International Journal of Internet, Broadcasting and Communication Vol.13 No.1 69-81 (2021)
http://dx.doi.org/10.7236/IJIBC.2021.13.1.69

IJIBC 21-1-9

Unipodal 2PAM NOMA without SIC: toward Super Ultra-Low Latency 6G

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Abstract

While the fifth generation (5G) and beyond 5G (B5G) mobile communication networks are being rolled over the globe, several world-wide companies have already started to prepare the sixth generation (6G). Such 6G mobile networks targets ultra-reliable low-latency communication (URLLC). In this paper, we challenge to reduce the inherent latency of existing non-orthogonal multiple access (NOMA) in 5G networks of massive connectivity.

First, we propose the novel unipodal binary pulse amplitude modulation (2PAM) NOMA, especially without SIC, which greatly reduce the latency in existing NOMA. Then, the achievable data rates for the unipodal 2PAM NOMA are derived. It is shown that for unequal gain channels, the sum rate of the unipodal 2PAM NOMA is comparable to that of the standard 2PAM NOMA, whereas for equal gain channels, the sum rate of the unipodal 2PAM NOMA is superior to that of the standard 2PAM NOMA. In result, the unipodal 2PAM could be a promising modulation scheme for NOMA systems toward 6G.

Keywords: *NOMA, 6G, Superposition coding, User-fairness, Successive interference cancellation, Power allocation.*

1. Introduction

In the fifth generation (5G) and beyond 5G (B5G) mobile communication networks, non-orthogonal multiple access (NOMA) [1-3] is superior than existing orthogonal multiple access (OMA) in the fourth generation (4G) mobile communications, such as long term evolution advanced (LTE-A) [4, 5], due to massive connectivity. Meanwhile, several world-wide companies have already started to prepare the sixth generation (6G) mobile networks [6]. Even though the conventional NOMA has provided lower latency than OMA, the successive interference cancellation (SIC) is still big decoding complexity and latency [7, 8]. Thus, in order to reduce latency, NOMA without SIC has been investigated with non-SIC decoding in discrete-input Lattice-based NOMA [9-12] and the impacts of channel estimation errors on the bit-error rate (BER) performance was studied in non-SIC NOMA [13]. Also, the non-SIC NOMA schemes were investigated for correlated information sources [14].

In this paper, we propose the unipodal binary pulse amplitude modulation (2PAM) NOMA without SIC. First, we derive the analytical expressions for the unipodal 2PAM NOMA for both users. Then, it is shown that for unequal gain channels, the sum rate of the unipodal 2PAM NOMA is comparable to that of the standard

Manuscript Received: November. 19, 2020 / Revised: November. 24, 2020 / Accepted: November. 30, 2020
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2PAM NOMA, whereas for equal gain channels, the sum rate of the unipodal 2PAM NOMA is superior to that of the standard 2PAM NOMA.

The remainder of this paper is organized as follows. In Section 2, the system and channel model are described. The review of the related previous works is presented in Section 3. The achievable data rates for the proposed unipodal 2PAM NOMA without SIC are derived in Section 4. The numerical results are presented and discussed in Section 5. Finally, the conclusions are presented in Section 6.

The main contributions of this paper is summarized as follows:

- We propose the novel unipodal 2PAM NOMA without SIC.
- We formally derive the achievable data rates for the proposed unipodal 2PAM NOMA without SIC.
- It is shown by numerically that for unequal gain channels, the sum rate of the unipodal 2PAM NOMA is comparable to that of the standard 2PAM NOMA.
- Furthermore, we show that for equal gain channels, the sum rate of the unipodal 2PAM NOMA is superior to that of the standard 2PAM NOMA.

