase the transmission reliability and fairness, a scheduling candidate acquisition method and a user scheduling scheme were proposed. In [6], the application of cooperative NOMA in two-layer wireless cache networks was studied, and a popular cooperative NOMA strategy for content pushing was proposed. Meanwhile, in order to analyze the performance of the proposed strategy, a new analysis framework was proposed. In [7], cooperative computing in a mobile edge computing network based on NOMA was investigated and a cooperative computing strategy including two modes was designed.

Simultaneous wireless information and power transfer (SWIPT) has been recognized as a key technology for the next generation of wireless communication. It can extend the operating time of energy-limited equipment and improve energy efficiency. In [8], a new cognitive communication network was investigated, and the optimal information and power transmission design problem was planned as a constrained Markov decision process to maximize the total throughput. In [9], the simultaneous transmission of information and energy in the cellular Internet of Things (IoT) was considered. In [10], a cooperative communication network based on SWIPT was considered, aimed at maximizing the cooperative throughput. In [11], a NOMA-assisted cooperative SWIPT CR network was proposed, under the condition of considering a full duplex (FD), the closed-form expressions of the outage probability for the network were derived. In [12], the secrecy outage performance of an SWIPT NOMA network was studied, and considering the max-min user selection (MMUS) strategy, the secrecy outage probability was studied. In [13], a combination network of SWIPT and NOMA was studied under the condition of considering imperfect CSI. A Poisson point process (PPP) model was used to achieve the distribution of macro-base stations (MBSs) and femto-base stations (FBSs). The outage probability and throughput were derived. In [14], an FD NOMA network with nonlinear energy harvesting was investigated; a more practical nonlinear EH model was used in the network and the closed-form expressions of the outage probability were derived.

Relays can expand signal coverage, and in many existing relay transmission methods, relays assist in transmission regardless of whether the signal-to-noise (SNR) ratio between the source and destination nodes meets the requirements. Furthermore, incremental relays only assist in transmission when the SNR ratio between the source and destination nodes does not meet the requirements. Compared with traditional relays, incremental relays can save resources on the basis of meeting requirements. A cooperative SWIPT based on the NOMA network was studied in [15], in which the user closest to the source node acted as a relay to aid distant nodes in transmission. The near user used a power splitting (PS) protocol to harvest energy and decode its own and the far user's node. To ensure fairness, a joint design scheme of power allocation and PS parameters was proposed. The theoretical expressions of outage probability and diversity gain were derived. The network studied in [15] was further investigated in [16] considering non-linear energy harvesting. An incremental cooperative NOMA protocol was proposed, which includes three modes: direct NOMA transmission, traditional point-to-point communication, and traditional cooperative NOMA. The probability and throughput of the network were derived. A UAV-based NOMA network was studied in [17], considering selective incremental relays and an incomplete CSI. A new selective incremental relay based on NOMA was proposed, which allowed the relay to judge whether to forward information according to the SNR of signals received by UAVs and ground nodes. The outage probability of UAVs and ground nodes were derived. However, the aforementioned works did not consider hardware impairments (HIs). Due to noise distortion, IQ imbalance, and other reasons, hardware impairments may sometimes exist, and will have a certain impact on system performance [18–23]. In [20], an FD DF two-way relay network was considered; the outage probability of the network was derived under the dual effects of hardware impairments and residual interference. In [21], a SWIPT two-way relay network was considered and the closed-form expressions of the outage probability were derived. Furthermore, the influence of two ceiling effects (relay cooperation ceiling (RCC) and overall system ceiling (OSC)) on the network was studied through the outage probability. In [22], the influence of HI and two other parameters (intelligent reflecting surface (IRS) channel correlation and phase errors) on an IRS-enabled MISO network was investigated. In [23], a reconfigurable intelligent surface (RIS) two-way network was studied and the effect of HIs and imperfect interference cancellation on the network was investigated.

In this paper, we consider a CR-NOMA transmission network based on SWIPT in the presence of HIs. The main contributions are summarized as follows:

- Taking into account the influence of HIs, the outage probabilities for the relay and destination node of the CR-NOMA network are derived based on the incremental relay algorithm.

- The expressions of the throughput for the relay and destination node are obtained on the basis of the expressions of the outage probability.
- The simulation results validate the correctness of the theoretical expressions and demonstrate the impact of three parameters (the transmission power for the power beacon, the interference power limit that the primary user can tolerate, and the HI) on outage probability and throughput.

2. System Model

The network consists of a primary network and a secondary one, in which the primary network includes a primary receiver node R and the secondary network includes a source node S, a relay node U, a destination node D, and a power beacon T. Suppose that all network nodes operate in half-duplex mode and are equipped with a single antenna. h_{xy} denotes the channel coefficient between v_1 and v_2, where $v_1 \in \{T, S, U\}$ and $v_2 \in \{S, U, R, D\}$. Each channel follows a flat Rayleigh fading and is independent and identically distributed (i.i.d.). Meanwhile, $|h_{v_1 v_2}|^2$ is subject to exponential distributions with the parameter $\frac{1}{\lambda_{v_1 v_2}}$. All the network channels have an additive white Gaussian noise (AWGN), whose mean is zero and variance is N_0.

The whole time block for energy harvesting and information transmission is T_0. In T_0, the channel remains constant and the variation from one block to another is independent and identical. The transmission process includes two time slots. During the first time slot, i.e., αT_0, the power beacon T transmits signals to S and U. The remaining time slot $(1-\alpha)T_0$ is used for information transmission.

During the duration of αT_0, as shown in Figure 1, the signals are transmitted from T to S and U, and the corresponding signals received at S and U can be given by:

$$y_{TS} = h_{TS}\sqrt{p_T}x_T + n_S \tag{1}$$

and

$$y_{TU} = h_{TU}\sqrt{p_T}x_T + n_U \tag{2}$$

where x_T is the transmission signal of T and p_T is the transmission power of T. h_{TS} is the channel coefficient between T and S. h_{TU} is the channel coefficient between T and U. n_S and n_U are the AWGN at S and U. The energy received at S is

$$EH_S = \beta\alpha T_0 p_T |h_{TS}|^2 \tag{3}$$

where β is the energy conversion efficiency. Correspondingly, the power generated by (3) for S is

$$p_S^a = \frac{2\beta\alpha p_T |h_{TS}|^2}{1-\alpha} \tag{4}$$

Then, the energy received at U is

$$EH_U = \beta\alpha T_0 p_T |h_{TU}|^2 \tag{5}$$

Correspondingly, the power generated by (5) for U is

$$p_U^a = \frac{2\beta\alpha p_T |h_{TU}|^2}{1-\alpha} \tag{6}$$

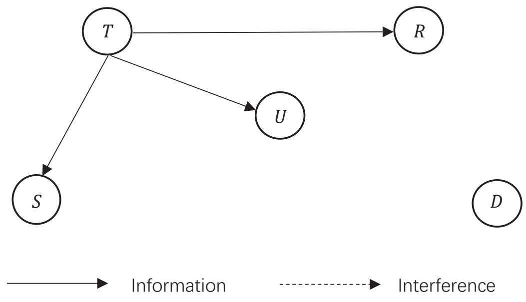

Figure 1. System transmission model for the first time slot.

