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Exploring Secrecy Outage Probability of AF-NOMA and AF-OMA Networks

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Abstract —A new design of non-orthogonal multiple access (NOMA) is explored in this study under secrecy outage probability performance considerations. In particular, the Amplify-and-Forward (AF) relaying scheme is applied in this system model. In case of existence of an external eavesdropper, a transmitter sends confidential messages to far users in concerned NOMA system. To highlight performance of NOMA system model, orthogonal multiple access (OMA) is compared with respect to tradeoff between secure performances and transmit SNR. As important observation, the secrecy outage probability is evaluated as the secrecy metric to limit impacts of the practical passive eavesdropper in real scenario. It is confirmed that the secrecy outage is significant lower than OMA due to related parameters characterization in NOMA, and it should be controlled by varying related coefficients. Finally, we show the both of NOMA and OMA against to impact of eavesdropper in the studied problems in terms of analytically result and numerically result.

Index Terms—Physical layer security, non-orthogonal multiple access, secrecy outage probability

I. INTRODUCTION

Multiple access technology is a serious subject which need be improved to adapt massive connections in wireless communications. As a favorable technology, non-orthogonal multiple access (NOMA) has expected as considerable methodology for future wireless communication systems because of its superior spectral effectiveness. In NOMA, the users located in clustered area are multiplexed in the power domain, i.e., the same frequency and time are allocated in their signals but the signal power levels are dissimilar. By deploying successive interference cancellation (SIC) at the receivers, it can be separated the composite signal to recover signal of different users [1]. Recently, different systems of NOMA can be suggested in the literature. The system performance including outage performance of separated users and ergodic sum rate in randomly locations of users are investigated in [2]. Considering on group users which have their channel gains with distinctive values under Rayleigh fading channels lead to better performance as in the analytical results in [2]. The fixed power allocation (F-NOMA) and cognitive radio inspired NOMA are examined to evaluate the performance of NOMA with respect to standard Rayleigh fading channels. As important result, only the user with higher channel gain affects the outage performance [3].

In principle of NOMA, the transmit equipment superimposes signals in the power domain for multiple users, which can be attained by distributing dissimilar powers to different services. At the user side, before decoding users' own desired signal, a user initially efforts to decode and eliminate the signals of other users. The higher data rate can be obtained by applying NOMA at the users who have the most distinguishing channel conditions as recent works [4], [5]. Typically, a better chance related to signal decoding can be achieved with the user assigned better channel condition compared with the user allocated worse channel condition, and power allocation problem need be careful considered at the base station (BS) to preserve user fairness related to data rate [6]. Due to the encouraging benefits of NOMA, many system models and their performance have received significant attentions in next generation wireless networks with massive access demands [7]-[10]. Several key enabling techniques in the fifth generation (5G) systems such as cooperative communications, relay networks, cognitive radios, heterogeneous networks are introduced in the literature showing advantages of NOMA scheme.

Additionally, to protect against wiretapping Physical Layer Security (PLS) has been proposed as a reliable additional layer of network in comparison with conventional cryptographic methodologies. The main characterization lies in the fact that wireless channels are in random manner and hence network security can be exploited. Very recently, a lot of attention from the research community is concerned to address the performance of PLS, e.g., in relay networks [11]–[13] and cognitive relay networks [14].

Recently, relaying networks are investigated in serveral scenarios to evaluate outage performance. The main advantage of relaying scheme is that expanding coverage and eliminating hidden objects can be served with assistance of relay node [15]-[19].

Motivated by above analysis and interesting results presented in [20], this paper presents analytical expressions to compare with OMA scheme in term of

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secure outage performance by controlling related coefficients consisting of SNR, power allocation factors.

