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Improved Performance of NOMA: Multilevel Symmetric Superposition Coding under Rayleigh Fading Channel

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ABSTRACT

The main principle of non-orthogonal multiple access (NOMA) recommends that low power is allocated to the strong channel user, in order to guarantee the user fairness. Recently, symmetric superposition coding (SSC) has been proposed to mitigate the effect of error propagation (EP) in NOMA with quadrature phase shift keying (QPSK) for visible light communication (VLC) networks. It has been verified analytically that SSC NOMA with binary phase shift keying (BPSK) achieves the performance of the perfect SIC for the power allocation factor range less than 50%. However, SSC for multilevel modulations has not been reported in the literature in NOMA. As continuing researches, we propose NOMA with the multilevel SSC for the 4-ary pulse amplitude modulation (4PAM). It is shown that the performance of 4PAM SSC NOMA achieves the perfect SIC performance for the power allocation factor range less than about 10 %, while the performance of 4PAM NOMA with the normal superposition coding (NSC) is the same as that of the perfect SIC NOMA for the power allocation factor range less than about 5 %. As a result, the promising feature of SSC, i.e., the improved performance on the low power allocation range, is still preserved for multilevel modulations.

Key Words : NOMA, Rayleigh fading channel, successive interference cancellation, 4-ary pulse amplitude modulation, maximum-likelihood, power allocation

Ⅰ. Introduction

The fifth generation (5G) mobile communication has been commercialized in Korea, April 3, 2019, for the first time in the world. One of the state of the art techniques for 5G and beyond mobile radio access networks is non-orthogonal multiple access (NOMA)[1-6]. Recently, the serious effect of the superposition coding on the NOMA performance has been mitigated with the symmetric superposition coding (SSC)[7]. In [7], for visible light communication (VLC) networks, the performance of NOMA with quadrature phase shift keying (QPSK) is shown to achieve the perfect successive interference cancellation (SIC) performance by computer simulations. In [8], it is shown analytically that NOMA with binary phase shift keying (BPSK) also achieves the perfect SIC performance for the power allocation factor range less than 50%. In addition, the performance of NOMA with QPSK is presented under fading channels[10]. However, in [7], [8] and [10], only single level modulations, such as BPSK and QPSK, are considered. On the other hand, in [9], the standard multilevel NOMA with normal superposition coding (NSC) is studied. It is shown in [9] that the 4-ary pulse amplitude modulation (4PAM) NSC NOMA achieves the perfect SIC performance only for the power allocation factor range less than about 5 %.

Therefore, we observe that the SSC technique improves the performance of NOMA for the single level modulations, such as QPSK and BPSK[7,8]. Nevertheless, the SSC technique for the multilevel modulations has not been reported in the literature of NOMA.

Lastly, we summarize our contributions with respect to the previous research results, in order to clarify new contributions of this paper;

- previous research results: QPSK NSC NOMA fading performance analysis[10], QPSK SSC NOMA VLC network performance analysis[7], BPSK SSC NOMA performance analysis[8],

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4PAM NSC NOMA fading performance analysis[9].

- our contributions: 4PAM SSC NOMA fading performance analysis, i.e., for the first time, the SSC technique, which is originally proposed for the single level modulation, such as QPSK[7], is applied to the multilevel modulation NOMA in this paper to the best knowledge of the authors.

In this paper, we propose the multilevel SSC for the 4PAM NOMA under Rayleigh fading channels. The paper is organized as follows. Section II defines the system and channel model. In Section III, the performance of 4PAM SSC NOMA is derived analytically. In Section IV, the results are presented and discussed. The paper is concluded in Section V.

