Secure transmission for uplink and downlink non-orthogonal multiple access system with imperfect channel state information

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ABSTRACT

In this paper, we design a secure transmission scheme in uplink and downlink of non-orthogonal multiple access (NOMA) system. In this scenario, two pairs of base station-user can operate under the presence of eavesdropper. The relay plays an important role to forward signals from group of base stations to serve distant users. However, the eavesdropper can overhear signal which leads to secure performance need be re-considered. To provide secure performance, we derive the closed-form expressions for strictly positive secrecy capacity (SPSC). In addition, we rely on relay for enlarge coverage area. The channel conditions meet imperfect channel state information (CSI) which shows degraded secure performance. Results confirm the relationship between transmit power at the source and and SPSC how many main parameters affecting secure performance metric. Furthermore, simulation results show that the uplink and downlink NOMA technique improves secure performance in the low SPSC region. We further conduct analysis by using Monte-Carlo simulations.

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1. INTRODUCTION

The massive evolution in wireless devices and information transfer in wireless communications has increased the requirement for massive connectivity and spectrum availability in wireless networks such as 5G communications [1]-[3]. Deployment of heterogenous networks (HetNet) has become the primary feature to increase the spectrum usage and allocate more users to the spectrum [4]-[6]. To deliver increased-data-rate services, in HetNet, numerous affordable low-power small base stations (SBSs) are installed [7]. The main work of SBSs is to get rid of data traffic from micro-base-stations (MBSs), thereby, solving the high traffic issue and increasing the spectral efficiency of the communicating networks. Furthermore, the SBSs also work similarly to relays to increase the data transmission in the networks between the users [8],[9]. To tackle these issues, the HetNets were introduced to work with device-to-device (D2D), non-orthogonal multiple access (NOMA) communications [10]-[13]. With the utilization of D2D communications, the data traffic can be reduced since there is no need of any base station (BS) involvement, thereby, establishing the direct connection between the devices. Meanwhile, these devices can also work as D2D relay nodes (DRN) to enhance the communication for the faded users [14], [15]. It is also found that the D2D communications are easier to be installed and also utilizes less infrastructure. Since the D2D applications of reducing data traffic is interesting, studies have been performed to understand these applications more deeply in [16], [17]. In [16], the data contents are saved by the cached users and shared among the other devices, whereas, in [17], NOMA is deployed to improve network connectivity and capacity, and D2D exhibits spectrum efficiency. In [18]-[20], deployment of uplink and downlink of NOMA is studied to prove its advantage compared with orthogonal multiple access (OMA) techniques.

Recently, physical layer security (PLS) techniques can eliminate difficulties of secure guarantee at upper layer. Such PLS can combine in current NOMA systems. In [21], a PLS uplink NOMA system was studied to allow one base station to serve many destinations in the presence of one eavesdropper. To get benefits from NOMA, uplink transmission of two users are processed opportunistically. In this system, idle users is used to operate as a friendly jammer which relies on artificial noise to reduce or refuse services to the eavesdropper. However, lack of works considered uplink downlink NOMA, which motivates us to examine secure performance of two pairs of base stations and destinations.

2. SYSTEM MODEL

In Figure 1, we consider uplink and downlink to allow two base stations BS_1, BS_2 serving two destinations via a relay R. The wireless channels are assumed to follow flat slow Rayleigh fading. We denote links $BS_1 \to R$, $BS_2 \to R$, $R \to D_1$, $R \to D_2$ and $R \to E$ correspond to channels h_1, h_2, h_3, h_4 and h_e, respectively. Accordingly, the corresponding channel power gains follow the distributions as $|h_1|^2 \sim CN(0,\varpi_1)$, $|h_2|^2 \sim CN(0,\varpi_2)$, $|h_3|^2 \sim CN(0,\varpi_3)$, $|h_4|^2 \sim CN(0,\varpi_4)$ and $|h_e|^2 \sim CN(0,\varpi_e)$, respectively. q_1, q_2 are signals proceeded from two corresponding base stations with respect to decoding at destinations.

