



A Novel Secure Protocol for Mobile Edge Computing Network Applied Downlink NOMA

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Abstract. In this paper, we study a mobile edge computing (MEC) network based on non-orthogonal multiple access (NOMA) scheme, in which a user can offload its tasks to two MEC servers through downlink NOMA. Due to security constraint, the confidential tasks must be computed on the trusted server, the remain tasks can be offloaded to other server if needed. In this scenario, we propose a novel secure protocol, namely APS-NOMA MEC, based on access point selection (APS) scheme to guarantee the security constraint. The exact closed-form expression of successful computation probability for this proposed system protocol is derived. We further study the impact of the network parameters on the system performance to confirm the effectiveness of deployment of NOMA in MEC network. The numerical results show that our proposed protocol outperforms the conventional NOMA MEC scheme in terms of computation efficiency. Finally, the simulation results are also provided to verify the accuracy of our analysis.

Keywords: Mobile edge computing · Non-orthogonal multiple access · Downlink NOMA · Successful computation probability · Trusted server

1 Introduction

Cloud computing has been seen emerging as a new paradigm of computing in the last decade. In the last few years, mobile edge computing (MEC) is a new trend in computing with the function of clouds moving towards the network edges to support the intensive computation needs of the next-generation wireless communication networks (NGWCN). In this MEC network, the edge servers serve as the computational access points to help in accomplishing the computation tasks of users through wireless links [1–6]. Meanwhile, NOMA technique has

been recognized as a strong candidate for NGWCN due to its ability of serving multiple users using the same time and frequency resources, so that it can improve network capacity [7–11]. Naturally, the application of NOMA technique in MEC is considered in a few of works to improve the performance of MEC networks [12–15]. In [12], a NOMA MEC network, in which two users may partially offload their respective tasks to a single MEC server through uplink NOMA, was studied. The offloading scheme in three different modes, namely the partial computation offloading, the complete local computation, and the complete offloading was proposed for this considered model. The optimal solutions for an optimization problem to maximize the successful computation probability were obtained by jointly optimizing the parameters of the proposed scheme. In [13], a computation efficiency maximization framework was proposed for wireless-powered MEC networks based on uplink NOMA according to both partial and binary computation offloading modes. Two algorithms, namely iterative algorithm and alternative optimization algorithm, were proposed to solve the computation efficiency non-convex problem. The authors in [14] proposed the efficient algorithms to solve the weighted sum-energy minimization problems under both cases with partial and binary offloading for multi-antenna NOMA multiuser MEC system. The work of [15] studied NOMA MEC networks for both uplink and downlink transmissions. The studied results have shown that the use of NOMA can efficiently reduce the latency and energy consumption of MEC offloading compared to their conventional orthogonal multiple access (OMA) counterparts.

Motivate by the work of [15], in this work we consider the scenario that the security requirement of MEC network is deployed based on trusted server. The confidential tasks must be computed on the trusted server, the remain tasks can be offloaded to other server if needed by using downlink NOMA scheme. The main contributions of our paper are as follows.

- A novel secure APS-NOMA MEC scheme for mobile edge computing system applied downlink NOMA network based on trusted server is proposed.
- We derive the exact closed-form expression of successful computation probability for this scheme.
- Numerical results are provided to investigate the impact of the network parameters, i.e., transmit power, power allocation ratio, on the system performance to verify the effectiveness of deployment of NOMA in MEC network.
- Simulation results show that our proposed protocol can achieve better successful computation probability compared with other NOMA scheme.

The rest of this paper is organized as follows. Section 2 presents the system model. The performance of this considered system is analyzed in Sect. 3. The numerical results and discussion are shown in Sect. 4. Finally, we conclude our work in Sect. 5.

Notation: g_i denotes the channel power gain of link $S - AP_i$ ($i = \{1, 2\}$), $g_i \sim \mathcal{CN}(0, N)$. B denotes the channel bandwidth. P_s stands for the transmit power of S . $\gamma_s = \frac{P_s}{N}$ is the average transmit signal-to-noise ratio (SNR).