Ⅱ. System and Channel Model

Assume that the total transmit power is P, the power allocation factor is α with $0 \le \alpha \le 1$, ($0\% \le \alpha \le 100\%$), and the channel gains $h_1 \sim \mathcal{CN}(0,\Sigma_1)$ and $h_2 \sim \mathcal{CN}(0,\Sigma_2)$ are Rayleigh faded, with $\Sigma_1 > \Sigma_2$. The notation $\mathcal{CN}(\mu,\Sigma)$ denotes the complex circularly-symmetric normal distribution with mean μ and variance Σ. Then αP is allocated to the user-1 signal s_1 and $(1-\alpha)P$ is allocated to the user-2 signal s_2, with $\mathbb{E}\left[|s_1|^2\right] = \mathbb{E}\left[|s_2|^2\right] = 1$. The superimposed signal is expressed by

$$x = \sqrt{\alpha P} s_1 + \sqrt{(1-\alpha)P} s_2 . \tag{1}$$

Before the successive interference cancellation (SIC) is performed on the user-1 with the better channel condition, the received signals of the user-1 and the user-2 are represented as

$$\begin{aligned} z_1 &= h_1 \sqrt{\alpha P} s_1 + \left(h_1 \sqrt{(1-\alpha)P} s_2 + w_1 \right) \\ z_2 &= h_2 \sqrt{(1-\alpha)P} s_2 + \left(h_2 \sqrt{\alpha P} s_1 + w_2 \right) \end{aligned} \tag{2}$$

where w_1 and $w_2 \sim \mathcal{CN}(0, N_0)$ are complex additive white Gaussian noise (AWGN) and N_0 is one-sided power spectral density. Moreover, if the 1-dimensional modulation constellation is considered, the following metrics are sufficient statistics;

$$\begin{aligned} r_1 &= |h_1| \sqrt{\alpha P} s_1 + \left(|h_1| \sqrt{(1-\alpha)P} s_2 + n_1 \right) \\ r_2 &= |h_2| \sqrt{(1-\alpha)P} s_2 + \left(|h_2| \sqrt{\alpha P} s_1 + n_2 \right) \end{aligned} \tag{3}$$

where n_1 and n_2 $n_2 \sim \mathcal{N}(0, N_0/2)$ are AWGN. The notation $\mathcal{N}(\mu,\Sigma)$ denotes the normal distribution with mean μ and variance Σ. In the standard NOMA, the SIC is performed only on the user-1. Then the received signal is given by, if the perfect SIC is assumed,

$$y_1 = r_1 - |h_1| \sqrt{(1-\alpha)P} s_2 = |h_1| \sqrt{\alpha P} s_1 + n_1 . \tag{4}$$

We assume the 4PAM modulations for both users in the standard NOMA, i.e., the 4PAM/4PAM NOMA,

$$s_1, s_2 \in \left\{ +\frac{3}{\sqrt{5}}, +\frac{1}{\sqrt{5}}, -\frac{1}{\sqrt{5}}, -\frac{3}{\sqrt{5}} \right\}. \tag{5}$$

Let the symbol indexes for the user-1 and the user-2 be $m_1, m_2 \in \{1,2,3,4\}$. Then in NSC, the modulation signal mapping is normal as

$$\begin{aligned} &s_1(m_1=4) = +\frac{3}{\sqrt{5}}, s_1(m_1=3) = +\frac{1}{\sqrt{5}}, s_1(m_1=2) = -\frac{1}{\sqrt{5}}, s_1(m_1=1) = -\frac{3}{\sqrt{5}} \\ &s_2(m_2=4) = +\frac{3}{\sqrt{5}}, s_2(m_2=3) = +\frac{1}{\sqrt{5}}, s_2(m_2=2) = -\frac{1}{\sqrt{5}}, s_2(m_2=1) = -\frac{3}{\sqrt{5}}. \end{aligned} \tag{6}$$

For the user-2, the modulation signal mapping of SSC is exactly the same as that of NSC. However, in SSC, the modulation signal mapping is changed only for the user-1, as

