Rate-Splitting Multiple Access-based Cognitive Radio Network With ipSIC and CEEs

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Abstract—In this paper, we study the outage and ergodic rate performance of a rate-splitting multiple access (RSMA)-based cognitive radio (CR) system, where the secondary transmitter aims to communicate with two RSMA users. Imperfect successive interference cancellation (ipSIC) and channel estimation errors (CEE) are considered in the proposed analysis. Analytical expressions for the outage probability (OP) and the ergodic rate (ER) are calculated. For a deeper understanding, the asymptotic behavior of OP and ER at high signal-to-noise ratio (SNR) regimes are carried out. Illustrative simulation results are presented and reveal that: i) The OP decreases and the ER gradually increases with the increase of SNR, and eventually approaching a constant; ii) ipSIC and CEE have a negative impact on the considered system; iii) The outage and ER performance of RSMA-based CR network outperforms CR-NOMA network due to its flexible control of interference; iv) The OP first decreases and then increases with the power allocated to the common message, and there exists an optimal power allocation factor to ensure the reliable performance.

Index Terms—Cognitive radio, ergodic rate, imperfect successive interference cancellation (ipSIC), outage probability, rate-splitting multiple access.

I. INTRODUCTION

Recently, the ever increasing demands for high data rates and the rapid development of intelligent terminals have led to the search for the higher efficient spectrum and massive connectivity schemes [1], [2]. As two promising candidate techniques of the future wireless communication networks, rate-splitting multiple access (RSMA) and cognitive radio (CR) have been widely studied since it have the capability to support massive connectivity and high spectral efficiency [3], [4].

RSMA has aroused a heated attention as a powerful multiple access technique [5]. The dominant feature of RSMA is that the message required by the each user is divided into a common part and a private part at the transmitter. The common parts of all users are combined into a common message for each user to decode, while the private parts are independently encoded as private message that can only be recovered by its own user [6], [7]. RSMA decodes partial interference and treats the rest as noise at the receiver [8]. Therefore, it enables flexible interference control and is considered as a bridge between non-orthogonal multiple access (NOMA) and space-division multiple access (SDMA) [9], [10].

On a parallel avenue, cognitive radio (CR) is known as a potential technique that can effectively improve spectrum utilization [11]. The CR network consists of a primary network and a secondary network. It provides an opportunity for the secondary network to share the licensed spectrum with the primary network. In general, underlay, overlay and interweave are the three typical modes in CR network according to the different spectrum access paradigms. Among these, underlay CR is more appealing since it needs less collaborative overhead and low implementation complexity [12]. In underlay network, the secondary network can access the spectrum of the primary network for communication as long as its interference power to the primary network is within a certain power constraint [13].

RSMA combines the advantages of NOMA and SDMA, achieving massive connection, flexibly interference control and data transmission, while avoiding the complex receiver design problem in NOMA. Furthermore, CR compensates for the shortcomings of static spectrum allocation by dynamically accessing idle spectrum through spectrum monitoring. Therefore, applying rate splitting (RS) strategy to CR network will further improve the system performance and alleviate the problem of spectrum efficiency. In [14], the authors proposed a underlay multiple-input single-output network based on the downlink RSMA, and achieved the goal of minimizing the total transmit power by optimizing the precoder vectors and common rate variables. The authors in [15] introduced RSMA into the downlink multi-antenna multi-carrier CR network and maximized the ergonomic mutual information of secondary users under the consideration of imperfect channel state information (CSI) at transmitter. However, the above literature did not take imperfect successive interference cancellation (ipSIC) into account and were all focused on optimization rather than performance analysis. Liu et al. in [16] introduced RS strategy
into an uplink CR-NOMA system, and proved the superiority of the RS for considered system’s reliability by analyzing the outage probability (OP) of users.

Currently, most works on the combination of CR and RSMA focus on optimizing network models to achieve better performance. Unfortunately, few works of performance analysis are quite few. In [16], Liu et al. proposed an uplink RS-based CR system with Rayleigh fading channels. There also exist many differences between uplink and downlink of the networks, and thus, the analysis for uplink may not be applied to downlink.

To the best of our knowledge, the work on the RMSA-underlay CR network is not available yet. Although both amplify-and-forward (AF) and underlay CR can improve the performance of primary users, these are two different schemes. Underlay CR communicates in two networks, while AF protocol has the drawback of noise amplification in the process of signal amplification. Motivated by above, the underlay CR is adopted.