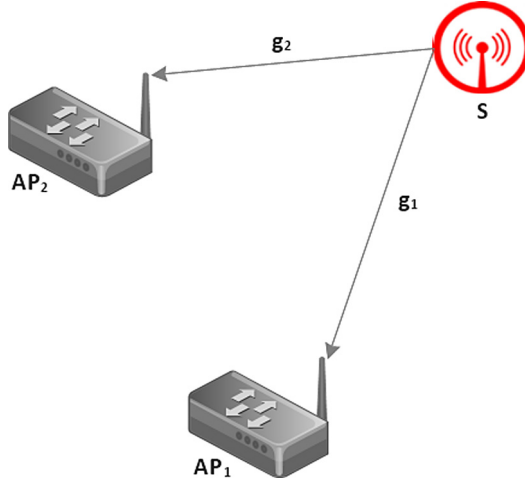


Fig. 1. System model for downlink NOMA MEC network

2 System Model

The Fig. 1 depicts the system model for a secure downlink NOMA mobile edge computing network, in which a single user partially offloads its tasks to two (trusted and untrusted) MEC access points (APs) through downlink NOMA. Without loss of generality, we denote user, trusted AP and untrusted AP as S , AP_1 and AP_2 , respectively. They are assumed to have a single antenna and operate in the half duplex mode. Assuming that S has a L -bit task with L_1 confidential bits ($L_1 < L$) to be executed and it may not be able to execute its tasks locally within the latency budget due to the limited computational ability. Therefore, S needs the help from APs through wireless links subject to quasi-static Rayleigh fading. However, due to security constraint the trusted server (AP_1) must be prioritized for selecting to compute the tasks of user, meanwhile, the untrusted server (AP_2) is only used to guarantee the performance of this considered system if needed. We assume that the task-input bits are bit-wise independent and can be arbitrarily divided into different groups [12]. Therefore, L -bit task can be divided into a confidential L_1 -bit task (Task 1) and a non-confidential L_2 -bit task (Task 2).

We propose a new secure protocol, called APS-NOMA MEC scheme, for MEC network as follows.

- In the first phase, the user S estimates the channel parameters at the beginning of each transmission in duration τ_0 .

- In the second phase, according to the channel state information (CSI), S assigns the servers and offloads its tasks to the corresponding APs during duration τ_1 according to APS Algorithm 1. Notice that, in APS Algorithm 1, Task 1 is confidential task with L_1 bits, Task 2 is non-confidential task with L_2 bits and $L_1 + L_2 = L$.

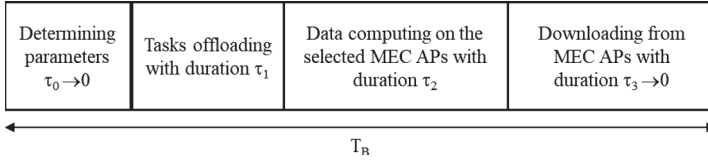


Fig. 2. Time flow chart for APS protocol

- In the third phase, data is executed on the selected MEC *APs* in duration τ_2 .
- Finally, in the fourth phase *S* downloads the results from *APs* during duration τ_3 .

The time flow chart for APS protocol is as Fig. 2, in which τ_0 and τ_3 are assumed very small and thus are neglected [12], and T_B denotes the transmission block time.

Algorithm 1. Access Point Selection (APS) Algorithm

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1: procedure SELECTION( $AP_1, AP_2$ )
2:   if  $g_1 > g_2$  then  $AP_1$  selected
3:   offload L-bit task to  $AP_1$ 
4:   goto 9
5:   else divide L-bit task into L1-bit task (Task 1) and L2-bit task (Task 2)
6:   applying NOMA, S offloads Task 1 to  $AP_1$  and Task 2 to  $AP_2$ 
7:   goto 9
8:   end if
9:   download results from corresponding APs

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The i.i.d. quasi-static Rayleigh channel gains $g_i, i \in \{1, 2\}$, follows exponential distributions with parameters λ_i . Therefore, the cumulative density function (CDF) and probability density function (PDF) of $g_i (i = 1, 2)$ are respectively given by

$$F_{g_i}(x) = 1 - e^{-\frac{x}{\lambda_i}}, \tag{1}$$

$$f_{g_i}(x) = \frac{1}{\lambda_i} e^{-\frac{x}{\lambda_i}}. \tag{2}$$

3 Performance Analysis

In order to characterize the performance of a MEC system, the successful computation probability, called Pr_s , is used as an important performance metric [12]. It is defined as the probability that all tasks are successfully executed within a given time $T > 0$, which is expressed as

$$Pr_s = \Pr(\tau_1 + \tau_2 \leq T) = \Pr(\tau \leq T), \tag{3}$$

where τ_1 and τ_2 are the transmission latency and computation latency, respectively; $\tau = \tau_1 + \tau_2$. The execution time τ is calculated as follows.