$$\begin{cases} s_1(m_1=4 \mid m_2=4) = +\frac{3}{\sqrt{5}} \\ s_1(m_1=3 \mid m_2=4) = +\frac{1}{\sqrt{5}} \\ s_1(m_1=2 \mid m_2=4) = -\frac{1}{\sqrt{5}} \\ s_1(m_1=1 \mid m_2=4) = -\frac{3}{\sqrt{5}} \end{cases} \begin{cases} s_1(m_1=4 \mid m_2=3) = -\frac{3}{\sqrt{5}} \\ s_1(m_1=3 \mid m_2=3) = -\frac{1}{\sqrt{5}} \\ s_1(m_1=2 \mid m_2=3) = +\frac{1}{\sqrt{5}} \\ s_1(m_1=1 \mid m_2=3) = +\frac{3}{\sqrt{5}} \end{cases} \begin{cases} s_1(m_1=4 \mid m_2=2) = +\frac{3}{\sqrt{5}} \\ s_1(m_1=3 \mid m_2=2) = +\frac{1}{\sqrt{5}} \\ s_1(m_1=2 \mid m_2=2) = -\frac{1}{\sqrt{5}} \\ s_1(m_1=1 \mid m_2=2) = -\frac{3}{\sqrt{5}} \end{cases} \begin{cases} s_1(m_1=4 \mid m_2=1) = -\frac{3}{\sqrt{5}} \\ s_1(m_1=3 \mid m_2=1) = -\frac{1}{\sqrt{5}} \\ s_1(m_1=2 \mid m_2=1) = +\frac{1}{\sqrt{5}} \\ s_1(m_1=1 \mid m_2=1) = +\frac{3}{\sqrt{5}}. \end{cases} \tag{7}$$

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Ⅲ. 4PAM SSC NOMA Performance Derivation

We derive the optimal receiver for the 4PAM SSC NOMA. The optimum detection is made, based on the maximum likelihood (ML), as

$$\hat{m}_1 = \underset{i \in \{1,2,3,4\}}{\arg\max}\, p_{R_1|M_1}(r_1 \mid m_1 = i) \tag{8}$$

where the likelihoods are expressed by

$$\begin{aligned} & p_{R_1|M_1}(r_1 \mid m_1 = i) \\ &= \frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}}\sum_{j=1}^{4} e^{-\frac{\left(r_1 - |h_1|\sqrt{\alpha P}s_1(m_1=i|m_2=j) - |h_1|\sqrt{(1-\alpha)P}s_2(m_2=j)\right)^2}{2N_0/2}}. \end{aligned} \tag{9}$$

Then the decision regions are given by, for $0 < \alpha < 0.1$, for $m_1 = 4$,

$$\begin{cases} r_1 > +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P},\ r_1 < -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \end{cases} \tag{10}$$

for $m_1 = 3$,

$$\begin{cases} +\frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < +\frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ -\frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < -\frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \end{cases} \tag{11}$$

for $m_1 = 2$,

$$\begin{cases} -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < +\frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ +\frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < -\frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ -\frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \end{cases} \tag{12}$$

for $m_1 = 1$,

$$\begin{cases} +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} + \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} \\ +\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{3}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P} < r_1 < -\frac{2}{\sqrt{5}}|h_1|\sqrt{\alpha P} - \frac{1}{\sqrt{5}}|h_1|\sqrt{(1-\alpha)P}. \end{cases} \tag{13}$$

Based on the decision regions, the probability of errors is calculated as, for $0 < \alpha < 0.1$,
where for the simplification, we define the notation as

$$\begin{aligned} P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} \simeq \frac{1}{4}\times\frac{1}{4}\times 2\times\Big[\\ +q^{(+0;+1)} - q^{(+2;+5)} + q^{(+4;+1)} - q^{(+6;+5)} \quad +q^{(+0;+1)} - q^{(+2;-5)} + q^{(+4;-1)} - q^{(+6;-5)} \\ -q^{(+2;+5)} + q^{(+0;+1)} + q^{(+2;-5)} - q^{(+4;-1)} \quad -q^{(+2;-5)} + q^{(+0;+1)} + q^{(+2;+5)} - q^{(+4;+1)} \\ +q^{(+0;+1)} + q^{(+0;+1)} - q^{(+2;+1)} + q^{(+2;+3)} - q^{(+4;-1)} + q^{(+4;+1)} - q^{(+6;+1)} + q^{(+6;+3)} \\ +q^{(+2;+3)} - q^{(+2;+1)} + q^{(+0;+1)} + q^{(+0;+1)} - q^{(+2;-3)} + q^{(+2;-1)} - q^{(+4;-1)} + q^{(+4;+1)} \\ +q^{(+0;+1)} + q^{(+0;+1)} - q^{(+2;-3)} + q^{(+2;-1)} - q^{(+4;-1)} + q^{(+4;+1)} - q^{(+6;-3)} + q^{(+6;-1)} \\ +q^{(+2;-1)} - q^{(+2;-3)} + q^{(+0;+1)} + q^{(+0;+1)} - q^{(+2;+1)} + q^{(+2;+3)} - q^{(+4;-1)} + q^{(+4;+1)} \Big] \end{aligned} \tag{14}$$