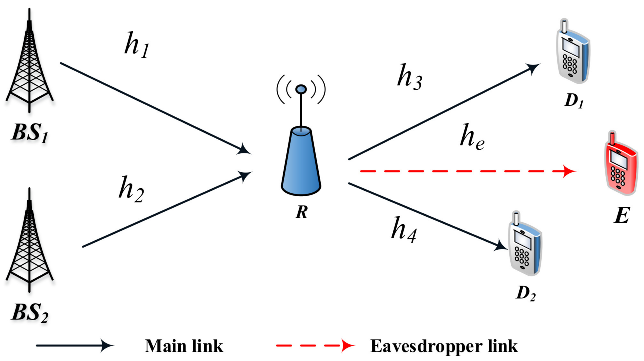

Figure 1. System model

Before computing received signals at destinations and the intermediate device, we denote P_{bsi} as the transmit power at base stations $BS_i, i = 1, 2$. It is noted that interference following the additive white Gaussian noise (AWGN) at R, namely ε_R corresponding its distribution $\varepsilon_R \sim CN(0, N_0)$. The base stations want to get signals q_i for each destination D_i. By conducting NOMA scheme, power allocation factors assigned to users, namely δ_i which satisfies two conditions $\delta_1 + \delta_2 = 1$ and $\delta_1 > \delta_2$ (based on how far user connects to relay, the far user needs higher power factor). The intermediate device first receives signals from the two base stations, hence we can formulate such received signal [22].

$$y_{S\to R} = \left(h_1 + \widehat{h}_1\right)\sqrt{\delta_1 P_{bs1}}q_1 + \left(h_2 + \widehat{h}_2\right)\sqrt{\delta_2 P_{bs2}}q_2 + \varepsilon_R \quad (1)$$

Where $\widehat{h}_i$ stands for error term which is considered as a complex Gaussian distributed random variable with $CN\left(0, \wp_{ui}^2\right)$. We adopt the case of $\wp_{ui}^2$ as constant [23].

Since the received signal-to-interference-plus-noise ratio (SINR) needs to be computed to detect separated signal at the intermediate device, we set order of signal detection based on channel gains. That means two signals q_1, q_2 can be detected following the way that treating q_2 as noise to detect q_1 and a successive interference cancellation (SIC) is adopted to detect signal q_2. Particularly, we have SINRs:

$$\gamma_{q_1}^{u} = \frac{\delta_1 \rho_{bs1} |h_1|^2}{\delta_2 \rho_{bs2} |h_2|^2 + \delta_1 \rho_{bs1} \wp_{u1}^2 + \delta_2 \rho_{bs2} \wp_{u2}^2 + 1}, \gamma_{q_2}^{u} = \frac{\delta_2 \rho_{bs2} |h_2|^2}{\delta_1 \rho_{bs1} \wp_{u1}^2 + \delta_2 \rho_{bs2} \wp_{u2}^2 + 1} \quad (2)$$

Where:
$\rho_{bs1} = \frac{P_{bs1}}{N_0}$
$\rho_{bs2} = \frac{P_{bs2}}{N_0}$

At the second hop, signal can be forwarded by the intermediate device to corresponding destinations. Specifically, the relay first transmits a superimposed composite signal, regenerated from q_i, to D_i. We characterize the AWGN term, namely ε_x at user D_i as $\varepsilon_x \sim CN(0, N_0)$. The destination D_i can achieve the received signal [24], [25].

$$y_{R \to D_i} = \left(h_x + \widehat{h}_x\right)\left(\sqrt{\delta_1 P_R} q_1 + \sqrt{\delta_2 P_R} q_2\right) + \varepsilon_x, (x = 3, 4) \quad (3)$$

Where P_R denote the transmit power at R, $\widehat{h}_x$ is the error term, which is typically modeled as a complex Gaussian distributed random variable with $CN\left(0, \wp_{di}^2\right)$.

After receiving signal from R, by considering the noise term is signal q_2 for user D_2 , D_1 can detect its signal q_1 by computing SINR as:

$$\gamma_{q_1}^{d} = \frac{\delta_1 \rho_R |h_3|^2}{\delta_2 \rho_R |h_3|^2 + \rho_R \wp_{d1}^2 + 1} \quad (4)$$

Where $\rho_R = \frac{P_R}{N_0}$.