II. SYSTEM MODEL

Consider main equipment illustrated in Fig. 1 including a base station (S), two users (D1 called as strong user, and D2 called as weak user), a helping relay, and unwanted eavesdropper (E) in a NOMA-aware cellular network. Normally, node S is situated in the center of the cell, and user D1 located cell-center while user D2 and user E are very close to the cell-edge. In this scenario no direct links are existed between S and the users, as well as E. We further assume that single antennas equipped at all nodes in the network. Regarding wireless channel, all the channels follow independent Rayleigh distribution fading. It worth noting that in non-secure circumstance, signal obtained the messages from relay to users can be overhear by user E, including the forwarding signal at relays, and corresponding decoding procedure. All links at each node pair of S-R, R-D1, R-D2, R-E have channel gains are represented by $\left|h_r\right|^2, \left|g_{r,1}\right|^2$, $\left|g_{r,2}\right|^2$, and $\left|g_{r,\mathrm{E}}\right|^2$, respectively. We denote Ω_0, Ω_1, Ω_2 and Ω_E are the Rayleigh channel parameters corresponding to channel $\left|h_r\right|^2$, $\left|g_{r,1}\right|^2$, $\left|g_{r,2}\right|^2$, and $\left|g_{r,\mathrm{E}}\right|^2$, respectively. Transmit power at node S and R are denoted by P, P_R and noise power terms denoting as N_0 at normal nodes are the same, and node E is N_E.

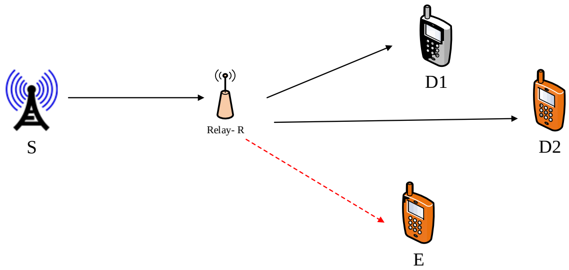

Fig. 1. System model of secure NOMA

Based on the aforementioned assumptions, the observation at the relay R is given by

$$y_R = h_r\left(\sqrt{a_1 P}x_1 + \sqrt{a_2 P}x_2\right) + w_r \tag{1}$$

where x_1, x_2 are the normalized signal for D1, D2, respectively, w_r is AWGN noise. It is assumed that $E\left\{x_1^2\right\} = E\left\{x_2^2\right\} = 1$, a_1, a_2 are power allocation factors. To stipulate better fairness between the users, we assume that $a_1 > a_2$ satisfying $a_1 + a_2 = 1$.

Based received signal at destination, we obtain the following instantaneous signal-to-interference-plus-noise ratio (SINR) as

$$\gamma_{r,1}^{AF} = \frac{\rho\rho\left|h_r\right|^2\left|g_{r,E}\right|^2 a_1^2}{\rho\rho\left|h_r\right|^2\left|g_{r,E}\right|^2 a_2^2 + \rho\left|g_{r,E}\right|^2 + \rho\left|h_r\right|^2 + 1} \tag{2}$$

$$\gamma_{r,2}^{AF} = \frac{\rho\rho\left|h_r\right|^2\left|g_{r,E}\right|^2 a_2^2}{\rho\rho\left|h_r\right|^2\left|g_{r,E}\right|^2 a_1^2 + \rho\left|g_{r,E}\right|^2 + \rho\left|h_r\right|^2 + 1} \tag{3}$$

where $\rho = P/N_0$ is transmit SNR at node S. In trusted relay-based NOMA, the parallel interference cancellation (PIC) is used at E to distinguish the superimposed mixture. Then, we can express the channel capacity from the relay to E as

$$C_{\mathrm{E},i}^{AF} = 0.5\log_2\left(1 + \gamma_{\mathrm{E},i}^{AF}\right) \tag{4}$$

where $\gamma_{E,i}^{AF} = \dfrac{\rho\rho_E\left|h_r\right|^2\left|g_{r,E}\right|^2\alpha_i^2}{\rho_E\left|g_{r,E}\right|^2 + \rho\left|h_r\right|^2 + 1}$ is the received SINR at E, while $\rho_E = P_R/N_E$ is the average SNR of the illegal link between the relay and E.

We first define $[x]^+ = \max\{x, 0\}$. It is denoted $C_{r,i}^{AF}$ as channel capacity at $D_i, i = 1, 2$, the AF-based NOMA systems obtains secrecy rate of the for user $D_i, i = 1, 2$ is given by

$$C_i^{AF} = \left[C_{r,i}^{AF} - C_{E,i}^{AF}\right]^+ \tag{5}$$

III. SECURE OUTAGE PERFORMANCE ANALYSIS IN NOMA

In NOMA systems, using the helping relay, two signals are transferred from the S to far user consist of D1 and D2. In the literature, secure outage probability (SOP) is defined as it falls below its own target rate. As a result, the SOP can be obtained as