In addition, there was no work to introduce Nakagami-m fading channels into RSMA-based underlay CR networks and the current studies do not consider the impact of ipSIC and the channel estimation errors (CEE). To fill this gap, RS strategy is adopted in the downlink underlay CR network in this paper. Secondary transmitter communicates with the secondary receivers without affecting the quality of service (QoS) of the primary network. The main contributions of this paper are as follows: 1) We analyze the OP and ER of the RSMA-based CR networks based on Nakagami-m fading channels under CEEs and ipSIC; 2) We discuss in depth the asymptotic performance of OP and ER at high signal-to-noise ratio (SNR) regions to shed light into the considered network; 3) We validate the advantage of the proposed RSMA-based CR networks by comparing with CR-NOMA networks.

II. SYSTEM MODEL

We consider a downlink RSMA-based underlay CR system, which consists of one secondary transmitter ST, one far user $SR_f$, one near user $SR_n$ and one primary user PR. The following assumptions are considered: i) All nodes are equipped with a single antenna; ii) All channels are subject to the independent non-identically Nakagami-m fading channels.

As [17], linear minimum mean square error (LMMSE) algorithm is adopted since the perfect CSI is impossible to acquire. Thus, the channel coefficient can be denoted by

$$h_i = h_i + e_i, i \in \{SR_f, SR_n, SP\},$$

where $h_i$ represents the estimated channel coefficient and $e_i \sim CN(0, \sigma_i^2)$ is the CEE. In addition, secondary communication is allowed if the PR does not receive harmful interference from the ST. Accordingly, the following restriction should be met at the ST: $P_s = \min \left( P_{\text{max}}, \frac{P_I}{|h_{SP}|^2} \right)$, where $P_{\text{max}}$ is the maximum transmit power of ST, and $P_I$ represents the interference of ST on PR.

According to the RSMA protocol, the signal transmitted by the ST can be written as

$$x_s = \sqrt{\alpha_c P_s} x_c + \sum_{k=1}^{2} \sqrt{\alpha_{p,k} P_s} x_{p,k},$$

where $\alpha_c$ and $\alpha_{p,1}, \alpha_{p,2}$ are the power allocation factors of common message and private messages of the $SR_f$ and $SR_n$, respectively, satisfying $\alpha_c + \sum_{k=1}^{2} \alpha_{p,k} = 1$.

The received message at $SR_i$ ($i = f, n$) can be expressed as

$$y_{SR_i} = (\tilde{h}_{SR_i} + e_{SR_i}) x_s + n_{SR_i},$$

where $n_i \sim CN(0, N_i)$ denotes the complex additive white Gaussian noise (AWGN).

The signal-interference-plus-noise ratio (SINR) of decoding the common message $x_c$ and private message $x_{p,k}$ for $SR_i$ is given by

$$\gamma_{SR_i}^{c} = \frac{\left| \tilde{h}_{SR_i} \right|^2 \gamma_s \alpha_c}{\sum_{k=1}^{2} \left| \tilde{h}_{SR_i} \right|^2 \alpha_{p,k} + \left| \tilde{h}_{SR_i} \right|^2 \sum_{i=1}^{2} \alpha_{p,i} + \sigma_i^2 \gamma_s + 1},$$

$$\gamma_{SR_i}^{p,i} = \frac{\left| \tilde{h}_{SR_i} \right|^2 \gamma_s \alpha_{p,k}}{\sum_{i=1}^{2} \left| \tilde{h}_{SR_i} \right|^2 \alpha_{p,i} + \sigma_i^2 \gamma_s + 1},$$

where $\gamma_s = \frac{P_s}{N_0}$, $\zeta$ is a coefficient that represents the level of ipSIC, and satisfies $0 \leq \zeta \leq 1$. $\zeta = 0$ and $\zeta = 1$ represent perfect SIC and no SIC, respectively.

III. PERFORMANCE ANALYSIS

This section evaluates the outage and ER performance of the RSMA-based underlay CR network by calculating the analytical expressions for OP and ER. Furthermore, we analyze the asymptotic behavior of OP and ER at high SNR regimes for the users to have a comprehensive sight of the proposed system.