Simultaneously, D_2 have similar signal detection to achieve noise term q_1 and then its own signal q_2. This is just possible with help of SIC. The expressions of SINR to detect signal q_1 and q_2 at D_2 are formulated respectively as:

$$\gamma_{1 \to 2}^{d} = \frac{\delta_1 \rho_R |h_4|^2}{\delta_2 \rho_R |h_4|^2 + \rho_R \wp_{d2}^2 + 1}, \gamma_{q_2}^{d} = \frac{\delta_2 \rho_R |h_4|^2}{\rho_R \wp_{d2}^2 + 1} \quad (5)$$

We deal with threat situation when the main signal is likely stolen by illegal user. Also, the received signal at eavesdropper could be considered with assumption it can obtain parameter of channel. The eavesdropper E wants to overhear signal transmitted from the intermediate device R and the received signal is:

$$y_E = h_e\left(\sqrt{\delta_1 P_R} q_1 + \sqrt{\delta_2 P_R} q_2\right) + n_e \quad (6)$$

In next step, we compute SINR as the second thing that is necessary to consider secure performance. We leverage the parallel interference cancellation (PIC) to detect signal for eavesdropper. More importantly, the eavesdropper possesses the received SINR to detect D_i's and the related received signal is expressed by Zhang *et al.* [24].

$$\gamma_{q_i}^{e} = a_i \rho_e |h_e|^2 \quad (7)$$

Where $\rho_e = \frac{P_R}{n_e}$.

Before evaluating secure performance, secrecy rate of each user must be computed. Then, we evaluate the relationship of secrecy rates between intended user and eavesdropper. Following above steps, the achievable secrecy rates can be computed for pairs of users $BS_1 - D_1$, $BS_2 - D_2$ respectively [25].

$$\Psi_1 = \frac{1}{2}\left[\log_2 \min\left(\frac{1 + \gamma_{q_1}^{u}}{1 + \gamma_{q_1}^{e}}, \frac{1 + \gamma_{q_1}^{d}}{1 + \gamma_{q_1}^{e}}\right)\right]^{+} \quad (8)$$

and

$$\Psi_2 = \frac{1}{2}\left[\log_2 \min\left(\frac{1 + \gamma_{q_2}^{u}}{1 + \gamma_{q_2}^{e}}, \frac{1 + \gamma_{1 \to 2}^{d}}{1 + \gamma_{q_2}^{e}}, \frac{1 + \gamma_{q_2}^{d}}{1 + \gamma_{q_2}^{e}}\right)\right]^{+} \quad (9)$$

In which $[x]^{+} = \max\{0, x\}$.

3. STRICTLY POSITIVE SECRECY CAPACITY (SPSC) ANALYSIS

3.1. SPSC for $BS_1 - D_1$

We examine SPSC performance to highlight secrecy performance. We compute such performance to exhibit the probability of existence of secrecy capacity [24], [26]. Thus, the SPSC for the base station - D_1 can be given by:

$$\begin{aligned} & SPSC_{D_1}^{BS_1} = \Pr\left(\Psi_1 > 0\right) \\ & = \underbrace{\Pr\left(\gamma_{q_1}^{u} \geq \gamma_{q_1}^{e}\right)}_{\partial_1} \underbrace{\Pr\left(\gamma_{q_1}^{d} \geq \gamma_{q_1}^{e}\right)}_{\partial_2} \end{aligned} \tag{10}$$

Proposition 1. The exact expression of the SPSC $BS_1 - D_1$ is:

$$SPSC_{D_1}^{BS_1} = -\frac{\eta_3 \beta_3}{\varpi_e} \exp\left(\beta_3 \beta_4\right) \mathrm{Ei}\left(-\beta_3 \beta_4\right) \tag{11}$$

Where:
$\Theta_1 = \delta_1 \rho_{bs1} \wp_{u1}^2 + \delta_2 \rho_{bs2} \wp_{u2}^2 + 1$
$\Theta_2 = \rho_R \wp_{d1}^2 + 1$
$\beta_3 = \frac{\rho_{bs1} \varpi_1}{\delta_2 \rho_{bs2} \rho_e \varpi_2 \varpi_e}$
$\beta_4 = \frac{\Theta_1 \rho_e}{\rho_{bs1} \varpi_1} + \frac{1}{\varpi_e}$