$$\begin{aligned} P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} \simeq \frac{1}{4}\times\frac{1}{4}\times 2\times\Big[\\ +q^{(+0;+1)} - q^{(+3;+2)} + q^{(+3;+4)} - q^{(+6;+5)} \quad +q^{(-1;+4)} + q^{(+1;-2)} - q^{(+5;-4)} + q^{(+5;-2)} \\ -q^{(+2;+5)} + q^{(-1;+4)} + q^{(+1;-2)} - q^{(+4;-1)} \quad +q^{(+1;-2)} + q^{(-1;+4)} - q^{(+3;+2)} + q^{(+3;+4)} \\ +q^{(+0;+1)} + q^{(+0;+1)} - q^{(+2;+1)} + q^{(+3;+0)} - q^{(+3;+2)} + q^{(+4;+1)} - q^{(+6;+1)} + q^{(+6;+3)} \\ +q^{(+2;+3)} - q^{(+2;+1)} + q^{(+0;+1)} + q^{(+1;-2)} - q^{(+1;-0)} + q^{(+2;-1)} - q^{(+4;-1)} + q^{(+4;+1)} \\ +q^{(+0;+1)} + q^{(+1;-2)} - q^{(+1;-0)} + q^{(+2;-1)} - q^{(+4;-1)} + q^{(+5;-2)} - q^{(+5;-0)} + q^{(+6;-1)} \\ +q^{(+2;-1)} - q^{(+1;-0)} + q^{(+1;-2)} + q^{(+0;+1)} - q^{(+2;+1)} + q^{(+3;+0)} - q^{(+3;+2)} + q^{(+4;+1)} \Big] \end{aligned} \tag{16}$$

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$$q^{(I;A)} = Q\left(\frac{|h_1|\sqrt{P}\left(\sqrt{(1-\alpha)}\frac{I}{\sqrt{5}} + \sqrt{\alpha}\frac{A}{\sqrt{5}}\right)}{\sqrt{N_0 / 2}}\right) \tag{15}$$

and $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz$. Similarly, for $0.1 < \alpha < 0.2$,
for $0.2 < \alpha < 0.4 / 13 \simeq 0.307$,
for $4 / 13 \simeq 0.307 < \alpha < 0.5$,
for $0.5 < \alpha < 9 / 13 \simeq 0.693$,
for $9 / 13 \simeq 0.693 < \alpha < 0.8$,
for $0.8 < \alpha < 0.9$,
for $0.9 < \alpha < 1$,

Then the fading performance is calculated by

$$P_e^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} = \mathbb{E}_{h_1}\left[P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)}\right]. \tag{23}$$