$$\begin{aligned} SOP^{AF} &= \Pr\left(C_1^{AF} < R_1 \text{ or } C_2^{AF} < R_2\right) \\ &= 1 - \Pr\left(\frac{1+\gamma_{r,1}^{AF}}{1+\gamma_{\mathrm{E},1}^{AF}} > C_{th}^1, \frac{1+\gamma_{r,2}^{AF}}{1+\gamma_{\mathrm{E},2}^{AF}} > C_{th}^2\right) \\ &= 1 - \Pr 1, \end{aligned} \tag{6}$$

where R_i is the target data rate for user $D_i, i = 1, 2$ and $C_{th}^i = 2^{2R_i}$. Since variables γ_1^{AF}, γ_2^{AF}, $\gamma_{E,r}^{AF}$ and $\gamma_{E,2}^{AF}$ are correlated and such factors leads to intractable exact computation. Fortunately, the following upper bounds can be achieved as $\gamma_{r,1}^{AF} < \dfrac{\alpha_1^2}{\alpha_2^2}$, $\gamma_{r,2}^{AF} < \dfrac{\rho\rho\left|h_r\right|^2\left|g_{r,2}\right|^2 a_2^2}{\rho\left|g_{r,2}\right|^2 + \rho\left|h_r\right|^2}$ and $\gamma_{E,i}^{AF} < \dfrac{\rho\rho_E\left|h_r\right|^2\left|g_{r,\mathrm{E}}\right|^2 a_i^2}{\rho_E\left|g_{r,\mathrm{E}}\right|^2 + \rho\left|h_r\right|^2}$, $i = 1, 2$. Then, approximate expression of Pr1 can be obtained as

$$\Pr 1 < \Pr\left(\varphi_1 < \xi_1, \varphi_2 > \frac{C_{th}^2 \rho\rho_E \left|h_r\right|^2 \left|g_{r,\mathrm{E}}\right|^2 a_2^2}{\rho_E \left|g_{r,\mathrm{E}}\right|^2 + \rho\left|h_r\right|^2} + C_{th}^2 - 1\right) \quad (7)$$

where $\varphi_1 = \frac{\rho\rho_E \left|h_r\right|^2 \left|g_{r,\mathrm{E}}\right|^2}{\rho_E \left|g_{r,\mathrm{E}}\right|^2 + \rho\left|h_r\right|^2}$, $\varphi_2 = \frac{\rho\rho\left|h_r\right|^2 \left|g_{r,2}\right|^2 a_2^2}{\rho\left|g_{r,\mathrm{E}}\right|^2 + \rho\left|h_r\right|^2}$, $\xi_1 = \frac{1 - a_2^2 C_{th}^1}{a_1^2 a_2^2 C_{th}^1}$. It is required $a_1^2 > a_2^2\left(C_{th}^1 - 1\right)$ due to $\xi_1 = \frac{a_1^2 - a_2^2\left(C_{th}^1 - 1\right)}{a_1^2 a_2^2 C_{th}^1} > 0$ and otherwise, SOP equals to 1. Deploying well-known inequality $xy/\left(x+y\right) \le \min\left\{x, y\right\}$, new variables are denoted as

$$\varepsilon_1 = \min\left\{\left|h_r\right|^2, \left|g_{r,2}\right|^2\right\} > \min\left\{C_{th}^2\left|h_r\right|^2, A\left|g_{r,\mathrm{E}}\right|^2\right\} + B \quad (8)$$

$$\varepsilon_2 = \min\left\{\rho\left|h_r\right|^2, \rho_E\left|g_{r,\mathrm{E}}\right|^2\right\} < \xi_1 \quad (9)$$

Therefore, Pr1 can be further computed as

$$\Pr 1 < \Pr\left(\varepsilon_1, \varepsilon_2\right) \quad (10)$$

where $A = \frac{C_{th}^2 \rho_E}{\rho}$ and $B = \frac{C_{th}^2 - 1}{\rho\alpha_2^2}$. We further change to new formula as $P\left(\varepsilon_1, \varepsilon_2\right) = P\left(\varepsilon_1\right) - P\left(\varepsilon_1, \overline{\varepsilon_2}\right)$, in which $\overline{\varepsilon_2}$ symbolizes the complementary event of ε_2. It then can be further expressed by

$$\Pr\left(J_1\right) - \Pr\left(J_2, J_3\right) = P_1 - P_2 \quad (11)$$

where

$J_1 = \min\left\{\left|h_r\right|^2, \left|g_{r,2}\right|^2\right\} > \min\left\{C_{th}^2\left|h_r\right|^2, A\left|g_{r,\mathrm{E}}\right|^2 + B\right\}$,