$\eta_3 = \int_0^\infty \exp\left(-\frac{\Theta_2 \delta_1 \rho_e x}{(1-\delta_2 \rho_e x)\delta_1 \rho_R \varpi_3} - \frac{x}{\varpi_e}\right) dx$
Proof: from (10), ∂_1 can:

$$\begin{aligned} & \partial_1 = \Pr\left(\gamma_{q_1}^{u} \geq \gamma_{q_1}^{e}\right) \\ & = \Pr\left(|h_1|^2 \geq \frac{\delta_1 \delta_2 \rho_{bs2} \rho_e |h_e|^2 |h_2|^2 + \Theta_1 \delta_1 \rho_e |h_e|^2}{\delta_1 \rho_{bs1}}\right) \\ & = \int_0^\infty \int_0^\infty \left(1 - F_{|h_1|^2}\left(\frac{\delta_1 \delta_2 \rho_{bs2} \rho_e x y + \Theta_1 \delta_1 \rho_e y}{\delta_1 \rho_{bs1}}\right)\right) f_{|h_2|^2}\left(x\right) f_{|h_e|^2}\left(y\right) dx dy \\ & = \frac{1}{\varpi_2} \frac{1}{\varpi_e} \int_0^\infty \int_0^\infty \exp\left(-\left(\frac{\delta_1 \delta_2 \rho_{bs2} \rho_e y}{\delta_1 \rho_{bs1} \varpi_1} + \frac{1}{\varpi_2}\right) x\right) \exp\left(-\left(\frac{\Theta_1 \delta_1 \rho_e}{\delta_1 \rho_{bs1} \varpi_1} + \frac{1}{\varpi_e}\right) y\right) dx dy \\ & = \frac{1}{\varpi_e} \int_0^\infty \frac{\delta_1 \rho_{bs1} \varpi_1}{\delta_1 \delta_2 \rho_{bs2} \rho_e \varpi_2 y + \delta_1 \rho_{bs1} \varpi_1} \exp\left(-\left(\frac{\Theta_1 \delta_1 \rho_e}{\delta_1 \rho_{bs1} \varpi_1} + \frac{1}{\varpi_e}\right) y\right) dx dy \end{aligned} \tag{12}$$

Based on [27] Eq. (3.352.4) and applying some polynomial expansion manipulations, ∂_1 can given by:

$$\partial_1 = -\beta_3 \exp\left(\beta_3 \beta_4\right) \mathrm{Ei}\left(-\beta_3 \beta_4\right) \tag{13}$$

Where:
$\beta_3 = \frac{\rho_{bs1} \varpi_1}{\delta_2 \rho_{bs2} \rho_e \varpi_2 \varpi_e}$
$\beta_4 = \frac{\Theta_1 \rho_e}{\rho_{bs1} \varpi_1} + \frac{1}{\varpi_e}$
From (10), ∂_2 can be calculated as:

$$\begin{aligned} & \partial_2 = \Pr\left(\gamma_{q_1}^{d} \geq \gamma_{q_1}^{e}\right) \\ & = \Pr\left(|h_3|^2 \geq \frac{\Theta_2 \delta_1 \rho_e |h_e|^2}{\left(1 - \delta_2 \rho_e |h_e|^2\right) \delta_1 \rho_R}\right) \\ & = \int_0^\infty \left(1 - F_{|h_3|^2}\left(\frac{\Theta_2 \delta_1 \rho_e x}{(1-\delta_2 \rho_e x)\delta_1 \rho_R}\right)\right) f_{|h_e|^2}\left(x\right) dx \\ & = \frac{1}{\varpi_e} \int_0^\infty \exp\left(-\frac{\Theta_2 \delta_1 \rho_e x}{(1-\delta_2 \rho_e x)\delta_1 \rho_R \varpi_3} - \frac{x}{\varpi_e}\right) dx \end{aligned} \tag{14}$$

Substituting (13) and (14) into (10), we can obtain (11). It completes the proof.

3.2. SPSC for $BS_2 - D_2$

Similar to $BS_1 - D_2$, the SPSC for $BS_2 - D_2$ case can be expressed as [24]:

$$\begin{aligned} & SPSC_{D_2}^{BS_2} = \Pr\left(\Psi_2 > R_2\right) \\ & = \underbrace{\Pr\left(\gamma_{q_2}^{u} \geq \gamma_{q_2}^{e}\right)}_{\xi_1} \underbrace{\Pr\left(\gamma_{1\to 2}^{d} \geq \gamma_{q_2}^{e}\right)}_{\xi_2} \underbrace{\Pr\left(\gamma_{q_2}^{d} \geq \gamma_{q_2}^{e}\right)}_{\xi_3} \end{aligned} \tag{15}$$

Proposition 2. The exact expression of the SPSC $BS_2 - D_2$ is given by:

$$SPSC_{D_2}^{BS_2} = \frac{\delta_2\rho_{bs2}\varpi_2}{\Theta_1\delta_2\rho_e\varpi_e + \delta_2\rho_{bs2}\varpi_2}\frac{\delta_2\rho_R\varpi_4\eta_4}{\left(\Theta_3\delta_2\rho_e\varpi_e + \delta_2\rho_R\varpi_4\right)\varpi_e} \tag{16}$$