During the first duration of $\frac{1-\alpha}{2}T_0$, S transmits signals to U and D, as shown in Figure 2. The signal received at U is:

$$y_{SU} = h_{SU}(\sqrt{a_1 p_S}x_D + \sqrt{a_2 p_S}x_U + \eta_{St}) + \eta_{Ur} + n_U \tag{7}$$

where x_D and x_U are the intended signals for D and U. p_S is the transmitting power. a_1 and a_2 are the power allocation factors for D and U, which satisfy $a_1 > a_2$ and $a_1 + a_2 = 1$. h_{SU} is the channel coefficient between S and U. $\eta_{St} \sim \mathbb{CN}(0, p_S k_{St}^2)$ and $\eta_{Ur} \sim \mathbb{CN}(0, k_{Ur}^2 p_S |h_{SU}|^2)$ are the distortion noise from transceiver HIs. n_U is the AWGN at U. First, U decodes x_D, and the SNR is

$$\gamma_{SU}^{D} = \frac{a_1 p_S |h_{SU}|^2}{p_S(a_2 + k_{St}^2 + k_{Ur}^2)|h_{SU}|^2 + N_0} \tag{8}$$

The probability of γ_{SU}^{D} being greater than γ_{th} is

$$\begin{aligned}
&\Pr(\gamma_{SU}^{D} > \gamma_{th}) \\
&= \Pr(\frac{a_1 p_S |h_{SU}|^2}{p_S A_1 |h_{SU}|^2 + N_0} > \gamma_{th}) \\
&= \Pr(a_1 p_S |h_{SU}|^2 > \gamma_{th}(p_S A_1 |h_{SU}|^2 + N_0)) \\
&= \Pr(a_1 p_S |h_{SU}|^2 > \gamma_{th} p_S A_1 |h_{SU}|^2 + \gamma_{th} N_0) \\
&= \Pr((a_1 p_S - \gamma_{th} p_S A_1)|h_{SU}|^2 > \gamma_{th} N_0) \\
&= \Pr(|h_{SU}|^2 > \frac{\gamma_{th} N_0}{a_1 p_S - \gamma_{th} p_S A_1}) \\
&= e^{-\frac{\gamma_{th} N_0}{\lambda_{SU} p_S (a_1 - \gamma_{th} A_1)}}
\end{aligned} \tag{9}$$

where

$$A_1 = a_2 + k_{St}^2 + k_{Ur}^2.$$

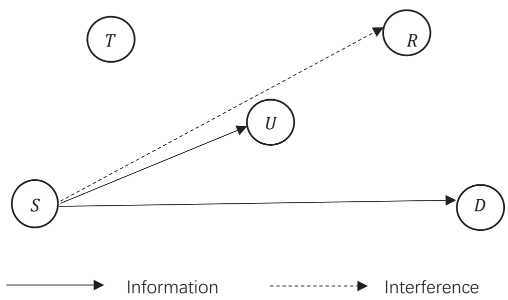

Figure 2. System transmission model for the first duration of information transmission time slot.

Then, x_U is decoded by U and the SNR is

$$\gamma_{SU}^{U} = \frac{a_2 p_S |h_{SU}|^2}{p_S (k_{St}^2 + k_{Ur}^2)|h_{SU}|^2 + N_0} \tag{10}$$

The probability of γ_{SU}^{U} being greater than γ_{th} is

$$\Pr(\gamma_{SU}^{U} > \gamma_{th}) = e^{-\frac{\gamma_{th} N_0}{\lambda_{SU} p_S (a_2 - \gamma_{th} A_2)}} \tag{11}$$

where

$$A_2 = k_{St}^2 + k_{Ur}^2.$$

The signal received at D is:

$$y_{SD} = h_{SD}(\sqrt{a_1 p_S} x_D + \sqrt{a_2 p_S} x_U + \eta_{St}) + \eta_{Dr} + n_D \tag{12}$$

where h_{SD} is the channel coefficient between S and D. $\eta_{St} \sim \mathbb{CN}(0, p_S k_{St}^2)$ and $\eta_{Dr} \sim \mathbb{CN}(0, k_{Dr}^2 p_S |h_{SD}|^2)$ are the distortion noise from transceiver HIs. n_D is the AWGN at D. D decodes x_D, and the SNR is

$$\gamma_{SD}^{D} = \frac{a_1 p_S |h_{SD}|^2}{p_S (a_2 + k_{St}^2 + k_{Dr}^2)|h_{SD}|^2 + N_0} \tag{13}$$

The probability of γ_{SD}^{D} being greater than γ_{th} is

$$\Pr(\gamma_{SD}^{D} > \gamma_{th}) = e^{-\frac{\gamma_{th} N_0}{\lambda_{SD} p_S (a_1 - \gamma_{th} A_3)}} \tag{14}$$

where

$$A_3 = a_2 + k_{St}^2 + k_{Ur}^2.$$

In the first $\frac{1-\alpha}{2} T_0$ period, to guarantee the QoS of R, the interference originating from S to R should be below a threshold. From this, we obtain that the transmit power of S is:

$$p_S^b = \frac{I_P}{|h_{SR}|^2} \tag{15}$$

where I_P is the maximum interference that the primary user can tolerate. By combining Equation (4), the transmit power of S is

$$p_S = \min(p_S^a, p_S^b)$$

Next, we investigate the transmission in the second duration of the second time slot. According to the transmission scheme in [17], in the time slot, if γ_{SD}^{D} is higher than γ_{th}, then the next round of transmission is started. If γ_{SD}^{D} is lower than γ_{th} and γ_{SU}^{D} is higher than γ_{th}, U forwards x_D to D. If both γ_{SD}^{D} and γ_{SU}^{D} are lower than γ_{th}, S retransmits x_D to D.

First, if γ_{SD}^{D} is higher than γ_{th}, the probability is as shown in Equation (14).