$$\begin{array}{l} P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} \simeq \frac{1}{4}\times\frac{1}{4}\times 2\times\Big[\\ +q^{(+0;+1)} - q^{(+2;+3)} + q^{(+3;+2)} - q^{(+3;+4)} + q^{(+4;+3)} - q^{(+6;+5)} \quad +q^{(+0;+1)} + q^{(+1;-1)} - q^{(+3;+0)} + q^{(+3;+2)} - q^{(+5;+3)} + q^{(+6;+3)} \\ -q^{(+2;+5)} + q^{(-0;+3)} - q^{(-1;+4)} + q^{(-1;+2)} + q^{(+2;-3)} - q^{(+4;-1)} \quad +q^{(+2;+3)} - q^{(+1;+3)} + q^{(-1;+2)} + q^{(+1;+0)} - q^{(+3;+1)} - q^{(+4;-1)} \\ +q^{(+1;-2)} + q^{(+1;+0)} - q^{(+5;-2)} + q^{(+5;-0)} \quad +q^{(-1;+5)} - q^{(-1;+4)} + q^{(-1;+2)} + q^{(+2;-3)} - q^{(+4;-3)} + q^{(+5;-4)} - q^{(+5;-2)} + q^{(+5;-1)} \\ +q^{(+1;-0)} + q^{(-1;+2)} - q^{(+3;+0)} + q^{(+3;+2)} \quad +q^{(+1;-1)} + q^{(-1;+2)} - q^{(-3;+4)} + q^{(+0;+3)} - q^{(+2;+3)} + q^{(+3;+2)} - q^{(+3;+4)} + q^{(+3;+5)} \Big] \end{array} \tag{17}$$

$$\begin{array}{l} P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} \simeq \frac{1}{4}\times\frac{1}{4}\times 2\times\Big[\\ +q^{(+0;+1)} - q^{(+3;+1)} + q^{(+2;+3)} - q^{(+4;+3)} + q^{(+3;+5)} - q^{(+6;+5)} \quad +q^{(+0;+1)} + q^{(+1;-1)} - q^{(+1;+3)} + q^{(+5;-1)} - q^{(+5;+3)} + q^{(+6;+3)} \\ -q^{(+2;+5)} + q^{(-1;+5)} - q^{(-0;+3)} + q^{(-2;+3)} + q^{(+1;-1)} - q^{(+4;-1)} \quad +q^{(+2;+3)} - q^{(+1;+3)} + q^{(+1;-1)} + q^{(+3;-3)} - q^{(+3;+1)} + q^{(+4;-1)} \\ +q^{(+1;-2)} + q^{(+3;-3)} - q^{(+3;+1)} + q^{(+5;-0)} \quad +q^{(-1;+5)} - q^{(-1;+4)} + q^{(-2;+3)} + q^{(+1;-1)} - q^{(+5;-5)} + q^{(+4;-3)} - q^{(+5;-2)} + q^{(+5;-1)} \\ +q^{(+1;-0)} + q^{(+1;+1)} - q^{(+1;+3)} + q^{(+3;+2)} \quad +q^{(+1;-1)} + q^{(-1;+2)} - q^{(-0;+3)} + q^{(-1;+5)} - q^{(+3;+1)} + q^{(+2;+3)} - q^{(+3;+4)} + q^{(+3;+5)} \Big] \end{array} \tag{18}$$

$$\begin{array}{l} P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} \simeq \frac{1}{4}\times\frac{1}{4}\times 2\times\Big[\\ +q^{(+1;+0)} - q^{(+2;+1)} + q^{(+3;+1)} - q^{(+3;+5)} + q^{(+4;+5)} - q^{(+5;+6)} \quad +q^{(-1;+1)} + q^{(+2;-1)} - q^{(+5;-1)} + q^{(+1;+3)} - q^{(+4;+3)} + q^{(+5;+3)} \\ -q^{(+1;+6)} + q^{(-0;+5)} - q^{(-1;+5)} + q^{(-1;+1)} + q^{(+2;-1)} - q^{(+3;-0)} \quad +q^{(+1;+3)} - q^{(+0;+3)} + q^{(-3;+3)} + q^{(-1;+1)} - q^{(+2;+1)} + q^{(+3;+1)} \\ +q^{(-3;+3)} + q^{(+3;-2)} - q^{(+3;+0)} + q^{(+3;+1)} \quad +q^{(-1;+6)} - q^{(-1;+5)} + q^{(-3;+4)} - q^{(-5;+5)} + q^{(-1;+1)} + q^{(+3;-3)} - q^{(+5;-1)} + q^{(+5;-0)} \\ +q^{(-1;+1)} + q^{(+1;+0)} - q^{(+2;+1)} + q^{(+1;+3)} \quad +q^{(+1;-0)} + q^{(-1;+1)} - q^{(+1;+2)} + q^{(+3;+1)} - q^{(-1;+5)} + q^{(+1;+4)} - q^{(+3;+5)} + q^{(+3;+6)} \Big] \end{array} \tag{19}$$