Where:
$\Theta_3 = \rho_R\wp_{d2}^2 + 1$
$\eta_4 = \int_0^\infty \exp\left(-\frac{\Theta_3\delta_2\rho_e x}{(\delta_1-\delta_2\delta_2\rho_e x)\rho_R\varpi_4} - \frac{x}{\varpi_e}\right)dx$
Proof: from (15), ξ_1 can be calculated as:

$$\begin{aligned}
\xi_1 &= \Pr\left(\gamma_{q_2}^u \geq \gamma_{q_2}^e\right) \\
&= \Pr\left(|h_2|^2 \geq \frac{\Theta_1\delta_2\rho_e|h_e|^2}{\delta_2\rho_{bs2}}\right) \\
&= \int_0^\infty \left(1 - F_{|h_2|^2}\left(\frac{\Theta_1\delta_2\rho_e x}{\delta_2\rho_{bs2}}\right)\right) f_{|h_e|^2}(x)\,dx \\
&= \frac{1}{\varpi_e}\int_0^\infty \exp\left(-\left(\frac{\Theta_1\delta_2\rho_e}{\delta_2\rho_{bs2}\varpi_2} + \frac{1}{\varpi_e}\right)x\right)dx \\
&= \frac{\delta_2\rho_{bs2}\varpi_2}{\Theta_1\delta_2\rho_e\varpi_e + \delta_2\rho_{bs2}\varpi_2}
\end{aligned} \tag{17}$$

Next, ξ_2 can be calculated as:

$$\begin{aligned}
\xi_2 &= \Pr\left(\gamma_{1\to2}^d \geq \gamma_{q_2}^e\right) \\
&= \Pr\left(|h_4|^2 \geq \frac{\Theta_3\delta_2\rho_e|h_e|^2}{\left(\delta_1 - \delta_2\delta_2\rho_e|h_e|^2\right)\rho_R}\right) \\
&= \int_0^\infty \left(1 - F_{|h_4|^2}\left(\frac{\Theta_3\delta_2\rho_e x}{(\delta_1 - \delta_2\delta_2\rho_e x)\rho_R}\right)\right) f_{|h_e|^2}(x)\,dx \\
&= \frac{1}{\varpi_e}\int_0^\infty \exp\left(-\frac{\Theta_3\delta_2\rho_e x}{(\delta_1 - \delta_2\delta_2\rho_e x)\rho_R\varpi_4} - \frac{x}{\varpi_e}\right)dx
\end{aligned} \tag{18}$$

From (15), ξ_3 can be calculated as:

$$\begin{aligned}
\xi_3 &= \Pr\left(\gamma_{q_2}^d \geq \gamma_{q_2}^e\right) \\
&= \Pr\left(|h_4|^2 \geq \frac{\Theta_3\delta_2\rho_e|h_e|^2}{\delta_2\rho_R}\right) \\
&= \int_0^\infty \left(1 - F_{|h_4|^2}\left(\frac{\Theta_3\delta_2\rho_e x}{\delta_2\rho_R}\right)\right) f_{|h_e|^2}(x)\,dx \\
&= \frac{1}{\varpi_e}\int_0^\infty \exp\left(-\left(\frac{\Theta_3\delta_2\rho_e}{\delta_2\rho_R\varpi_4} + \frac{1}{\varpi_e}\right)x\right)dx \\
&= \frac{\delta_2\rho_R\varpi_4}{\Theta_3\delta_2\rho_e\varpi_e + \delta_2\rho_R\varpi_4}
\end{aligned} \tag{19}$$

The proof is completed.

4. SIMULATION RESULTS

In this section, we simulate the system with these parameters $\rho = \rho_{bs1} = \rho_{bs2} = \rho_R$, $\wp = \wp_{u1}^2 = \wp_{u2}^2 = \wp_{d1}^2 = \wp_{d2}^2$. The SPSC performance is evaluated via Monte-Carlo and analytical simulations. Then, we expect that these simulations provide good match in term of values of numerical simulations.