$$\tau = \begin{cases} \frac{L}{B \log(1 + \gamma_s g_1)} + \frac{\rho L}{f_1}, & g_1 > g_2 \\ \max \left\{ t_1 + \frac{\rho L_1}{f_1}, t_2 + \frac{\rho L_2}{f_2} \right\}, & g_1 < g_2 \end{cases} \quad (4)$$

where $t_1 = \frac{L_1}{B \log \left[1 + \frac{a \gamma_s g_1}{(1-a) \gamma_s g_1 + 1} \right]}$ is the transmission latency from S to AP_1 , $t_2 = \frac{L_2}{B \log [1 + (1-a) \gamma_s g_2]}$ is the transmission latency from S to AP_2 , a ($0 < a < 1$) is the power allocation ratio when applying NOMA scheme, ρ denotes the number of required CPU cycles for each bit, and f_i stands for the CPU-cycle frequency at the AP_i , $i = \{1, 2\}$.

Therefore, according to APS Algorithm 1, the successful computation probability can be rewritten as

$$\begin{aligned} Pr_s = & \Pr \left(g_1 > g_2, \frac{L}{B \log(1 + \gamma_s g_1)} + \frac{\rho L}{f_1} \leq T \right) \\ & + \Pr \left(g_1 < g_2, \max \left\{ t_1 + \frac{\rho L_1}{f_1}, t_2 + \frac{\rho L_2}{f_2} \right\} \leq T \right). \end{aligned} \quad (5)$$

In order to evaluate the performance of this considered NOMA MEC system, we obtain the following theorems.

Theorem 1.

Under quasi-static Rayleigh fading, the exact closed-form expression of the successful computation probability Pr_s for this considered downlink NOMA MEC system based on proposed APS-NOMA MEC scheme is given by

$$Pr_s = \begin{cases} e^{-\frac{\beta}{\lambda_1}} \left[1 - e^{-\frac{\beta}{\lambda_2}} \right] + e^{-\frac{\beta_1}{\lambda_1} - \frac{\beta^*}{\lambda_2}} + \\ \quad \frac{\lambda_1}{\lambda_1 + \lambda_2} \left[e^{-\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right)\beta} - e^{-\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right)\beta^*} \right], & a > \frac{\Phi}{1-\Phi} \\ e^{-\frac{\beta}{\lambda_1}} \left[1 - e^{-\frac{\beta}{\lambda_2}} \right] + \frac{\lambda_1}{\lambda_1 + \lambda_2} e^{-\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right)\beta}, & a < \frac{\Phi}{1-\Phi} \end{cases} \quad (6)$$

where $\beta = \frac{2^{\frac{L}{B}} - 1}{\gamma_s}$, $\beta_1 = \frac{\Phi}{\gamma_s [a - (1-a)\Phi]}$, $\beta^* = \max \{\beta_1, \beta_2\}$, $\beta_2 = \frac{2^{\frac{L_2}{B}} - 1}{(1-a)\gamma_s}$, $\Phi = 2^{\frac{L_1}{B}} - 1$, $\Omega = T - \frac{\rho L}{f_1}$, $\Omega_1 = T - \frac{\rho L_1}{f_1}$, $\Omega_2 = T - \frac{\rho L_2}{f_2}$.

Proof. See Appendix A.

In the work [15], the application of downlink NOMA transmission to MEC was investigated. In this scenario, the user S always offloads Task 1 to AP_1 and Task 2 to AP_2 by using NOMA scheme. In order to verify the effectiveness of this proposed protocol, we derive the exact closed-form expression for successful computation probability of conventional downlink NOMA MEC system similar to [15] as following theorem.

Theorem 2.