$$\begin{array}{l} P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} \simeq \frac{1}{4}\times\frac{1}{4}\times 2\times\Big[\\ +q^{(+1;+0)} - q^{(+2;+1)} + q^{(+3;+1)} - q^{(+3;+5)} + q^{(+4;+5)} - q^{(+5;+6)} \quad +q^{(-1;+1)} + q^{(+2;-1)} - q^{(+2;+1)} + q^{(+4;+1)} - q^{(+4;+3)} + q^{(+5;+3)} \\ -q^{(+1;+6)} + q^{(-0;+5)} - q^{(-1;+5)} + q^{(-1;+1)} + q^{(+2;-1)} - q^{(+3;-0)} \quad +q^{(+1;+3)} - q^{(+0;+3)} + q^{(-0;+1)} + q^{(+2;-1)} - q^{(+2;+1)} + q^{(+3;+1)} \\ +q^{(-3;+3)} - q^{(-4;+3)} + q^{(+3;-2)} + q^{(+2;-1)} - q^{(+4;-1)} + q^{(+3;+0)} - q^{(+2;+1)} + q^{(+3;+1)} \\ +q^{(-1;+1)} + q^{(+2;-1)} - q^{(+1;+0)} + q^{(-0;+1)} - q^{(+2;+1)} + q^{(+1;+2)} - q^{(+0;+3)} + q^{(+1;+3)} \\ +q^{(-1;+6)} - q^{(-1;+5)} + q^{(-4;+5)} - q^{(-3;+4)} + q^{(-3;+2)} + q^{(+3;-1)} - q^{(+5;-1)} + q^{(+5;-0)} \\ +q^{(+1;-0)} + q^{(-1;+1)} - q^{(+2;+1)} + q^{(+1;+2)} - q^{(+1;+4)} + q^{(+0;+5)} - q^{(+3;+5)} + q^{(+3;+6)} \Big] \end{array} \tag{20}$$

$$\begin{array}{l} P_{e|h_1}^{(1;\,M=4;\,SSC;\,NOMA;\,optimal\ ML)} \simeq \frac{1}{4}\times\frac{1}{4}\times 2\times\Big[\\ +q^{(+1;+0)} - q^{(+3;+0)} + q^{(+2;+1)} - q^{(+4;+5)} + q^{(+3;+6)} - q^{(+5;+6)} \quad +q^{(-4;+3)} - q^{(-3;+2)} + q^{(-2;+1)} + q^{(+4;-1)} - q^{(+3;+0)} + q^{(+2;+1)} \\ -q^{(+1;+6)} + q^{(-1;+6)} - q^{(-0;+5)} + q^{(-2;+1)} + q^{(+1;-0)} - q^{(+3;-0)} \quad +q^{(+2;-1)} + q^{(+1;+0)} - q^{(-0;+1)} + q^{(+2;+1)} - q^{(+1;+2)} + q^{(+0;+3)} \\ +q^{(-2;+1)} + q^{(+3;-1)} - q^{(+3;-0)} + q^{(+2;+1)} - q^{(+4;+1)} + q^{(+3;+2)} - q^{(+3;+3)} + q^{(+4;+3)} \\ +q^{(+0;+3)} - q^{(-1;+3)} + q^{(-1;+2)} - q^{(-0;+1)} + q^{(-2;+1)} + q^{(+2;-1)} - q^{(+2;+1)} + q^{(+3;+1)} \\ +q^{(-1;+6)} - q^{(-3;+6)} + q^{(-3;+5)} - q^{(-4;+5)} + q^{(-2;+1)} + q^{(+3;-1)} - q^{(+3;-0)} + q^{(+5;-0)} \\ +q^{(+1;-0)} + q^{(+1;-0)} - q^{(+1;+1)} + q^{(+2;+1)} - q^{(+0;+5)} + q^{(+1;+5)} - q^{(+1;+6)} + q^{(+3;+6)} \Big] \end{array} \tag{21}$$