2. System and Channel Model

In block fading channels, the complex channel coefficients between the mth user and the base station are denoted by h_1 and h_2 with $|h_1| \geq |h_2|$, $m=1,2$. The base station transmits the superimposed signal $x=\sqrt{P\,\alpha_1}s_1+\sqrt{P\,\alpha_2}s_2$ or $x=\sqrt{P_A\alpha_1}c_1+\sqrt{P_A\alpha_2}c_2$, where s_m or c_m are the message for the mth user with unit power for the standard or unipodal 2PAM, respectively, α_m is the power allocation coefficient, with $\sum_{m=1}^{M}\alpha_m=1$, $M=2$. The observation at the mth user is given by

$$y_m=|h_m|x+n_m, \tag{1}$$

where $n_m \sim \mathcal{N}(0, N_0/2)$ is additive white Gaussian noise (AWGN). It should be noted that for the average total transmitted power P at the base station, P_A is given by [15]

$$P_A=\frac{P}{1+2\rho_{1,2}\sqrt{\alpha_1\alpha_2}}, \tag{2}$$

where the correlation coefficient is $\rho_{1,2}=\mathbb{E}\left[c_1c_2^*\right]$.

It is assumed that for the given information bits $b_1,b_2\in\{0,1\}$, the bit-to-symbol mapping of the standard 2PAM is given by

$$\begin{cases} s_1(b_1=0)=+1 \\ s_1(b_1=1)=-1 \end{cases} \quad \begin{cases} s_2(b_2=0)=+1 \\ s_2(b_2=1)=-1 \end{cases}, \tag{3}$$

whereas the bit-to-symbol mapping of the unipodal 2PAM is given by

$$\begin{cases} c_1(b_1=0)=+1 \\ c_1(b_1=1)\ =-1 \end{cases}, \quad \begin{cases} c_2(b_2=0\,|\,b_1=0)=+\sqrt{2-u} \\ c_2(b_2=1\,|\,b_1=0)\ =+\sqrt{u} \end{cases},$$
$$\begin{cases} c_2(b_2=0\,|\,b_1=1)=-\sqrt{2-u} \\ c_2(b_2=1\,|\,b_1=1)\ =-\sqrt{u} \end{cases}, \tag{4}$$

where u is the unipodal factor, $0<u<1$.

3. Review of Related Previous Works

In this section, we summarize the achievable data rates of both users for the standard 2PAM NOMA. $h(y)=-\mathbb{E}\left[\log_2 p_Y(y)\right]$ is the differential entropy, and $p_Y(y)$ is the probability density function (PDF). First, for the first user, if the perfect SIC is assumed, the achievable data rate R_1 is given by

$$\begin{aligned} R_1 &= h(y_1\,|\,b_2)-h(y_1\,|\,b_1,b_2) \\ &= -\int_{-\infty}^{\infty} p_{Y_1|B_2}(y_1\,|\,b_2=0)\log_2 p_{Y_1|B_2}(y_1\,|\,b_2=0)\,dy_1-\frac{1}{2}\log_2\left(2\pi e N_0/2\right). \end{aligned} \tag{5}$$

where the conditional PDF $p_{Y_1|B_2}(y_1\,|\,b_2=0)$ is calculated by

$$p_{Y_1|B_2}(y_1\,|\,b_2=0)=\frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{\left(y_1-|h_1|\sqrt{\alpha P}\,s_1(b_1=0)\right)^2}{2N_0/2}}+\frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{\left(y_1-|h_1|\sqrt{\alpha P}\,s_1(b_1=1)\right)^2}{2N_0/2}}. \tag{6}$$

Second, for the second user, the achievable data rate R_2 is expressed by

$$R_2=\int_{-\infty}^{\infty} p_{Y_2|B_2}(y_2\,|\,b_2=0)\log_2\frac{p_{Y_2|B_2}(y_2\,|\,b_2=0)}{p_{Y_2|}(y_2)}dy_1, \tag{7}$$

where the PDF $p_{Y_2|}(y_2)$ of y_2 is represented by

$$
\begin{aligned}
p_{Y_2|}\left(y_2\right) = & \frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2-|h_2|\sqrt{P}\left(\sqrt{\alpha}s_1(b_1=0)+\sqrt{(1-\alpha)}s_2(b_2=0)\right)\right)^2}{2N_0/2}} \\
& +\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2-|h_2|\sqrt{P}\left(\sqrt{\alpha}s_1(b_1=1)+\sqrt{(1-\alpha)}s_2(b_2=0)\right)\right)^2}{2N_0/2}} \\
& +\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2-|h_2|\sqrt{P}\left(\sqrt{\alpha}s_1(b_1=0)+\sqrt{(1-\alpha)}s_2(b_2=1)\right)\right)^2}{2N_0/2}} \\
& +\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2-|h_2|\sqrt{P}\left(\sqrt{\alpha}s_1(b_1=1)+\sqrt{(1-\alpha)}s_2(b_2=1)\right)\right)^2}{2N_0/2}}.
\end{aligned}
\tag{8}
$$