Under quasi-static Rayleigh fading, the exact closed-form expression of the successful computation probability $Pr_s^{(ref)}$ for the conventional downlink NOMA MEC system is expressed as

$$Pr_s^{(ref)} = \begin{cases} e^{-\left(\frac{\beta_1}{\lambda_1} + \frac{\beta_2}{\lambda_2}\right)}, & a > \frac{\Phi}{1-\Phi} \\ 0, & a < \frac{\Phi}{1-\Phi} \end{cases} \quad (7)$$

where $\beta_1 = \frac{\Phi}{\gamma_s[a-(1-a)\Phi]}$, $\beta_2 = \frac{2^{\frac{L_2}{\Omega_2 B}} - 1}{(1-a)\gamma_s}$, $\Phi = 2^{\frac{L_1}{\Omega_1 B}} - 1$, $\Omega_1 = T - \frac{\rho L_1}{f_1}$, $\Omega_2 = T - \frac{\rho L_2}{f_2}$.

Proof. See Appendix B.

4 Numerical Results and Discussion

In this section, we provide the numerical results in terms of successful computation probability Pr_s to reveal the impact of key system parameters to system performance. The simulation parameters used in this work are provided in Table 1.

Table 1. Simulation parameters

| Parameters | Notation | Typical values |
|---------------------------------------|----------|----------------|
| Environment | | Rayleigh |
| Number of antennas of each device | N | 1 |
| Transmit power | P_s | 0–30 dB |
| CPU-cycle frequency of AP_1 | f_1 | 5 GHz |
| CPU-cycle frequency of AP_2 | f_2 | 10 GHz |
| The number of CPU cycles for each bit | ρ | 10 |
| Channel bandwidth | B | 100 MHz |
| The threshold of latency | T | 0.5 s |
| The number of data bits | L | 80 Mbits |

4.1 Impact of Average Transmit SNR and the Length of Task 1

In order to study the impact of the length of confidential task to the performance, we let $L_1 = \epsilon L$, $L_2 = (1 - \epsilon)L$, where ϵ is denoted as data allocation coefficient, $0 \leq \epsilon \leq 1$. We set the power allocation ratio as $a = 0.75$ for our simulation. The impact of average transmit SNR (γ_s) and the length of Task

1 (L_1) on system performance in terms of successful computation probability Pr_s is shown in Fig. 3 and Fig. 4. We can observe from these figures that Pr_s increases when γ_s increases. In other words, the performance can improve by increasing the transmit power of user. Meanwhile, the impact of the length L_1 on the performance is quite different, i.e., the variation of L_1 does not affect to the performance much. However, there exists an optimal value of L_1^* corresponding to ϵ^* that Pr_s achieves a maximum value.

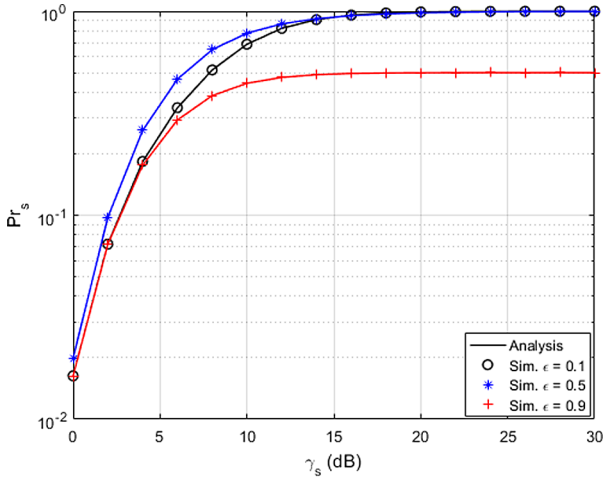


Fig. 3. Pr_s vs. average transmit SNR γ_s with different ϵ .

4.2 Impact of Transmit Power Allocation Ratio and the Length of Task 1

The impact of transmit power allocation ratio (a) and data allocation coefficient (ϵ) on system performance in terms of successful computation probability Pr_s is shown in Fig. 5 and Fig. 6. For a given value of ϵ , Pr_s increases when $a > \frac{\phi}{1-\phi}$ and it does not change when $a \leq \frac{\phi}{1-\phi}$. It means that in order to improve the performance of this considered system we can allocate the more transmit power the better. However, when a moves closer to 1, the performance degrades. Therefore, there exists an optimal value of a^* that Pr_s achieves a maximum value. Figure 7 and Fig. 8 also depict this conclusion.