Second, as shown in Figure 3, if γ_{SD}^{D} is lower than γ_{th} and γ_{SU}^{D} is higher than γ_{th}, U transmits x_D to D, and the signal received at D is

$$y_{UD} = h_{UD}(\sqrt{p_U} x_D + \eta_{Ut}) + \eta_{Dr} + n_D \tag{16}$$

where p_U is the transmitting power, h_{UD} is the channel coefficient between U and D, $\eta_{Ut} \sim \mathbb{CN}(0, p_U k_{Ut}^2)$ and $\eta_{Dr} \sim \mathbb{CN}(0, p_U k_{Dr}^2 |h_{UD}|^2)$ are the distortion noise, and n_D is the AWGN at D. The SNR is

$$\gamma_{UD}^{2} = \frac{p_U |h_{UD}|^2}{p_U (k_{Ut}^2 + k_{Dr}^2)|h_{UD}|^2 + N_0} \tag{17}$$

The probability of γ^2_{UD} being higher than γ_{th} is

$$\Pr(\gamma^2_{UD} > \gamma_{th}) = e^{-\frac{\gamma_{th} N_0}{\lambda_{UD} p_U (1-\gamma_{th} A_4)}} \tag{18}$$

where

$$A_4 = k^2_{Ut} + k^2_{Dr}.$$

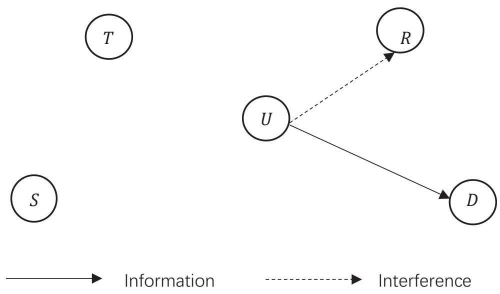

Figure 3. System transmission model for the second duration of information transmission time slot (γ^D_{SD} is lower than γ_{th} and γ^D_{SU} is higher than γ_{th}).

Third, both γ^D_{SD} and γ^D_{SU} are lower than γ_{th}, and S retransmits x_D to D.

$$y^2_{SD} = h_{SD}(\sqrt{p_S} x_D + \eta_{St}) + \eta_{Dr} + n_D \tag{19}$$

The SNR is

$$\gamma^2_{SD} = \frac{p_S |h_{SD}|^2}{p_S (k^2_{St} + k^2_{Dr}) |h_{SD}|^2 + N_0} \tag{20}$$

The probability of γ^2_{SD} being higher than γ_{th} is

$$\Pr(\gamma^2_{SD} > \gamma_{th}) = e^{-\frac{\gamma_{th} N_0}{\lambda_{SD} p_S (1-\gamma_{th} A_5)}} \tag{21}$$

where

$$A_4 = k^2_{St} + k^2_{Dr}.$$

The derivation processes of Equations (11), (14), (18), and (21) are similar to that of Equation (9).

In the second $\frac{1-\alpha}{2} T_0$ period, to guarantee the QoS of R, the interference originating from U to R should be below a threshold. Considering this constraint, the transmit power of U is:

$$p^b_U = \frac{I_P}{|h_{UR}|^2} \tag{22}$$

By combining this with Equation (6), the transmit power of S can be expressed as

$$p_U = \min(p^a_U, p^b_U)$$

3. Outage Probability

The probability of decoding x_U is [17]

$$\begin{aligned} OP_{x_U} =& 1 - \underbrace{\Pr(\gamma_{SD}^{D} > \gamma_{th}, \gamma_{SU}^{D} > \gamma_{th}, \gamma_{SU}^{U} > \gamma_{th})}_{J_1} \\ & - \underbrace{\Pr(\gamma_{SD}^{D} < \gamma_{th}, \gamma_{UD}^{D} > \gamma_{th}, \gamma_{SU}^{U} > \gamma_{th})}_{J_2} \\ & - \underbrace{\Pr(\gamma_{SD}^{D} < \gamma_{th}, \gamma_{UD}^{D} < \gamma_{th}, \gamma_{SU}^{U} > \gamma_{th})}_{J_3} \end{aligned} \tag{23}$$

where

$$J_1 = J_{11} + J_{12}$$

$$\begin{aligned} J_{11} =& \frac{2}{\lambda_{TS}}(\frac{A(1-\alpha)\lambda_{TS}}{2\alpha\beta p_T})^{1/2} K_1(2\sqrt{\frac{A(1-\alpha)}{2\alpha\beta p_T \lambda_{TS}}}) \\ & - \frac{2}{\lambda_{TS}}[(\frac{A(1-\alpha)}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T})\lambda_{TS}]^{1/2} \\ & \times K_1(2\sqrt{\frac{A(1-\alpha)}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}}) \end{aligned} \tag{24}$$

$$\begin{aligned} J_{12} =& \frac{2}{\lambda_{SR}}(\frac{I_P(1-\alpha)}{2\lambda_{TS}\alpha\beta p_T(\frac{A}{I_P} + \frac{1}{\lambda_{SR}})})^{1/2} \\ & \times K_1(2\sqrt{\frac{I_P(1-\alpha)}{2\lambda_{TS}\alpha\beta p_T}(\frac{A}{I_P} + \frac{1}{\lambda_{SR}})}) \end{aligned} \tag{25}$$

and

$$J_2 = J_{21} + J_{22} \tag{26}$$

where

$$\begin{aligned} J_{21} =& (e^{-\frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T |h_{TS}|^2}} - e^{-(\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T |h_{TS}|^2}}) \\ & \times (1 - e^{-\frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T |h_{TS}|^2}}) \\ =& e^{-\frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T |h_{TS}|^2}} - e^{-(\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T |h_{TS}|^2}} \\ & - e^{-w_{25}\frac{1}{|h_{TS}|^2}} + e^{-w_{26}\frac{1}{|h_{TS}|^2}} \\ =& \sum_{i=1}^{4} J_{21i} \end{aligned} \tag{27}$$

where

$$w_{25} = \frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

$$w_{26} = (\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

$$\begin{aligned} J_{211} =& \int_0^{+\infty} e^{-w_{23}\frac{1}{x}} \frac{1}{\lambda_{TS}} e^{-\frac{1}{\lambda_{TS}}x} dx \\ =& \frac{2}{\lambda_{TS}}(w_{23}\lambda_{TS})^{1/2} K_1(2\sqrt{\frac{w_{23}}{\lambda_{TS}}}) \end{aligned} \tag{28}$$

$$J_{212} = \frac{2}{\lambda_{TS}}(w_{24}\lambda_{TS})^{1/2} K_1(2\sqrt{\frac{w_{24}}{\lambda_{TS}}}) \tag{29}$$

$$J_{213} = \frac{2}{\lambda_{TS}}(w_{25}\lambda_{TS})^{1/2}K_1(2\sqrt{\frac{w_{25}}{\lambda_{TS}}}) \tag{30}$$

$$J_{214} = \frac{2}{\lambda_{TS}}(w_{26}\lambda_{TS})^{1/2}K_1(2\sqrt{\frac{w_{26}}{\lambda_{TS}}}) \tag{31}$$

$$w_{23} = \frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T}$$

$$w_{24} = (\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T}$$

$$\begin{aligned} J_{22} = &\frac{2}{\lambda_{SR}}(\frac{w_{29}}{w_{27}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{29}(w_{27}+\frac{1}{\lambda_{SR}})}) \\ &- \frac{2}{\lambda_{SR}}(\frac{w_{29}}{w_{28}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{29}(w_{28}+\frac{1}{\lambda_{SR}})}) \end{aligned} \tag{32}$$

where

$$w_{27} = \frac{w_{21}}{\lambda_{SU}I_P}, w_{28} = \frac{\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22}}{I_P}$$

$$w_{29} = \frac{1}{\lambda_{TS}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