$J_2 = \min\left\{\rho\left|h_r\right|^2, \rho_E\left|g_{r,\mathrm{E}}\right|^2\right\} > \xi_1$,

$J_3 = \min\left\{\left|h_r\right|^2, \left|g_{r,2}\right|^2\right\} > \min\left\{C_{th}^2\left|h_r\right|^2, A\left|g_{r,\mathrm{E}}\right|^2\right\} + B$.

Applying some manipulations, P_1 is given by [20]

$$\begin{aligned} P_1 &= \Pr\left(\left|h_r\right|^2 > A\left|g_{r,\mathrm{E}}\right|^2 + B, \left|g_{r,2}\right|^2 > A\left|g_{r,\mathrm{E}}\right|^2 + B\right) \\ &= \int_0^\infty \Pr\left(\left|h_r\right|^2 > Ax + B, \left|g_{r,2}\right|^2 > Ax + B\right) f_{\left|g_{r,\mathrm{E}}\right|^2}\left(x\right) dx \\ &= \int_0^\infty e^{-\left(\Omega_0 + \Omega_2\right)\left(Ax + B\right)} \lambda_E e^{-\Omega_E x} dx = \frac{\Omega_E e^{-\left(\Omega_0 + \Omega_2\right)B}}{\Omega_0 A + \Omega_2 A + \Omega_E} \end{aligned} \quad (12)$$

On the other hand, P_2 can be obtained as [20]

$$\begin{aligned} P_2 &= \int_{\frac{\xi_1}{\rho_E}}^{\infty} e^{-\left(\Omega_0 + \Omega_2\right)\left(Ax + B\right)} \Omega_E e^{-\Omega_E x} dx \\ &= \frac{\Omega_E e^{-\left(\Omega_0 + \Omega_2\right)B} \exp\left[-\left(\Omega_0 A + \Omega_2 A + \Omega_E\right)\frac{\xi_1}{\rho_E}\right]}{\Omega_0 A + \Omega_2 A + \Omega_E} \end{aligned} \quad (13)$$

Finally, the SOP in case of AF based NOMA systems is

$$\begin{aligned} SOP^{AF} &= 1 - \frac{\Omega_E e^{-\left(\Omega_0 + \Omega_2\right)B}}{\Omega_0 A + \Omega_2 A + \Omega_E} \\ &+ \frac{\exp\left[-\left(\Omega_0 A + \Omega_2 A + \Omega_E\right)\frac{\xi_1}{\rho_E}\right] \Omega_E e^{-\left(\Omega_0 + \Omega_2\right)B}}{\Omega_0 A + \Omega_2 A + \Omega_E} \end{aligned} \quad (14)$$

IV. SECURE OUTAGE PERFORMANCE ANALYSIS IN OMA

In OMA mode, the received signal at the relay can be written as

$$\begin{aligned} y_{r,i}^{AF-OMA} &= \beta y_r g_{r,i} + w_{r,i} \\ &= \beta h_r s_i \sqrt{P_s} g_{r,i} + \beta g_{r,i} w_r + w_{r,i} \end{aligned} \quad (15)$$

where $w_{r,i}$ is AWGN noise at destination. The amplify factor in AF scheme can be defined as

$$\beta = \sqrt{\frac{1}{\left|h_r\right|^2 + \frac{1}{\rho}}} \quad (16)$$

Then, the SINR to evaluate performance of D1 can be formulated by

$$\gamma_{r,1}^{AF-OMA} = \frac{\rho\rho\left|g_{r,1}\right|^2 \left|h_r\right|^2}{\rho\left|g_{r,1}\right|^2 + \rho\left|h_r\right|^2 + 1} \quad (17)$$

Similarly, the SINR to evaluate performance of D2 can be expressed by

$$\gamma_{r,2}^{AF-OMA} = \frac{\rho\rho\left|g_{r,2}\right|^2 \left|h_r\right|^2}{\rho\left|g_{r,2}\right|^2 + \rho\left|h_r\right|^2 + 1} \quad (18)$$