A. Outage Performance Analysis

1) Outage Probability of $SR_i$: When both the common message $x_c$ and private message $x_{p,k}$ can be successfully decoded by $SR_i$, the outage behavior will not occur. Therefore, the OP of $SR_i$ can be denoted as

$$P_{\text{out}}^{SR_i} = 1 - \text{Pr} \left( \gamma_{SR_i}^{c} > \gamma_t^{c}, \gamma_{SR_i}^{p,i} > \gamma_t^{p,i}, P_{\text{max}} \leq \frac{P_I}{|h_{SP}|^2} \right),$$

$$+ \text{Pr} \left( \gamma_{SR_i}^{c} > \gamma_t^{c}, \gamma_{SR_i}^{p,i} > \gamma_t^{p,i}, P_{\text{max}} > \frac{P_I}{|h_{SP}|^2} \right),$$

where $\gamma_t^{c}$ and $\gamma_t^{p,i}$ are the target rate of decoding $x_c$ and $x_{p,k}$ of $SR_i$. 

Nakagami-m fading channel is a general fading channel, and it can reduce to Gaussian fading channel, Rayleigh fading channel and Rician fading channel by setting $m_i = 1/2$, $m_i = 1$ and $m_i = \frac{K+1}{2K+1}$, respectively, where $K$ is the Rician factor.
Theorem 1: For Nakagami-\(m\) fading channels, the OP of 
\(SR_f\) is represented as 
\[
P_{SR_f} = 1 - \left( e^{-A_1} \sum_{g_1=0}^{m_{SR_f}-1} \frac{A_1^{g_1} \gamma_1}{g_1!} \right) \left( 1 - e^{-A_2} \sum_{g_2=0}^{m_{SR_f}-1} \frac{A_2^{g_2} \gamma_2}{g_2!} \right) + e^{-A_1 \sigma_{SR_f}^2 P_1} \left( \frac{m_{SP}}{\Omega_{SP}} \right)^{m_{SP}} \frac{1}{\Gamma(m_{SP})} \sum_{g_2=0}^{m_{SR_f}-1} \frac{A_2^{g_2} \gamma_2}{g_2!} \times \left( \frac{g_2}{k_2} \right) \left( \sigma_{SR_f}^2 P_1 \right)^{g_2-k_2} A_4^{k_2-m_{SR_f} A_5}, \tag{7} \]

where the integer \(m_i\) represents the fading severity parameter, \(\Omega_i\) denotes the average power and its value is positive, 
\[
\Delta_1 = \frac{\alpha_1 \gamma_1 \gamma_2 \gamma_3}{\gamma_1 \gamma_2 \gamma_3 \Omega_1 \Omega_2 \Omega_3}, \quad \Delta_2 = \frac{\alpha_1 \gamma_1 \gamma_2 \gamma_3}{\gamma_1 \gamma_2 \gamma_3 \Omega_1 \Omega_2 \Omega_3}, \quad \Delta_3 = \max(\Delta_1, \Delta_2), \quad \Delta_4 = \max(\Delta_2, \Delta_3), \quad \Delta_5 = \max(\Delta_1, \Delta_2), \quad \Delta_6 = \max(\Delta_2, \Delta_3), \quad \text{and} \quad \gamma_4 = \frac{p_{max}}{\Omega_1}. \tag{8} \]

Proof: See Appendix A.

Corollary 1: At high SNRs, the asymptotic expression of 
\(OP\) for \(SR_f\) is given by 
\[
P_{SR_f} = 1 - e^{-A_1} \sum_{g_1=0}^{m_{SR_f}-1} \frac{A_1^{g_1} \gamma_1}{g_1!}. \tag{9} \]

Next, the optimal value of \(\alpha_i\) are derived to achieve the 
optimal reliability of the \(SR_f\) by performing a series of 
calculations on Eq. (8). We set \(\alpha_{p,1} = b_1 (1 - \alpha_c)\) and \(\alpha_{p,2} = b_2 (1 - \alpha_c)\), where \(b_1 > b_2 \) and \(b_1 + b_2 = 1\), \(\Delta_1 = \frac{\gamma_1 \gamma_2 \gamma_3}{\gamma_1 \gamma_2 \gamma_3 \Omega_1 \Omega_2 \Omega_3}\) and \(\Delta_2 = \frac{\gamma_1 \gamma_2 \gamma_3}{\gamma_1 \gamma_2 \gamma_3 \Omega_1 \Omega_2 \Omega_3}\). 
It is obvious that \(C > 0\) and \(C < 0\), so the values of \(\Delta_1\) and \(\Delta_2\) decrease and increase with respect to \(\alpha_c\), respectively. 
Accordingly, \(P_{SR_f} \rightarrow \infty\) will reach its optimal value when 
\(\Delta_1 = \Delta_2\). Therefore, the optimal power allocation coefficient 
for the common messages \(\alpha_c = \frac{D_{p,1} \gamma_1 \gamma_2 \gamma_3}{C_{p,1} \gamma_1 \gamma_2 \gamma_3}\). Similarly, the optimal value for the \(SR_r\) can be computed using the similar methodology.