and

$$J_3 = J_{31} + J_{32} \tag{33}$$

where

$$\begin{aligned} J_{31} = &\frac{2}{\lambda_{TS}}(w_{35}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{35}\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}(w_{36}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{36}\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}(w_{37}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{37}\frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}}(w_{38}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{38}\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}((w_{35}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{35}+w_{39})\frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}}((w_{36}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{36}+w_{39})\frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}}((w_{37}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{37}+w_{39})\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}((w_{38}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{38}+w_{39})\frac{1}{\lambda_{TS}}}) \end{aligned} \tag{34}$$

where

$$w_{31} = \frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)}, w_{32} = \frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_2-\gamma_{th}A_2)}$$

$$w_{33} = \frac{1}{\lambda_{SD}}\frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)} + \frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)}$$

$$w_{34}=\frac{1}{\lambda_{SD}}\frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)}+\frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_2-\gamma_{th}A_2)}$$

$$w_{39}=\frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

$$w_{310}=\frac{1}{\lambda_{TS}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

$$\begin{aligned}J_{32}=&-\frac{2}{\lambda_{TS}}\Big(\frac{w_{310}}{\frac{w_{31}}{I_P}+\frac{1}{\lambda_{SR}}}\Big)^{1/2}K_1\Big(2\sqrt{w_{310}\Big(\frac{w_{31}}{I_P}+\frac{1}{\lambda_{SR}}\Big)}\Big)\\&+\frac{2}{\lambda_{TS}}\Big(\frac{w_{310}}{\frac{w_{32}}{I_P}+\frac{1}{\lambda_{SR}}}\Big)^{1/2}K_1\Big(2\sqrt{w_{310}\Big(\frac{w_{32}}{I_P}+\frac{1}{\lambda_{SR}}\Big)}\Big)\\&+\frac{2}{\lambda_{TS}}\Big(\frac{w_{310}}{\frac{w_{33}}{I_P}+\frac{1}{\lambda_{SR}}}\Big)^{1/2}K_1\Big(2\sqrt{w_{310}\Big(\frac{w_{33}}{I_P}+\frac{1}{\lambda_{SR}}\Big)}\Big)\\&-\frac{2}{\lambda_{TS}}\Big(\frac{w_{310}}{\frac{w_{34}}{I_P}+\frac{1}{\lambda_{SR}}}\Big)^{1/2}K_1\Big(2\sqrt{w_{310}\Big(\frac{w_{34}}{I_P}+\frac{1}{\lambda_{SR}}\Big)}\Big)\end{aligned}\tag{35}$$

The specific derivation process can be seen in Appendix A.

The probability of decoding x_D is [17]

$$\begin{aligned}OP_{x_D}=&1-\underbrace{\Pr(\gamma_{SD}^D>\gamma_{th})}_{J_4}\\&-\underbrace{\Pr(\gamma_{SD}^D<\gamma_{th},\gamma_{UD}^D>\gamma_{th},\gamma_{MRC}>\gamma_{th})}_{J_5}\\&-\underbrace{\Pr(\gamma_{SD}^D<\gamma_{th},\gamma_{UD}^D<\gamma_{th},\gamma_{OMA}^U>\gamma_{th})}_{J_6}\end{aligned}\tag{36}$$

where

$$\begin{aligned}J_4=&\frac{2}{\lambda_{TS}}(w_{42}\lambda_{TS})^{1/2}K_1\Big(2\sqrt{w_{42}\frac{1}{\lambda_{TS}}}\Big)\\&-\frac{2}{\lambda_{TS}}((w_{42}+w_{43})\lambda_{TS})^{1/2}K_1\Big(2\sqrt{(w_{42}+w_{43})\frac{1}{\lambda_{TS}}}\Big)\\&+\frac{2}{\lambda_{SR}}\Big(\frac{w_{44}}{\frac{w_{41}}{I_P}+\frac{1}{\lambda_{SR}}}\Big)^{1/2}K_1\Big(2\sqrt{w_{44}\Big(\frac{w_{41}}{I_P}+\frac{1}{\lambda_{SR}}\Big)}\Big)\end{aligned}\tag{37}$$

and

$$\begin{aligned}J_5&=\Pr(\gamma_{SD}^D<\gamma_{th},\gamma_{SU}^D>\gamma_{th},\gamma_{UD}^2>\gamma_{th})\\&=\Pr(|h_{SD}|^2<\frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)p_S},\\&|h_{SU}|^2>\frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)p_S},|h_{UD}|^2>\frac{\gamma_{th}N_0}{(1-\gamma_{th}A_4)p_U})\\&=(1-e^{-\frac{\gamma_{th}N_0}{\lambda_{SD}p_S(a_3-\gamma_{th}A_3)}})e^{-\frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{a_1-\gamma_{th}A_1}\frac{1}{p_S}}e^{-\frac{\gamma_{th}N_0}{\lambda_{UD}p_U(1-\gamma_{th}A_4)}}\end{aligned}\tag{38}$$

J_5 can be reexpressed as

$$\begin{aligned}J_5 &= (1 - e^{-\frac{\gamma_{th} N_0}{\lambda_{SD} p_S^a (a_3 - \gamma_{th} A_3)}}) e^{-\frac{1}{\lambda_{SU}} \frac{\gamma_{th} N_0}{a_1 - \gamma_{th} A_1} \frac{1}{p_S^a}} e^{-\frac{\gamma_{th} N_0}{\lambda_{UD} p_U^a (1 - \gamma_{th} A_4)}} \\ &+ (1 - e^{-\frac{\gamma_{th} N_0}{\lambda_{SD} p_S^b (a_3 - \gamma_{th} A_3)}}) e^{-\frac{1}{\lambda_{SU}} \frac{\gamma_{th} N_0}{a_1 - \gamma_{th} A_1} \frac{1}{p_S^b}} e^{-\frac{\gamma_{th} N_0}{\lambda_{UD} p_U^a (1 - \gamma_{th} A_4)}} \\ &+ (1 - e^{-\frac{\gamma_{th} N_0}{\lambda_{SD} p_S^a (a_3 - \gamma_{th} A_3)}}) e^{-\frac{1}{\lambda_{SU}} \frac{\gamma_{th} N_0}{a_1 - \gamma_{th} A_1} \frac{1}{p_S^a}} e^{-\frac{\gamma_{th} N_0}{\lambda_{UD} p_U^b (1 - \gamma_{th} A_4)}} \\ &+ (1 - e^{-\frac{\gamma_{th} N_0}{\lambda_{SD} p_S^b (a_3 - \gamma_{th} A_3)}}) e^{-\frac{1}{\lambda_{SU}} \frac{\gamma_{th} N_0}{a_1 - \gamma_{th} A_1} \frac{1}{p_S^b}} e^{-\frac{\gamma_{th} N_0}{\lambda_{UD} p_U^b (1 - \gamma_{th} A_4)}}\end{aligned} \tag{39}$$