Next, SINR to address impact of eavesdropper at E is given by

$$\gamma_{E,i}^{AF} = \frac{\rho\rho_E\left|h_r\right|^2 \left|g_{r,E}\right|^2}{\rho_E\left|g_{r,E}\right|^2 + \rho\left|h_r\right|^2 + 1} \quad (19)$$

Then, SOP in OMA mode can be written as

$$\begin{aligned} SOP^{AF-OMA} &= \Pr\left(C_1^{AF-OMA} < R_1 \; or \; C_2^{AF-OMA} < R_2\right) \\ &= 1-\Pr\left(\frac{1+\gamma_{r,1}^{AF-OMA}}{1+\gamma_{E,1}^{AF-OMA}} > C_{th-OMA}^{1}, \frac{1+\gamma_{r,2}^{AF-OMA}}{1+\gamma_{E,2}^{AF-OMA}} > C_{th-OMA}^{2}\right) \\ &= 1-\Pr 2 \end{aligned} \tag{20}$$

Interestingly, in similar way with previous section, it can be following result

$$\begin{aligned} \Pr 2 \approx & \frac{\Omega_E \exp\left(-\left(\Omega_0+\Omega_1\right)N_1\right)}{\left(\left(\Omega_0+\Omega_1\right)M_1+\Omega_E\right)} \\ & \times \frac{\Omega_E \exp\left(-\left(\Omega_0+\Omega_2\right)N_2\right)}{\left(\left(\Omega_0+\Omega_{r,1}\right)M_2+\Omega_E\right)} \end{aligned} \tag{21}$$

In which, we use following denotations $C_{th-OMA}^{1} = 2^{4R_1}$, $C_{th-OMA}^{2} = 2^{4R_2}$, $M_1 = \frac{C_{th-OMA}^{1}\rho_E}{\rho}$, $N_1 = \frac{C_{th-OMA}^{1}-1}{\rho}$, $M_2 = \frac{C_{th-OMA}^{2}\rho_E}{\rho}$, $N_2 = \frac{C_{th-OMA}^{2}-1}{\rho}$.

V. NUMERICAL RESULTS

In this section, the outage performance of the downlink AF-NOMA network under Rayleigh fading channel is evaluated via numerical examples to validate derived formula. Moreover, the fixed power allocation is applied in order to further evaluation in NOMA. Without loss of generality, we assume the distance in each link of two-hop relaying NOMA is normalized to unity. In the following simulations, we set the fixed power allocation factors for NOMA users as. The NOMA result will be compared with OMA counterpart.

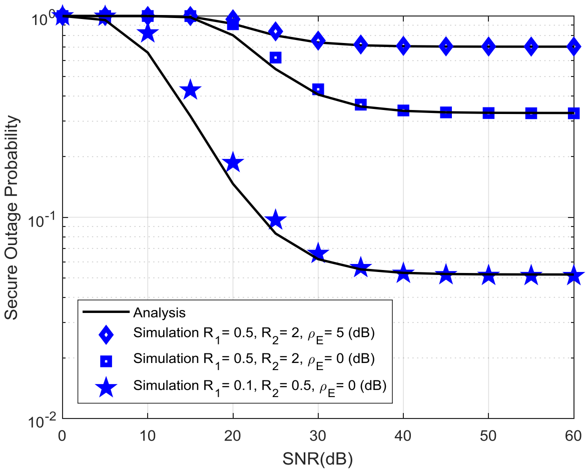

Fig. 2. NOMA mode: Secure outage probability vs. the transmit SNR

Fig. 2 plots the secure outage probability of considered NOMA scheme versus transmit SNR at S for a simulation varying setting of concerned target rates. It can be seen that the exact analytical results and simulation results are matched very well. In particular, it shown that as the system SNR increases, the outage probability decreases. Another important observation is that the secure outage probability remains constant at high SNR regime. Note that the results related to such secure outage performance resulted from fixed power allocation for each user in NOMA.