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Thus we can use the well-known Rayleigh fading integration formula,

$$\begin{aligned}
&\int_0^\infty q^{(I;A)} \frac{1}{\gamma_b} e^{-\frac{\gamma}{\gamma_b}} d\gamma \\
&= \int_0^\infty Q\left(\frac{|h_1|\sqrt{P}\left(\sqrt{(1-\alpha)}\frac{I}{\sqrt{5}} + \sqrt{\alpha}\frac{A}{\sqrt{5}}\right)}{\sqrt{N_0/2}} \right) \frac{1}{\gamma_b} e^{-\frac{\gamma}{\gamma_b}} d\gamma \\
&= \int_0^\infty Q\left(\sqrt{2\frac{|h_1|^2 P\left(\sqrt{(1-\alpha)}\frac{I}{\sqrt{5}} + \sqrt{\alpha}\frac{A}{\sqrt{5}}\right)^2}{N_0}} \right) \frac{1}{\gamma_b} e^{-\frac{\gamma}{\gamma_b}} d\gamma \\
&= \int_0^\infty Q\left(\sqrt{2\gamma}\right) \frac{1}{\gamma_b} e^{-\frac{\gamma}{\gamma_b}} d\gamma = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_b}{1+\gamma_b}}\right)
\end{aligned} \tag{24}$$

where the random variable (RV) γ is exponentially distributed and γ is defined as

$$\gamma = \frac{|h_1|^2 P\left(\sqrt{(1-\alpha)}\frac{I}{\sqrt{5}} + \sqrt{\alpha}\frac{A}{\sqrt{5}}\right)^2}{N_0} \tag{25}$$

Then the mean of γ is calculated as

$$\gamma_b = \mathbb{E}[\gamma] = \mathbb{E}\left[\frac{|h_1|^2 P\left(\sqrt{(1-\alpha)}\frac{I}{\sqrt{5}} + \sqrt{\alpha}\frac{A}{\sqrt{5}}\right)^2}{N_0} \right] = \frac{\Sigma_1 P\left(\sqrt{(1-\alpha)}\frac{I}{\sqrt{5}} + \sqrt{\alpha}\frac{A}{\sqrt{5}}\right)^2}{N_0}. \tag{26}$$

Ⅳ. Results and Discussions

Assume that $\Sigma_1 = (2.0)^2$ and the total transmit signal power to one-sided power spectral density ratio $P/N_0 = 50\ \mathrm{dB}$. In Fig. 1, we compare $P_e^{(1;\, M=4;\, SSC;\, NOMA;\, optimal\ ML)}$ to $P_e^{(1;\, M=4;\, NSC;\, NOMA;\, optimal\ ML)}$ in [9] and $P_e^{(1;\, M=4;\, NOMA;\, ideal\ perfect\ SIC)}$, which is given by

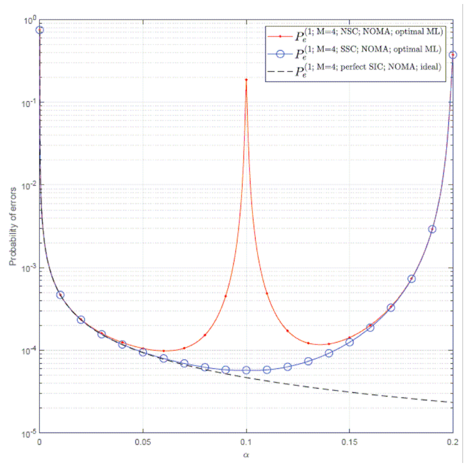

Fig. 1. Comparison of probabilities of errors for 4PAM NOMA with SSC, NSC, and perfect SIC ($0 < \alpha < 0.2$).

$$P_e^{(1;\, M=4;\, NOMA;\, ideal\ perfect\ SIC)} = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{\alpha P \Sigma_1}{N_0}}{1 + \frac{\alpha P \Sigma_1}{N_0}}}\right). \tag{27}$$