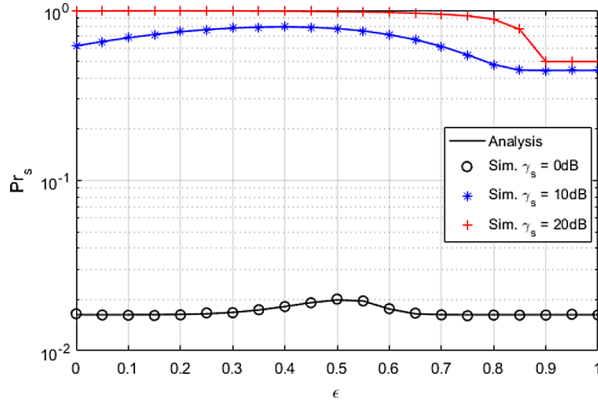


Fig. 4. Pr_s vs. data allocation coefficient ϵ with different γ_s .

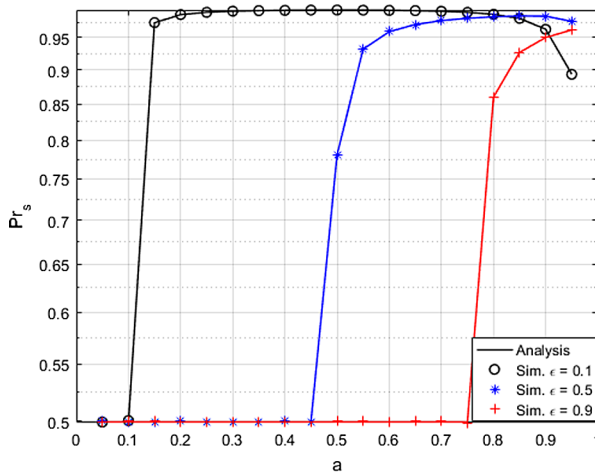


Fig. 5. Pr_s vs. power allocation ratio a with different ϵ .

4.3 Comparison to Conventional NOMA Scheme

Figure 9 and Fig. 10 depict the comparison results between APS-NOMA scheme and conventional NOMA scheme in terms of Pr_s vs. γ_s with different ϵ and with different a . We can see from these figures that our proposed protocol outperforms the conventional NOMA scheme in terms of successful computation probability.

Finally, from above Figs. 3, 4, 5, 6, 7 and 8 we can see that the superior match between analytical and simulation results. This verifies the correctness of our analysis.

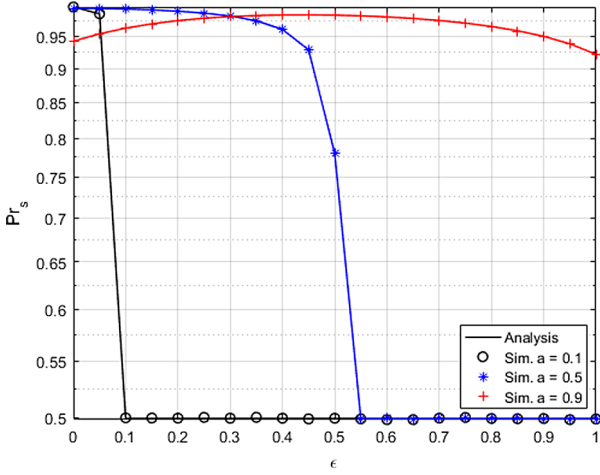


Fig. 6. P_{r_s} vs. data allocation coefficient ϵ with different a .

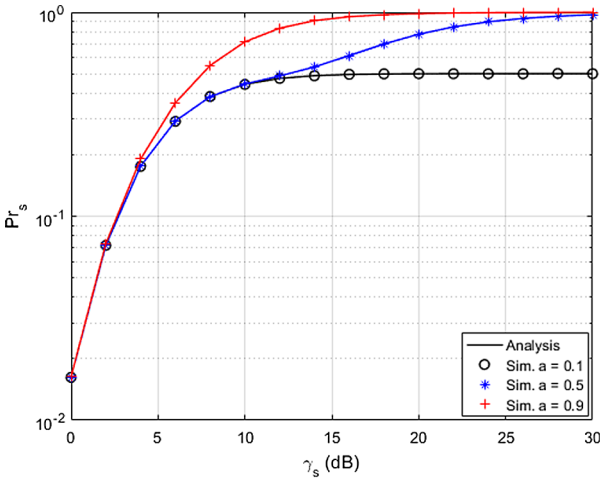


Fig. 7. P_{r_s} vs. γ_s with different a .