Similarly, the following Theorem gives the analytical OP 
expression of \(SR_r\).

Theorem 2: For Nakagami-\(m\) fading channels, the analytical 
expression for the OP of \(SR_r\) is represented as 
\[
P_{SR_r} = 1 - \left( e^{-A_6} \sum_{g_1=0}^{m_{SR_r}-1} \frac{A_6^{g_1}}{g_1!} \right) \left( 1 - e^{-A_7} \sum_{g_2=0}^{m_{SR_r}-1} \frac{A_7^{g_2}}{g_2!} \right) + e^{-A_8 \sigma_{SR_r}^2 P_1} \left( \frac{m_{SP}}{\Omega_{SP}} \right)^{m_{SP}} \frac{1}{\Gamma(m_{SP})} \sum_{g_2=0}^{m_{SR_r}-1} \frac{A_2^{g_2} \gamma_2}{g_2!} \times \left( \frac{g_2}{k_2} \right) \left( \sigma_{SR_r}^2 P_1 \right)^{g_2-k_2} A_8^{k_2-m_{SR_r} A_9}, \tag{10} \]

where \(A_6 = \frac{m_{SR_r} \Delta_6}{\Omega_{SR_r} \Omega_p P_1}, \quad A_7 = \frac{m_{SR_r} \Delta_7}{\Omega_{SR_r} \Omega_p P_1}, \quad A_8 = \frac{m_{SR_r} \Delta_8}{\Omega_{SR_r} \Omega_p P_1}, \quad A_9 = \frac{m_{SR_r} \Delta_9}{\Omega_{SR_r} \Omega_p P_1+m_{SR_r} \Omega_p P_1}, \quad A_{10} = \Gamma \left( k_2 + m_{SP}, \frac{P_1 A_4}{P_{max}} \right), \quad \Delta_5 = \max(\Delta_1, \Delta_2), \quad \text{and} \quad \Delta_6 = \max(\Delta_2, \Delta_3). \tag{11} \]

Proof: See Appendix B.

Corollary 2: The asymptotic OP expression for \(SR_r\) at 
high SNRs can be written as 
\[
P_{SR_r} = 1 - e^{-A_6} \sum_{g_2=0}^{m_{SR_r}-1} \frac{A_6^{g_2} \gamma_2}{g_2!}. \tag{12} \]

For a deeper exploration of the RSMA-based underlay CR 
network, we analyze the diversity orders of \(SR_f\) and \(SR_r\). 
The diversity order is represented as 
\[
d = -\lim_{\gamma \rightarrow \infty} \frac{\log(P_{SR_l})}{\log \gamma}. \tag{13} \]

Corollary 3: The diversity orders of \(SR_f\) and \(SR_r\) can be represented as 
\[
d_{SR_f} = d_{SR_r} = 0. \tag{14} \]

Remark 1: From Corollaries 1 and 2, we can observe that 
the OP of \(SR_f\) and \(SR_r\) decreases with \(P_1\); the reliability 
continues to increase, and eventually saturates to a constant. 
This implies that the OPs have error floors, resulting in the 
diversity orders to be 0. In addition, there is an optimal 
value for \(\alpha_c\) to ensure the most reliable performance for the 
considered system.

B. Ergodic Rate Analysis

The analytical expression for the ER of \(SR_l\) can be represented as 
\[
R_{SER} = \begin{cases} 
E \left[ \log_2 \left( 1 + \gamma_{SR_l} \right) \right] + E \left( \log_2 \left( 1 + \gamma_{SR,1} \right) \right), & \text{if } P_1 = P_{max} \\
E \left[ \log_2 \left( 1 + \gamma_{SR,l2} \right) \right] + E \left( \log_2 \left( 1 + \gamma_{SR,1} \right) \right), & \text{if } P_1 \neq P_{max} 
\end{cases}. \tag{15} \]

Unfortunately, it is very difficult, if not impossible, to obtain 
exact expressions for the ERs of \(SR_f\) and \(SR_r\). To this end, 
we seek to obtain the approximations of the ER of the two 
users in the following Theorem.