where

$$\begin{aligned}J_{51} &= (\frac{2}{\lambda_{TS}} (w_{52} \lambda_{TS})^{1/2} K_1 (2 \sqrt{w_{52} \frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}} ((w_{51} + w_{52}) \lambda_{TS})^{1/2} K_1 (2 \sqrt{(w_{51} + w_{52}) \frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}} ((w_{52} + w_{54}) \lambda_{TS})^{1/2} K_1 (2 \sqrt{(w_{52} + w_{54}) \frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}} ((w_{51} + w_{52} + w_{54}) \lambda_{TS})^{1/2} K_1 (2 \sqrt{(w_{51} + w_{52} + w_{54}) \frac{1}{\lambda_{TS}}})) \\ &\times (\frac{2}{\lambda_{TS}} (w_{53} \lambda_{TS})^{1/2} K_1 (2 \sqrt{w_{53} \frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}} ((w_{53} + w_{55}) \lambda_{TS})^{1/2} K_1 (2 \sqrt{(w_{53} + w_{55}) \frac{1}{\lambda_{TS}}}))\end{aligned} \tag{40}$$

$$\begin{aligned}J_{52} &= \frac{2}{\lambda_{SR}} (\frac{w_{58}}{w_{57} + \lambda_{SR}})^{1/2} K_1 (2 \sqrt{w_{58} (w_{57} + \lambda_{SR})}) \\ &- \frac{2}{\lambda_{SR}} (\frac{w_{58}}{w_{56} + w_{57} + \lambda_{SR}})^{1/2} K_1 (2 \sqrt{w_{58} (w_{56} + w_{57} + \lambda_{SR})}) \\ &\times (\frac{2}{\lambda_{TU}} (w_{59} \lambda_{TU})^{1/2} K_1 (2 \sqrt{w_{59} \frac{1}{\lambda_{TU}}}) \\ &- \frac{2}{\lambda_{TU}} ((w_{59} + w_{510}) \lambda_{TU})^{1/2} K_1 (2 \sqrt{(w_{59} + w_{510}) \frac{1}{\lambda_{TU}}}))\end{aligned} \tag{41}$$

$$\begin{aligned}J_{53} &= (\frac{2}{\lambda_{TS}} (w_{512} \lambda_{TS})^{1/2} K_1 (2 \sqrt{w_{512} \frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}} ((w_{511} + w_{512}) \lambda_{TS})^{1/2} K_1 (2 \sqrt{(w_{511} + w_{512}) \frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}} ((w_{511} + w_{513}) \lambda_{TS})^{1/2} K_1 (2 \sqrt{(w_{511} + w_{513}) \frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}} ((w_{511} + w_{512} + w_{513}) \lambda_{TS})^{1/2} \\ &\times K_1 (2 \sqrt{(w_{511} + w_{512} + w_{513}) \frac{1}{\lambda_{TS}}})) \\ &\times \frac{2}{\lambda_{SR}} (\frac{w_{515}}{w_{514} + \lambda_{UR}})^{1/2} K_1 (2 \sqrt{w_{515} (w_{514} + \lambda_{UR})})\end{aligned} \tag{42}$$

$$J_{54} = (\frac{2}{\lambda_{SR}}(\frac{w_{518}}{w_{517}+\lambda_{UR}})^{1/2}K_1(2\sqrt{w_{518}(w_{517}+\lambda_{UR})}) - \frac{2}{\lambda_{SR}}(\frac{w_{518}}{w_{516}+w_{517}+\lambda_{UR}})^{1/2} \times K_1(2\sqrt{w_{518}(w_{516}+w_{517}+\lambda_{UR})})) \times \frac{2}{\lambda_{UR}}(\frac{w_{520}}{w_{519}+\lambda_{UR}})^{1/2}K_1(2\sqrt{w_{520}(w_{519}+\lambda_{UR})}) \quad (43)$$

J_6 can be expressed as

$$\begin{aligned} J_6 &= \Pr(\gamma_{SD}^{D} < \gamma_{th}, \gamma_{SU}^{D} < \gamma_{th}, \gamma_{SD}^{2} > \gamma_{th}) \\ &= \Pr(|h_{SD}|^2 < \frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)p_S}, |h_{SU}|^2 < \frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)p_S}, \\ &|h_{SD}|^2 > \frac{\gamma_{th}N_0}{(1-\gamma_{th}A_5)p_S}) \\ &= \Pr(\frac{\gamma_{th}N_0}{(1-\gamma_{th}A_5)p_S} < |h_{SD}|^2 < \frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)p_S}, \\ &|h_{SU}|^2 < \frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)p_S}) \\ &= (e^{-\frac{1}{\lambda_{SD}}\frac{\gamma_{th}N_0}{(1-\gamma_{th}A_5)p_S}} - e^{-\frac{1}{\lambda_{SD}}\frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)p_S}}) \\ &\times (1-e^{-\frac{1}{\lambda_{SD}}\frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)p_S}}) \end{aligned} \quad (44)$$

where

$$\begin{aligned} J_{61} &= \frac{2}{\lambda_{TS}}(w_{64}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{64}\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}(w_{65}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{65}\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}(w_{66}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{66}\frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}}(w_{67}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{67}\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}((w_{64}+w_{68})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{64}+w_{68})\frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}}((w_{65}+w_{68})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{65}+w_{68})\frac{1}{\lambda_{TS}}}) \\ &+ \frac{2}{\lambda_{TS}}((w_{66}+w_{68})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{66}+w_{68})\frac{1}{\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}((w_{67}+w_{68})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{67}+w_{68})\frac{1}{\lambda_{TS}}}) \end{aligned} \quad (45)$$

and

$$
\begin{aligned}
J_{62} = &\left(\frac{2}{\lambda_{SR}}\left(\frac{w_{64}}{w_{65}+\lambda_{UR}}\right)^{1/2} K_1\left(2\sqrt{w_{64}(w_{65}+\lambda_{UR})}\right)\right. \\
&- \left(\frac{2}{\lambda_{SR}}\left(\frac{w_{64}}{w_{66}+\lambda_{UR}}\right)^{1/2} K_1\left(2\sqrt{w_{64}(w_{66}+\lambda_{UR})}\right)\right. \\
&- \left(\frac{2}{\lambda_{SR}}\left(\frac{w_{64}}{w_{67}+\lambda_{UR}}\right)^{1/2} K_1\left(2\sqrt{w_{64}(w_{67}+\lambda_{UR})}\right)\right. \\
&+ \left(\frac{2}{\lambda_{SR}}\left(\frac{w_{64}}{w_{68}+\lambda_{UR}}\right)^{1/2} K_1\left(2\sqrt{w_{64}(w_{68}+\lambda_{UR})}\right)\right.
\end{aligned}
\tag{46}
$$

The derivation process of the outage probability of x_D is similar to that of x_U.

4. Throughput

The throughput can be given as:

$$T = R(1 - p_{out})\frac{1-\alpha}{2} \tag{47}$$

where R is the transmission rate.