As shown in Fig. 1, the SSC NOMA improves the performance of the NSC NOMA. Especially, the severe performance degradation of the NSC NOMA at $\alpha = 0.1$ is effectively fixed. Then, the question of where the performance improvement comes from is answered in Fig. 2; the SSC NOMA performance is worse than the NSC NOMA performance for $\alpha > 0.9$. Note that NOMA practically does not operate for $\alpha > 0.9$, based on the main NOMA principle, i.e., the user fairness; the less power should be allocated to the strong channel user. Therefore, we could exploit the performance improvement of the SSC NOMA over the NSC NOMA for $\alpha < 0.2$, over which NOMA normally operates.

$$\begin{aligned}
P_{e|h_1}^{(1;\, M=4;\, SSC;\, NOMA;\, optimal\ ML)} \simeq \frac{1}{4} \times \frac{1}{4} \times 2 \times \Big[\\
&+q^{(+1;+0)} - q^{(+3;+0)} + q^{(+5;+0)} - q^{(+1;+6)} + q^{(+3;+6)} - q^{(+5;+6)} \quad +q^{(-1;+2)} - q^{(-3;+2)} + q^{(-5;+2)} + q^{(+1;-0)} - q^{(+3;+0)} + q^{(+5;+0)} \\
&-q^{(+1;+6)} + q^{(-1;+6)} - q^{(-3;+6)} + q^{(+1;-0)} + q^{(+1;-0)} - q^{(+3;-0)} \quad +q^{(+1;+0)} + q^{(+1;+0)} - q^{(+3;+0)} + q^{(-1;+2)} - q^{(+1;+2)} + q^{(+3;+2)} \\
&+q^{(-3;+1)} + q^{(+1;-0)} - q^{(+3;-0)} + q^{(+5;+0)} - q^{(+1;+2)} + q^{(+3;+2)} - q^{(+5;+2)} + q^{(+3;+3)} \\
&+q^{(+0;+3)} - q^{(-1;+3)} + q^{(-1;+2)} - q^{(-0;+1)} + q^{(-2;+1)} + q^{(+2;-1)} - q^{(+2;+1)} + q^{(+3;+1)} \\
&+q^{(-1;+6)} - q^{(-3;+6)} + q^{(-5;+6)} - q^{(-3;+5)} + q^{(-3;+1)} + q^{(+1;-0)} - q^{(+3;-0)} + q^{(+5;-0)} \\
&+q^{(+1;-0)} + q^{(+1;-0)} - q^{(+3;+0)} + q^{(+1;+1)} - q^{(+1;+5)} + q^{(-1;+6)} - q^{(+1;+6)} + q^{(+3;+6)} \quad \Big].
\end{aligned} \tag{22}$$

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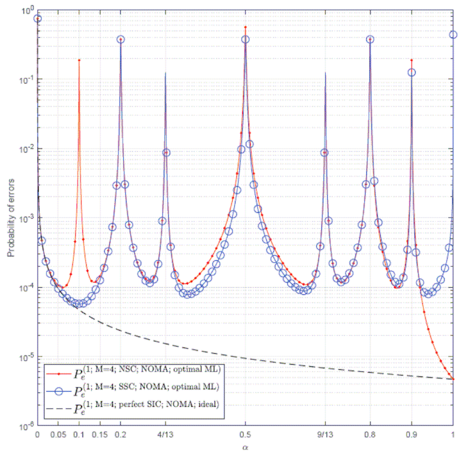

Fig. 2. Comparison of probabilities of errors for 4PAM NOMA with SSC, NSC, and perfect SIC ($0 < \alpha < 1$).

V. Conclusion

First we derived the optimal ML receiver for the 4PAM SSC NOMA, under Rayleigh fading channels. Then we investigated the effect of the multilevel SSC on NOMA systems. It was shown the performance of the 4PAM SSC NOMA achieves the perfect SIC performance for the power allocation factor range up to about 10 %, while the performance of the 4PAM NSC NOMA achieves the perfect SIC performance, only for the power allocation factor range less than about 5 %. As a result, the promising feature of the SSC of the improved performance on the low power allocation range was still preserved for the multilevel modulations.

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