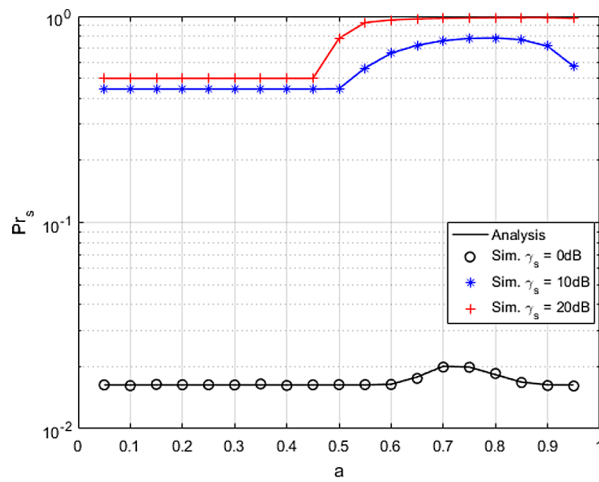


Fig. 8. P_{r_s} vs. power allocation ratio a with different γ_s .

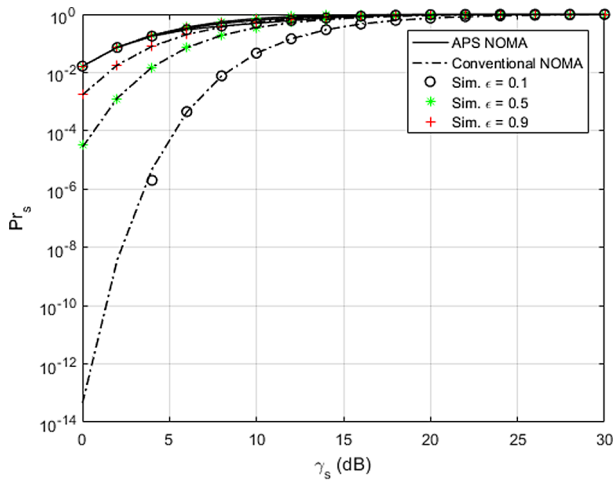


Fig. 9. The comparison between APS-NOMA scheme and conventional NOMA scheme in terms of P_{r_s} vs. γ_s with different ϵ .

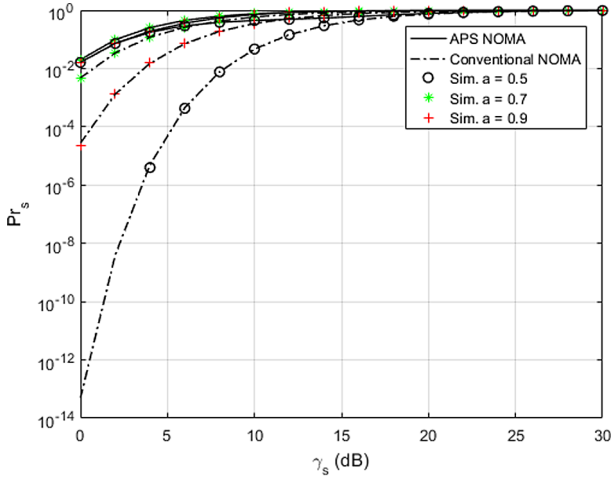


Fig. 10. The comparison between APS-NOMA scheme and conventional NOMA scheme in terms of Pr_s vs. γ_s with different a .

5 Conclusion

In this paper, we have proposed a new offloading APS-NOMA MEC scheme for a secure NOMA MEC network. We have also derived the exact closed-form expressions of successful computation probability for this proposed system. The numerical results have been provided to reveal that our proposed scheme achieves better performance than conventional NOMA scheme. Moreover, the performance of this system can be improved by increasing the transmit power and/or by select the optimal value of power allocation ratio.