5. Simulation Results

In this section, simulations are conducted to validate the theoretical results. The parameters used for theoretical analysis and simulations are $\gamma_{th} = 3$ bps/Hz, $R = 2$ bps/Hz, and $N_0 = 1$. I_P represents the maximum interference value that the primary user can withstand. The value of I_P is shown in the figure. k represents the degree of hardware impairments. The SNR is $\frac{p_T}{N_0}$.

Figure 4 presents the outage probability versus the SNR with different I_P values. It can be seen in the figure that the outage probability decreases as the SNR increases. Further, with the increase in I_P, the outage probability will reduce. In addition, the simulation results are in good agreement with the analytical results in the high SNR regime.

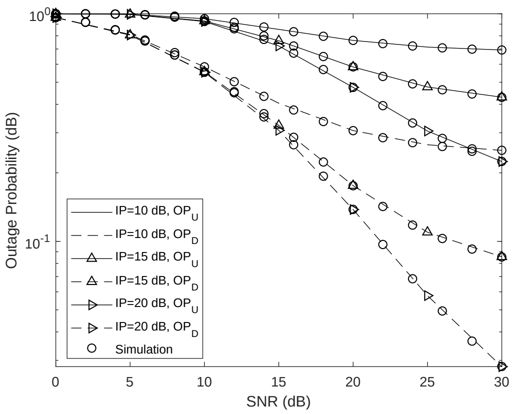

Figure 4. Outage probability versus SNR with different I_P.

Figure 5 shows the outage probability versus the SNR with different k. We can find that the outage probability decreases as the SNR increases. Further, with the increase in k, the outage probability will increase. In addition, the simulation results are in good agreement with the analytical results in the high SNR regime.

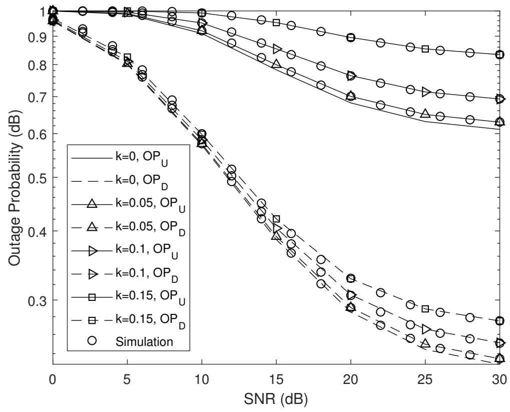

Figure 5. Outage probability versus SNR with different k.

Figure 6 presents the throughput versus the SNR with different I_P. It can be seen that the throughput increases as the SNR increases. Moreover, with the increase in I_P, the throughput will increase.

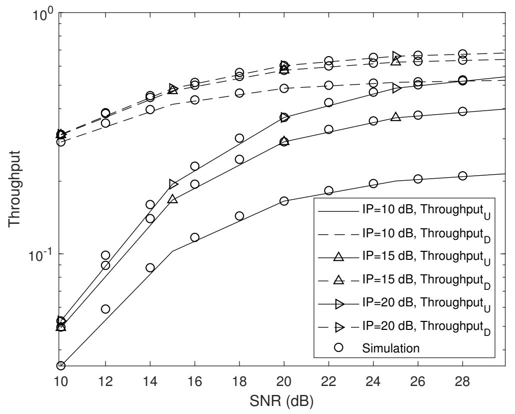

Figure 6. Throughput versus SNR with different I_P.

Figure 7 shows the throughput versus the SNR with different k. It can be found that the throughput increases as the SNR increases. Moreover, with the increase in k, the throughput will decrease. The throughput corresponding to $k = 0$ is the largest. Finally, the simulation results are in good agreement with the analytical results in the high SNR regime. In this regard, Figures 4–6 are the same as Figure 7.

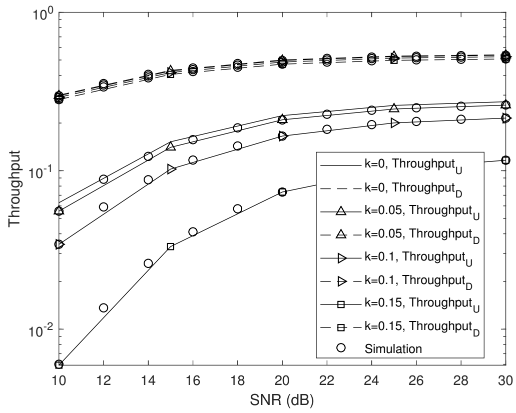

Figure 7. Throughput versus the SNR with different k.

6. Conclusions

Considering the influence of HIs, the closed-form expressions of the outage probability for relay and destination node in a CR-NOMA network were derived based on the incremental relay algorithm. Then, the expressions of the throughput of relay and destination node were derived based on the expressions of the outage probability. Finally, the correctness of the theoretical expressions was verified by the simulation results, followed by revealing the influence of some parameters on the outage probability and throughput in the simulation results.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The probability of decoding x_U is [17]

$$\begin{aligned} OP_{x_U} = & 1 - \underbrace{\Pr(\gamma_{SD}^D > \gamma_{th}, \gamma_{SU}^D > \gamma_{th}, \gamma_{SU}^U > \gamma_{th})}_{J_1} \\ & - \underbrace{\Pr(\gamma_{SD}^D < \gamma_{th}, \gamma_{UD}^D > \gamma_{th}, \gamma_{SU}^U > \gamma_{th})}_{J_2} \\ & - \underbrace{\Pr(\gamma_{SD}^D < \gamma_{th}, \gamma_{UD}^D < \gamma_{th}, \gamma_{SU}^U > \gamma_{th})}_{J_3} \end{aligned} \tag{A1}$$

where J_1 represents the first situation and the SNR from S to D, i.e., γ_{SD}^D, is higher than γ_{th}.

$$\begin{aligned} J_1 &= \Pr(\gamma_{SD}^D > \gamma_{th}, \gamma_{SU}^D > \gamma_{th}, \gamma_{SU}^U > \gamma_{th}) \\ &= \Pr(|h_{SD}|^2 > \frac{\gamma_{th} N_0}{(a_1 - \gamma_{th} A_3) p_S}, |h_{SU}|^2 > \frac{\gamma_{th} N_0}{(a_1 - \gamma_{th} A_1) p_S}, \\ & |h_{SU}|^2 > \frac{\gamma_{th} N_0}{(a_2 - \gamma_{th} A_2) p_S}) \\ &= \Pr(|h_{SD}|^2 > \frac{\gamma_{th} N_0}{(a_1 - \gamma_{th} A_3) p_S}, \\ & |h_{SU}|^2 > \max(\frac{\gamma_{th} N_0}{(a_1 - \gamma_{th} A_1) p_S}, \frac{\gamma_{th} N_0}{(a_2 - \gamma_{th} A_2) p_S})) \\ &= e^{-A \frac{1}{p_S}} \end{aligned} \tag{A2}$$

where

$$A = \frac{\gamma_{th} N_0}{\lambda_{SD}(a_1 - \gamma_{th} A_3)} + \frac{1}{\lambda_{SU}} \max(\frac{\gamma_{th} N_0}{a_1 - \gamma_{th} A_1}, \frac{\gamma_{th} N_0}{a_2 - \gamma_{th} A_2}).$$