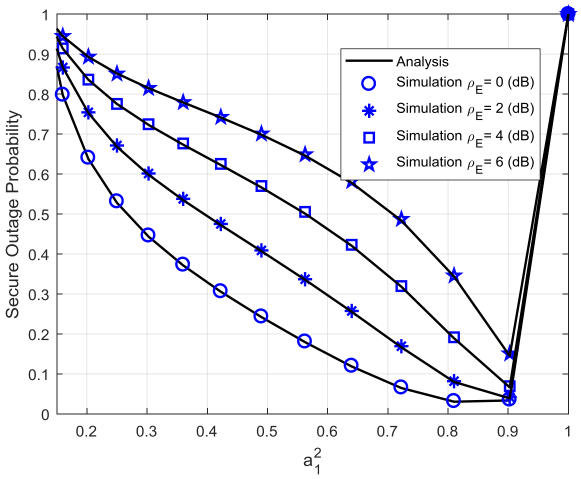

Fig. 3. NOMA mode: Outage probability vs. the transmit SNR with different impacts of eavesdropper

In Fig. 3, the secure outage probability versus power allocation factor of a_1^2 is presented in different impact of parameters related to the eavesdropper. In this case, our parameter is $\{R_1, R_2\} = \{1, 2\}$ bits/s/Hz for target rates. Obviously in this case, the secure outage probability curves match exactly with the Monte Carlo simulation results. It is worth noting that the setting of reasonable power allocation factor to achieve optimal secure performance.

Fig. 4 illustrates secure outage probability versus target rate. It can be observed that the analytical results meet with that in low range of target rate. One can observe that adjusting the target rates of NOMA users will affect the outage behaviors of considered scheme. As the value of target rates increases, the outage performance will becomes worse. This illustration indicates that our derived expressions are tight result for evaluation in related NOMA networks.

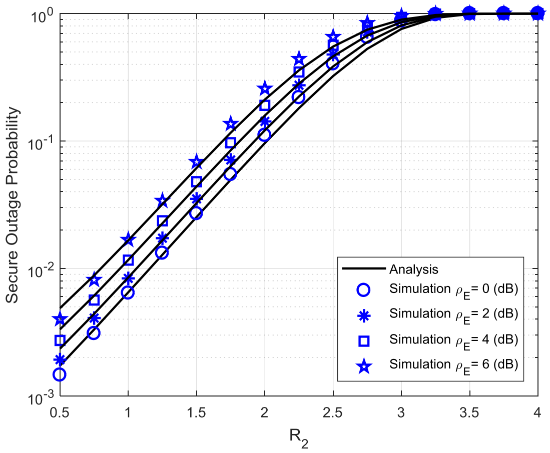

Fig. 4. OMA mode: Secure performance vs. the range of target rates

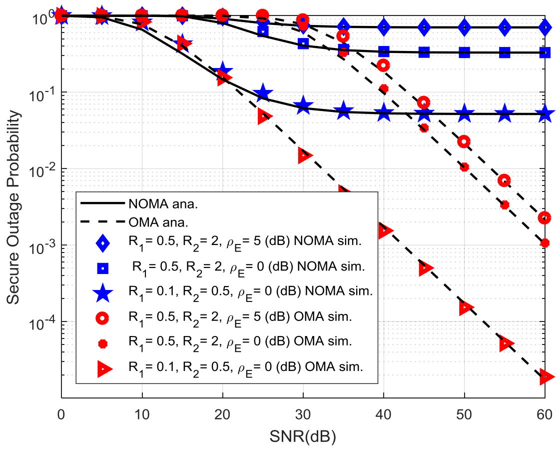

Fig. 5. Comparison on secure outage performance between OMA and NOMA

Fig. 5 plots secure outage performance between OMA and NOMA system versus SNR. Here, we set several case of target rates to show their impacts. Furthermore, the AF-based NOMA scheme is significantly worse than OMA scheme in terms of secure performance. This phenomenon indicates that it is of significance to consider the impact of power allocation for such NOMA scheme when designing practical cooperative NOMA systems.

VI. CONCLUSIONS

This paper studied a novel downlink cooperative communication system that compare NOMA and OMA scenarios in analytical model for secure outage analysis with respect to AF relaying technique. The considered schemes achieve secure outage performance under impacts of related various parameters in these systems. Additionally, influence of the transmit SNR of the source node in both NOMA and OMA on their secure outage probability is achieved via simulation and acceptable power allocation factor can be selected to perform system evaluation. The performance comparison of the suggested schemes was verified by the numerical results. More importantly, reducing impact of eavesdropper on the secure outage probability of both strong and weak users NOMA or OMA in the system to approach reasonable performance requirements.

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