APPENDIX A: PROOF OF THEOREM 1

Here, from (5) we derive the closed-form expression of Pr_s as follows.

$$\begin{aligned}
 P_s &= \Pr \left(g_1 > g_2, g_1 > \frac{2^{\frac{L}{\alpha B}} - 1}{\gamma_s} \right) \\
 &+ \Pr \left(g_1 < g_2, \left[1 - \frac{(1-a)(2^{\frac{L_1}{\alpha_1 B}} - 1)}{a} \right] g_1 > \frac{2^{\frac{L_1}{\alpha_1 B}} - 1}{a\gamma_s}, g_2 > \frac{2^{\frac{L_2}{\alpha_2 B}} - 1}{(1-a)\gamma_s} \right) \\
 &= \begin{cases} \underbrace{\Pr(g_1 > g_2, g_1 > \beta)}_{I_1} + \underbrace{\Pr(g_1 < g_2, g_1 > \beta_1, g_2 > \beta_2)}_{I_2}, & a > \frac{\phi}{1-\phi} \\ \underbrace{\Pr(g_1 > g_2, g_1 > \beta)}_{I_1}, & a < \frac{\phi}{1-\phi} \end{cases} \quad (\text{A-1})
 \end{aligned}$$

where $\beta = \frac{2^{\frac{L}{\Omega_2 B}} - 1}{\gamma_s}$, $\Omega = T - \frac{\rho L}{f_1}$, $\beta_1 = \frac{\Phi}{\gamma_s [a - (1-a)\Phi]}$, $\Phi = 2^{\frac{L_1}{\Omega_1 B}} - 1$, $\beta_2 = \frac{2^{\frac{L_2}{\Omega_2 B}} - 1}{(1-a)\gamma_s}$, $\Omega_1 = T - \frac{\rho L_1}{f_1}$, $\Omega_2 = T - \frac{\rho L_2}{f_2}$,

$$\begin{aligned} I_1 &= [1 - F_{g_1}(\beta)] F_{g_2}(\beta) + \int_{\beta}^{\infty} [1 - F_{g_1}(y)] f_{g_2}(y) dy \\ &= [1 - F_{g_1}(\beta)] F_{g_2}(\beta) + \frac{1}{\lambda_2} \int_{\beta}^{\infty} e^{-\frac{y}{\lambda_1} - \frac{y}{\lambda_2}} dy \\ &= [1 - F_{g_1}(\beta)] F_{g_2}(\beta) + \frac{\lambda_1}{\lambda_1 + \lambda_2} e^{-\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right)\beta}. \end{aligned} \quad (\text{A-2})$$

$$\begin{aligned} I_2 &= [1 - F_{g_1}(\beta_1)] [1 - F_{g_2}(\beta^*)] - \int_{\beta^*}^{\infty} [1 - F_{g_1}(y)] f_{g_2}(y) dy \\ &= [1 - F_{g_1}(\beta_1)] [1 - F_{g_2}(\beta^*)] - \frac{\lambda_1}{\lambda_1 + \lambda_2} e^{-\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right)\beta^*}, \end{aligned} \quad (\text{A-3})$$

where $\beta^* = \max\{\beta_1, \beta_2\}$.

From (1), (A-2), (A-3) and (A-1), we obtain the result as (6). This concludes our proof.

APPENDIX B: PROOF OF THEOREM 2

Here, we derive the closed-form expression of $Pr_s^{(ref)}$ as follows.

$$\begin{aligned} Pr_s^{(ref)} &= \Pr\left(t_1 + \frac{\rho L_1}{f_1} < T, t_2 + \frac{\rho L_2}{f_2} < T\right) \\ &= \Pr\left(\left[1 - \frac{(1-a)(2^{\frac{L_1}{\Omega_1 B}} - 1)}{a}\right] g_1 > \frac{2^{\frac{L_1}{\Omega_1 B}} - 1}{a\gamma_s}, g_2 > \frac{2^{\frac{L_2}{\Omega_2 B}} - 1}{(1-a)\gamma_s}\right) \\ &= \begin{cases} [1 - F_{g_1}(\beta_1)] [1 - F_{g_2}(\beta_2)], & a > \frac{\Phi}{1-\Phi} \\ 0, & a < \frac{\Phi}{1-\Phi} \end{cases} \\ &= \begin{cases} e^{-\left(\frac{\beta_1}{\lambda_1} + \frac{\beta_2}{\lambda_2}\right)}, & a > \frac{\Phi}{1-\Phi} \\ 0, & a < \frac{\Phi}{1-\Phi} \end{cases} \end{aligned} \quad (\text{B-1})$$

This concludes our proof.

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