J_{11} can be calculated as

$$\begin{aligned} J_{11} &= e^{-A\frac{1}{p_S}} \\ &= e^{-A\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}} \Pr(\frac{2\alpha\beta p_T|h_{TS}|^2}{1-\alpha} < \frac{I_P}{|h_{SR}|^2}) \\ &= e^{-A\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}}(1 - e^{-\frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T|h_{TS}|^2}}) \\ &= \frac{1}{\lambda_{TS}}\int_0^{+\infty} e^{-A\frac{1-\alpha}{2\alpha\beta p_T x}} e^{-\frac{1}{\lambda_{TS}}x} dx \\ &- \frac{1}{\lambda_{TS}}\int_0^{+\infty} e^{-(A\frac{1-\alpha}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T})} e^{-\frac{1}{\lambda_{TS}}x} dx. \end{aligned} \tag{A3}$$

According to (3.471.9) in [24], we can obtain

$$\begin{aligned} J_{11} = &\frac{2}{\lambda_{TS}}(\frac{A(1-\alpha)\lambda_{TS}}{2\alpha\beta p_T})^{1/2} K_1(2\sqrt{\frac{A(1-\alpha)}{2\alpha\beta p_T\lambda_{TS}}}) \\ &- \frac{2}{\lambda_{TS}}[(\frac{A(1-\alpha)}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T})\lambda_{TS}]^{1/2} \\ &\times K_1(2\sqrt{\frac{A(1-\alpha)}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}}) \end{aligned} \tag{A4}$$

and J_{12} can be calculated as

$$\begin{aligned} J_{12} &= e^{-A\frac{|h_{SR}|^2}{I_P}} \Pr(\frac{2\alpha\beta p_T|h_{TS}|^2}{1-\alpha} > \frac{I_P}{|h_{SR}|^2}) \\ &= e^{-A\frac{|h_{SR}|^2}{I_P}} e^{-\frac{1}{\lambda_{TS}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T|h_{SR}|^2}} \\ &= \int_0^{+\infty} e^{-A\frac{x}{I_P}} e^{-\frac{1}{\lambda_{TS}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T x}} \frac{1}{\lambda_{SR}} e^{-\frac{1}{\lambda_{SR}}x} dx. \end{aligned} \tag{A5}$$

By using (3.471.9) in [24], J_{12} can

$$\begin{aligned} J_{12} = &\frac{2}{\lambda_{SR}}(\frac{I_P(1-\alpha)}{2\lambda_{TS}\alpha\beta p_T(\frac{A}{I_P} + \frac{1}{\lambda_{SR}})})^{1/2} \\ &\times K_1(2\sqrt{\frac{I_P(1-\alpha)}{2\lambda_{TS}\alpha\beta p_T}(\frac{A}{I_P} + \frac{1}{\lambda_{SR}})}). \end{aligned} \tag{A6}$$

Thus, we can obtain J_1 as

$$J_1 = J_{11} + J_{12}$$

J_2 represents the second situation, γ_{SD}^D is lower than γ_{th}, and the SNR of U decodes x_D, i.e., γ_{SU}^D, is higher than γ_{th}.

$$\begin{aligned} J_2 &= \Pr(\gamma_{SD}^D < \gamma_{th}, \gamma_{SU}^D > \gamma_{th}, \gamma_{SU}^U > \gamma_{th}) \\ &= \Pr(|h_{SD}|^2 < \frac{\gamma_{th}N_0}{(a_1 - \gamma_{th}A_3)p_S}, |h_{SU}|^2 > \frac{\gamma_{th}N_0}{(a_1 - \gamma_{th}A_1)p_S}, \\ &|h_{SU}|^2 > \frac{\gamma_{th}N_0}{(a_2 - \gamma_{th}A_2)p_S}) \\ &= (1 - e^{-\frac{\gamma_{th}N_0}{\lambda_{SD}p_S(a_1-\gamma_{th}A_3)}}) e^{-\frac{1}{\lambda_{SU}}\max(\frac{\gamma_{th}N_0}{a_1-\gamma_{th}A_1}, \frac{\gamma_{th}N_0}{a_2-\gamma_{th}A_2})\frac{1}{p_S}} \\ &= e^{-\frac{1}{\lambda_{SU}}w_{21}\frac{1}{p_S}} - e^{-(\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22})\frac{1}{p_S}} \end{aligned} \tag{A7}$$

where

$$w_{21} = \max(\frac{\gamma_{th}N_0}{a_1 - \gamma_{th}A_1}, \frac{\gamma_{th}N_0}{a_2 - \gamma_{th}A_2}), w_{22} = \frac{\gamma_{th}N_0}{a_1 - \gamma_{th}A_1}.$$

J_2 can be recalculated as

$$\begin{aligned} J_2 &= (e^{-\frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}} - e^{-(\frac{1}{\lambda_{SU}}w_{21}+\frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}}) \\ &\times \Pr(\frac{2\alpha\beta p_T|h_{TS}|^2}{1-\alpha} < \frac{I_P}{|h_{SR}|^2}) \\ &+ (e^{-\frac{w_{21}}{\lambda_{SU}}\frac{|h_{SR}|^2}{I_P}} - e^{-(\frac{1}{\lambda_{SU}}w_{21}+\frac{1}{\lambda_{SD}}w_{22})\frac{|h_{SR}|^2}{I_P}}) \\ &\times \Pr(\frac{2\alpha\beta p_T|h_{TS}|^2}{1-\alpha} > \frac{I_P}{|h_{SR}|^2}) \\ &= J_{21} + J_{22} \end{aligned} \tag{A8}$$

where

$$\begin{aligned} J_{21} &= (e^{-\frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}} - e^{-(\frac{1}{\lambda_{SU}}w_{21}+\frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}}) \\ &\times (1 - e^{-\frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T|h_{TS}|^2}}) \\ &= e^{-\frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}} - e^{-(\frac{1}{\lambda_{SU}}w_{21}+\frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T|h_{TS}|^2}} \\ &- e^{-w_{25}\frac{1}{|h_{TS}|^2}} + e^{-w_{26}\frac{1}{|h_{TS}|^2}} \\ &= \sum_{i=1}^{4} J_{21i} \end{aligned} \tag{A9}$$

where

$$w_{25} = \frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

$$w_{26} = (\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T} + \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

$$\begin{aligned} J_{211} &= \int_0^{+\infty} e^{-w_{23}\frac{1}{x}}\frac{1}{\lambda_{TS}}e^{-\frac{1}{\lambda_{TS}}x}dx \\ &= \frac{2}{\lambda_{TS}}(w_{23}\lambda_{TS})^{1/2}K_1(2\sqrt{\frac{w_{23}}{\lambda_{TS}}}) \end{aligned} \tag{A10}$$

$$J_{212} = \frac{2}{\lambda_{TS}}(w_{24}\lambda_{TS})^{1/2}K_1(2\sqrt{\frac{w_{24}}{\lambda_{TS}}}) \tag{A11}$$

$$J_{213} = \frac{2}{\lambda_{TS}}(w_{25}\lambda_{TS})^{1/2}K_1(2\sqrt{\frac{w_{25}}{\lambda_{TS}}}) \tag{A12}$$

$$J_{214} = \frac{2}{\lambda_{TS}}(w_{26}\lambda_{TS})^{1/2}K_1(2\sqrt{\frac{w_{26}}{\lambda_{TS}}}) \tag{A13}$$

$$w_{23} = \frac{w_{21}}{\lambda_{SU}}\frac{1-\alpha}{2\alpha\beta p_T}$$

$$w_{24} = (\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22})\frac{1-\alpha}{2\alpha\beta p_T}$$