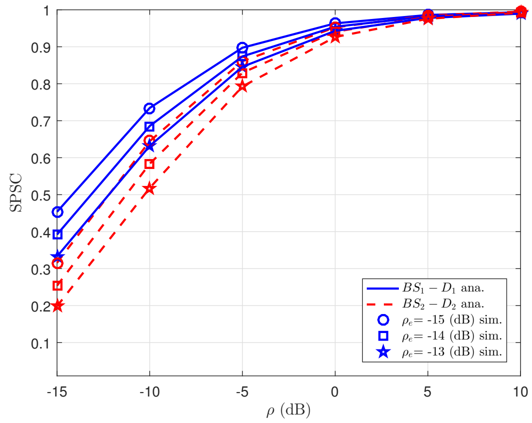

Figure 2. SPSC for $BS_1 - D_1$ and $BS_2 - D_2$ versus ρ as changing ρ_e with $\delta_1 = 0.9$, $\wp = 0.001$, $\varpi_1 = \varpi_2 = 1$, $\varpi_3 = 10$, $\varpi_4 = 2$, $\varpi_e = 1$

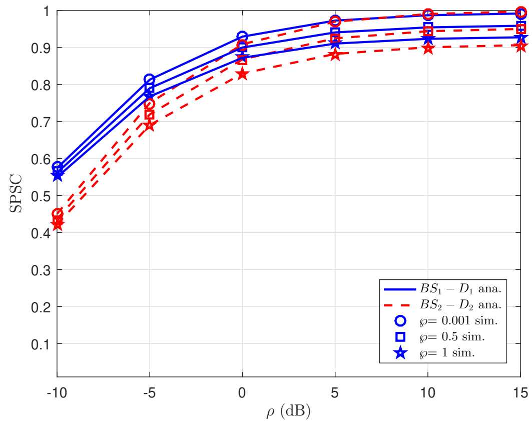

Figure 3. SPSC for $BS_1 - D_1$ and $BS_2 - D_2$ versus ρ as changing $\wp$ with $\delta_1 = 0.9$, $\varpi_1 = \varpi_2 = 1$, $\varpi_3 = 10$, $\varpi_4 = 2$, $\varpi_e = 1$, $\rho_e = -12$ (dB)

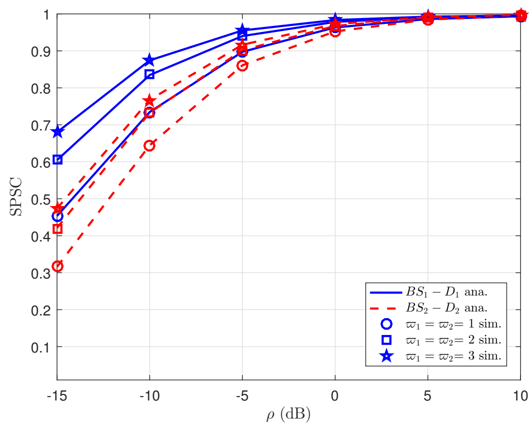

Figure 4. SPSC for $BS_1 - D_1$ and $BS_2 - D_2$ versus ρ as changing $\varpi_1 = \varpi_2$ with $\delta_1 = 0.9$, $\wp = 0.001$, $\varpi_3 = 10$, $\varpi_4 = 2$, $\varpi_e = 1$, $\rho_e = -12$ (dB)

Figure 2 demonstrates that the SPSC of two pairs of users is decided by varying impact of eavesdropper ρ_e. More importantly, two destinations exhibit different performance since power allocation factors are different too. The impact of imperfect (channel state information) CSI $\wp$ leads to variance in consideration of SPSC, shown in Figure 3. Therefore, by controlling CSI we can remain the stable operation of secure performance. Similarly, Figure 4 indicates that SPSC relies on how strong channels are. We employ the simulation with three cases of channel gains, $\varpi_1 = \varpi_2 = 1$, $\varpi_1 = \varpi_2 = 2$, $\varpi_1 = \varpi_2 = 3$. Two pairs of base station-destination still show their performance gaps.

5. CONCLUSION

In this paper, two pairs of base station-destination are studied to exhibit secure performance. We deploy NOMA to allow base station increase spectrum efficiency and to reduce risk of attack from eavesdroppers. In this circumstance, we consider two pair of users from the base stations to destinations to evaluate secure performance once an eavesdropper also wants to overhear the main signal is being processing at main links. The main results are represented in terms of closed-form formulas for the SPSC and main parameters can be determined to know how SPSC can be changed. The uplink and downlink scenario in this paper can be applied to lots of applications for Internet of Things. The results are useful guidelines for engineers who can performance secure uplink and downlink NOMA systems.

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