Theorem 3: For Nakagami-\(m\) fading channels, the analytic 
expression for the ER of \(SR_f\) is approximately denoted by 
\[
R_{SR_f} \approx \log_2 (1 + \phi_1) + \log_2 (1 + \phi_2) \tag{16} \]

\[
+ \log_2 (1 + \phi_3) + \log_2 (1 + \phi_4), \tag{17} \]

where \(\phi_1 = \Omega_{SR_f} \gamma_m \alpha_c \left( \Omega_{SR_f} \gamma_m \right)^2 \left( \sum_{k=1}^{m_{SR_f}} \alpha_{p,k} + \sigma_{SR_f}^2 \gamma_1^2 \right), \quad \phi_2 = \Omega_{SR_f} \gamma_m \alpha_c \left( \Omega_{SR_f} \gamma_m \right)^2 \left( \sum_{k=1}^{m_{SR_f}} \alpha_{p,k} + \sigma_{SR_f}^2 \gamma_1^2 \right), \quad \phi_3 = \Omega_{SR_f} \gamma_m \alpha_c \left( \Omega_{SR_f} \gamma_m \right)^2 \left( \sum_{k=1}^{m_{SR_f}} \alpha_{p,k} + \sigma_{SR_f}^2 \gamma_1^2 \right), \quad \phi_4 = \Omega_{SR_f} \gamma_m \alpha_c \left( \Omega_{SR_f} \gamma_m \right)^2 \left( \sum_{k=1}^{m_{SR_f}} \alpha_{p,k} + \sigma_{SR_f}^2 \gamma_1^2 \right), \quad \phi_5 = \Omega_{SR_f} \gamma_m \alpha_c \left( \Omega_{SR_f} \gamma_m \right)^2 \left( \sum_{k=1}^{m_{SR_f}} \alpha_{p,k} + \sigma_{SR_f}^2 \gamma_1^2 \right). \tag{18} \]

Proof: See Appendix B.
Corollary 4: At high SNRs, the asymptotic expression for ER of $SR_f$ can be written as

$$R_{SR_f}^\infty = \log_2 (1 + \phi_1') + \log_2 (1 + \phi_2')$$

$$+ \log_2 (1 + \phi_3) + \log_2 (1 + \phi_4),$$

(15)

where $\phi_1' = \Omega_{SR_f} \alpha_c \left( \frac{1}{\Omega_{SR_f}} \sum_{k=1}^{a_k} \alpha_{p,k} + \alpha_{e,SR_f} \gamma + 1 \right)$

and $\phi_2' = \Omega_{SR_f} \alpha_{p,2} \left( \frac{1}{\Omega_{SR_f}} \sum_{k=1}^{a_k} \alpha_{p,k} + \alpha_{e,SR_f} \gamma + 1 \right)$

Similar to $SR_f$, the following Theorem gives the ER of $SR_n$.

Theorem 4: For Nakagami-$m$ fading channels, the analytical expression for the ER of $SR_n$ is approximately written by

$$R_{SR_n} \approx \log_2 (1 + \phi_5) + \log_2 (1 + \phi_6)$$

$$+ \log_2 (1 + \phi_7) + \log_2 (1 + \phi_8),$$

(16)

where $\phi_5 = \Omega_{SR_n} \gamma \alpha_c \left/ \left( \Omega_{SR_n} \gamma \alpha_c + \alpha_{e,SR_n} + 1 \right) \right.$

$\phi_6 = \Omega_{SR_n} \gamma \alpha_{p,2} \left/ \left( \Omega_{SR_n} \gamma \alpha_{p,2} + \alpha_{e,SR_n} + 1 \right) \right.$