J_{22} can be expressed as

$$\begin{aligned} J_{22} &= (e^{-w_{27}|h_{SR}|^2} - e^{-w_{28}|h_{SR}|^2})e^{-\frac{1}{\lambda_{TS}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T|h_{SR}|^2}} \\ &= \frac{1}{\lambda_{SR}}\int_0^{+\infty} e^{-w_{27}x}e^{-w_{29}\frac{1}{x}}e^{-\frac{1}{\lambda_{SR}}x}dx \\ &- \frac{1}{\lambda_{SR}}\int_0^{+\infty} e^{-w_{28}x}e^{-w_{29}\frac{1}{x}}e^{-\frac{1}{\lambda_{SR}}x}dx. \end{aligned} \tag{A14}$$

According to (3.471.9) in [24], it can be obtained that

$$\begin{aligned} J_{22} &= \frac{2}{\lambda_{SR}}(\frac{w_{29}}{w_{27}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{29}(w_{27}+\frac{1}{\lambda_{SR}})}) \\ &- \frac{2}{\lambda_{SR}}(\frac{w_{29}}{w_{28}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{29}(w_{28}+\frac{1}{\lambda_{SR}})}) \end{aligned} \tag{A15}$$

where

$$w_{27} = \frac{w_{21}}{\lambda_{SU}I_P}, w_{28} = \frac{\frac{1}{\lambda_{SU}}w_{21} + \frac{1}{\lambda_{SD}}w_{22}}{I_P}$$

$$w_{29} = \frac{1}{\lambda_{TS}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

Further, J_3 represents the third situation; both γ_{SD}^D and γ_{SU}^D are lower than γ_{th}. The process of deriving J_3 is similar to that of deriving J_1 and J_2.

$$\begin{aligned} J_3 &= \Pr(\gamma_{SD}^D < \gamma_{th}, \gamma_{SU}^D < \gamma_{th}, \gamma_{SU}^U > \gamma_{th}) \\ &= \Pr(|h_{SD}|^2 < \frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_3)p_S}, |h_{SU}|^2 < \frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)p_S}, \\ &\times |h_{SU}|^2 > \frac{\gamma_{th}N_0}{(a_2-\gamma_{th}A_2)p_S}) \\ &= \Pr(|h_{SD}|^2 < \frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_3)p_S}, \\ &\frac{\gamma_{th}N_0}{(a_2-\gamma_{th}A_2)p_S} < |h_{SU}|^2 < \frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)p_S}) \\ &= (1-e^{-\frac{\gamma_{th}N_0}{\lambda_{SD}p_S(a_1-\gamma_{th}A_3)}})(e^{-\frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_2-\gamma_{th}A_2)p_S}} - e^{-\frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)p_S}}) \end{aligned} \tag{A16}$$

where

$$\begin{aligned}
J_{31} = & \frac{2}{\lambda_{TS}}(w_{35}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{35}\frac{1}{\lambda_{TS}}}) \\
& - \frac{2}{\lambda_{TS}}(w_{36}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{36}\frac{1}{\lambda_{TS}}}) \\
& - \frac{2}{\lambda_{TS}}(w_{37}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{37}\frac{1}{\lambda_{TS}}}) \\
& + \frac{2}{\lambda_{TS}}(w_{38}\lambda_{TS})^{1/2}K_1(2\sqrt{w_{38}\frac{1}{\lambda_{TS}}}) \\
& - \frac{2}{\lambda_{TS}}((w_{35}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{35}+w_{39})\frac{1}{\lambda_{TS}}}) \\
& + \frac{2}{\lambda_{TS}}((w_{36}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{36}+w_{39})\frac{1}{\lambda_{TS}}}) \\
& + \frac{2}{\lambda_{TS}}((w_{37}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{37}+w_{39})\frac{1}{\lambda_{TS}}}) \\
& - \frac{2}{\lambda_{TS}}((w_{38}+w_{39})\lambda_{TS})^{1/2}K_1(2\sqrt{(w_{38}+w_{39})\frac{1}{\lambda_{TS}}})
\end{aligned} \tag{A17}$$

where

$$w_{31} = \frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)}, w_{32} = \frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_2-\gamma_{th}A_2)}$$

$$w_{33} = \frac{1}{\lambda_{SD}}\frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)} + \frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_1-\gamma_{th}A_1)}$$

$$w_{34} = \frac{1}{\lambda_{SD}}\frac{\gamma_{th}N_0}{(a_3-\gamma_{th}A_3)} + \frac{1}{\lambda_{SU}}\frac{\gamma_{th}N_0}{(a_2-\gamma_{th}A_2)}$$

$$w_{39} = \frac{1}{\lambda_{SR}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

$$w_{310} = \frac{1}{\lambda_{TS}}\frac{I_P(1-\alpha)}{2\alpha\beta p_T}$$

J_{32} can be calculated as

$$\begin{aligned}
J_{32} = & -\frac{2}{\lambda_{TS}}(\frac{w_{310}}{\frac{w_{31}}{I_P}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{310}(\frac{w_{31}}{I_P}+\frac{1}{\lambda_{SR}})}) \\
& + \frac{2}{\lambda_{TS}}(\frac{w_{310}}{\frac{w_{32}}{I_P}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{310}(\frac{w_{32}}{I_P}+\frac{1}{\lambda_{SR}})}) \\
& + \frac{2}{\lambda_{TS}}(\frac{w_{310}}{\frac{w_{33}}{I_P}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{310}(\frac{w_{33}}{I_P}+\frac{1}{\lambda_{SR}})}) \\
& - \frac{2}{\lambda_{TS}}(\frac{w_{310}}{\frac{w_{34}}{I_P}+\frac{1}{\lambda_{SR}}})^{1/2}K_1(2\sqrt{w_{310}(\frac{w_{34}}{I_P}+\frac{1}{\lambda_{SR}})}).
\end{aligned} \tag{A18}$$

Thus, we can obtain

$$J_3 = J_{31} + J_{32}. \tag{A19}$$

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