$\phi_7 = \Omega_{SR_n} \gamma \alpha_{p,1} + \alpha_{e,SR_n} + 1$

and $\phi_8 = \Omega_{SR_n} \gamma \alpha_{p,2} + \alpha_{e,SR_n} + 1$

$+ A_{11}$

Corollary 5: At high SNRs, we obtain the ER asymptotic expression of $SR_n$ as

$$R_{SR_n}^\infty = \log_2 (1 + \phi_5') + \log_2 (1 + \phi_6')$$

$$+ \log_2 (1 + \phi_7') + \log_2 (1 + \phi_8'),$$

(17)

where $\phi_5' = \Omega_{SR_n} \alpha_c \left/ \left( \Omega_{SR_n} \alpha_c + \alpha_{e,SR_n} + 1 \right) \right.$

$\phi_6' = \Omega_{SR_n} \alpha_{p,2} \left/ \left( \Omega_{SR_n} \alpha_{p,2} + \alpha_{e,SR_n} + 1 \right) \right.$

Remark 2: From Corollaries 4 and 5, it can be observed that the ER increases with $P_f$ and finally tends to be a fixed constant, indicating that there exists a ceiling for ER. The ER of $SR_f$ and $SR_n$ increases with $\alpha_c$, but decreases with the coefficients of ipSIC and CEEs. Therefore, a higher value of $\alpha_c$ is preferred and more accurate hardware devices should be selected to reduce the coefficients of ipSIC and CEEs.

IV. NUMERICAL RESULTS

The analysis of this work is corroborated by the Monte Carlo simulations. All experiments are established on $10^6$ times. Unless stated explicitly, we have the following settings: The noise power is $N_0 = N_1 = 1$, The maximum transmit power of ST is $P_{\text{max}} = 1$. The target rates are $\gamma_h = \gamma_{th} = 0.1$. The power allocation coefficients for common and private messages are $\alpha_c = 0.6$, $\alpha_{p,1} = 0.25$ and $\alpha_{p,2} = 0.15$. The fading severity parameters are $m_{SR_f} = 6$, $m_{SR_n} = 2$. The average power is $\Omega_{SR_f} = 4$, $\Omega_{SR_n} = 3$, $\Omega_{SR_n} = 4$. The channel estimation errors are $\sigma_{e,SR_f}^2 = 0.08$. The ipSIC is $\zeta = 0.01$.

Fig. 1 presents the OP of the far user and near user versus $P_f$, respectively. We can clearly observe that OP decreases with $P_f$, while the reliability of the system increases with $P_f$, which can be deduced from (7) and (9). OP gradually reaches a fixed constant when $P_f$ tends to infinity, resulting in an error floor. This is due to the flexible decoding method of RSMA. As the OP reaches saturation, the ability to increase the reliable performance of the system by adding $P_f$ is no longer significant. In addition, it also finds that the reliable of CR-RSMA system outperforms CR-NOMA system because of the flexible management of interference.

Fig. 2 plots the effect of power allocation coefficient $\alpha_c$ on the reliable performance under the Nakagami-$m$ fading channels and Rayleigh fading channels. It is clear that OP first decreases and then increases with $\alpha_c$, showing a critical point. There exists an optimal $\alpha_c$ to minimize the OPs, and the system performance will deteriorate if $\alpha_c$ deviates from the optimal value. The larger $\alpha_c$ becomes, the larger corresponding power of common message and the smaller corresponding power of private message. The common message link is basically in an outage state if $\alpha_c$ is extremely small, vice versa. The change in the value of $\alpha_c$ causes the OP to generate the state shown in the Fig. 2. Furthermore, we consider the effect of different $P_f$ values on user OP. It is not difficult to see that when the $P_f$ gets larger, the performance improves better. In addition, we can observe that the OPs of $SR_f$ and $SR_n$ are smaller and the reliability is higher under the Nakagami-$m$ fading channels.

Under ideal and nonideal conditions, the curves of ER are
depicted versus $P_f$ in Fig. 3. The experiments are established on $10^5$ times. We set $m_{SR} = 2$, $m_{SRf} = 8$, $m_{SRn} = 7$, $\Omega_{SR} = 2$, $\Omega_{SRf} = 3$, and $\Omega_{SRn} = 0.3$. It can be clearly seen that with the increase of $P_f$, the ER performance of the RSMA-based underlay CR system improves, which can be inferred from (14) and (16). The ER tends to be a fixed constant when $P_f$ reaches infinity. As can be seen from the Fig. 3, the CEEs and ipSIC negatively affect the ER performance of the considered system. By comparing RSMA-based CR network with CR-NOMA, we find that RSMA system outperforms NOMA system for ER.

V. CONCLUSION

In this paper, we analyzed the outage and ER performance of the proposed RSMA-based CR systems. To obtain a better view of the system performance, the approximate behavior of OP and ER at high SNR were investigated. The simulation results showed that the OP decreases and the ER increases gradually with the transmit SNR of ST, and tended to be a fixed constant. Moreover, ipSIC and non-ideal CSI had a negative impact on the considered network. Finally, we found that the performance of RSMA-based CR networks was better than that of CR-NOMA networks.

APPENDIX A

Plugging (4) and (5) into (6), the OP of $SR_f$ is given by

$$P_{SR_f} = 1 - \Pr \left( \gamma_{SR_f} > \gamma_{SRn} > \gamma_{SRf}, p_{\max} \leq \frac{P_f}{\Omega_{SRf}} \right) + \Pr \left( \gamma_{SR} > \gamma_{SRn}, \gamma_{SRf} > \gamma_{SRf}, p_{\max} > \frac{P_f}{\Omega_{SRf}} \right),$$

(A.1)

$I_1$ and $I_2$ can be denoted as

$$I_1 = \int_{0}^{\infty} (\sigma_{SRf}^{2} + 1) f_{\gamma_{SRf}}(x) dx \int_{0}^{\infty} f_{\gamma_{SRf}}(y) dy$$

$$= e^{-A_1} \sum_{g_1=0}^{m_{SRf}-1} \frac{A_1 g_1}{g_1!} \left( 1 - e^{-A_2} \sum_{g_2=0}^{m_{SRf}-1} \frac{A_2 g_2}{g_2!} \right),$$

(A.2)

$$I_2 = \int_{0}^{\infty} \int_{0}^{\infty} \Delta_4 \left( \sigma_{SRf}^{2} + 1 \right) f_{\gamma_{SRf}}(x) f_{\gamma_{SRf}}(y) dx dy$$

$$= e^{-A_3 \sigma_{SRf}^{2} P_f} \left( \frac{m_{SRf}}{\Omega_{SRf}} \right)^{m_{SRf}} \frac{1}{\Gamma \left( m_{SRf} \right)} \sum_{g_1=0}^{m_{SRf}-1} \sum_{k_1=0}^{m_{SRf}-1} \frac{A_3 g_1}{g_1!} \times \left( \frac{g_1}{k_1} \right)^{g_1-k_1} \left( A_4 \right)^{-k_1-m_{SRf}} A_{SRf},$$

(A.3)

In conclusion, (A.2) and (A.3) are substituted into (A.1) to obtain (7).

The solution process of outage performance for $SR_n$ is similar to $SR_f$, so it is omitted due the space limited.

APPENDIX B

Substituting (4) and (5) into (13), the ER of $SR_f$ can be expressed as

$$R_{SR_f} \approx \log_2 \left[ 1 + E \left( \phi_9 \right) \right] + \log_2 \left[ 1 + E \left( \phi_{10} \right) \right] + \log_2 \left[ 1 + E \left( \phi_{11} \right) \right] + \log_2 \left[ 1 + E \left( \phi_{12} \right) \right],$$

(B.1)

where

$$\phi_9 = \frac{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}}}{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}} + E \left( \gamma_{SRn}^2 \right)^{\gamma_{SRn}} + E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf} + 1}}$$

$$\phi_{10} = \frac{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}}}{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}} + E \left( \gamma_{SRn}^2 \right)^{\gamma_{SRn}} + E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf} + 1}}$$

$$\phi_{11} = \frac{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}}}{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}} + E \left( \gamma_{SRn}^2 \right)^{\gamma_{SRn}} + E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf} + 1}}$$

and

$$\phi_{12} = \frac{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}}}{E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf}} + E \left( \gamma_{SRn}^2 \right)^{\gamma_{SRn}} + E \left( \gamma_{SRf}^2 \right)^{\gamma_{SRf} + 1}}$$

where

$$E \left( \gamma_{SR_f}^2 \right)^{\gamma_{SRf}} = \int_0^{\infty} x f_{\gamma_{SRf}}(x) dx = \Omega_{SRf}.$$

Similarly, we can get

$$E \left( \gamma_{SR_n}^2 \right)^{\gamma_{SRn}} = \Omega_{SRn} \text{ and } E \left( \gamma_{SR_f}^2 \right)^{\gamma_{SRf}} = \Omega_{SRf}.$$