and the conditional PDF $p_{Y_2|B_2}\left(y_2 \mid b_2\right)$ of y_2 conditioned on b_2 is represented by

$$
\begin{aligned}
p_{Y_2|B_2}\left(y_2 \mid b_2=0\right) = & \frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2-|h_2|\sqrt{P_A}\left(\sqrt{\alpha}s_1(b_1=0)+\sqrt{(1-\alpha)}s_2(b_2=0)\right)\right)^2}{2N_0/2}} \\
& +\frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2-|h_2|\sqrt{P_A}\left(\sqrt{\alpha}s_1(b_1=1)+\sqrt{(1-\alpha)}s_2(b_2=0)\right)\right)^2}{2N_0/2}}.
\end{aligned}
\tag{9}
$$

4. Derivations of Achievable Data Rates for Unipodal 2PAM NOMA

When the first user does not perform SIC, i.e., NOMA without SIC, the achievable data rate R_1 is given by

$$
\begin{aligned}
R_1 &= I\left(r_1;b_1\right) \\
&= h\left(r_1\right)-h\left(r_1 \mid b_1\right).
\end{aligned}
\tag{10}
$$

Now, the PDF $p_{Y_1|}\left(y_1\right)$ of y_1 is represented by

$$
\begin{aligned}
p_{Y_1|}(y_1) &= \frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_1-|h_1|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=0)+\sqrt{(1-\alpha)}c_2(b_2=0|b_1=0)\right)\right)^2}{2N_0/2}} \\
&+\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_1-|h_1|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=0)+\sqrt{(1-\alpha)}c_2(b_2=1|b_1=0)\right)\right)^2}{2N_0/2}} \\
&+\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_1-|h_1|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=1)+\sqrt{(1-\alpha)}c_2(b_2=0|b_1=1)\right)\right)^2}{2N_0/2}} \\
&+\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_1-|h_1|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=1)+\sqrt{(1-\alpha)}c_2(b_2=1|b_1=1)\right)\right)^2}{2N_0/2}}.
\end{aligned}
\tag{11}
$$

Then, the differential entropy is calculated by

$$
\begin{aligned}
h(r_1) &= -\mathbb{E}\left[\log_2 p_{Y_1|}(y_1)\right] \\
&= -\int_{-\infty}^{\infty} p_{Y_1|}(y_1)\log_2 p_{Y_1|}(y_1)\,dy_1.
\end{aligned}
\tag{12}
$$

And the conditional differential entropy is calculated by

$$
\begin{aligned}
h(y_1 \mid b_1) &= -\mathbb{E}\left[\log_2 p_{Y_1|B_1}(y_1 \mid b_1)\right] \\
&= -\sum_{b_1=0}^{1} P(b_1)\int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 \mid b_1)\log_2 p_{Y_1|B_1}(y_1 \mid b_1)\,dy_1.
\end{aligned}
\tag{13}
$$

where the conditional PDF is given by

$$
\begin{aligned}
p_{Y_1|B_1}(y_1 \mid b_1) &= \frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_1-|h_1|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1)+\sqrt{(1-\alpha)}c_2(b_2=0|b_1)\right)\right)^2}{2N_0/2}} \\
&+\frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_1-|h_1|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1)+\sqrt{(1-\alpha)}c_2(b_2=1|b_1)\right)\right)^2}{2N_0/2}}.
\end{aligned}
\tag{14}
$$

Then, we have the achievable data rate $R_1^{(\text{non-SIC})}$ for the first user as follows:

$$
\begin{aligned}
R_1 &= I(r_1;b_1) \\
&= h(r_1)-h(r_1 \mid b_1) \\
&= h(r_1)+\int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 \mid b_1=0)\log_2 p_{Y_1|B_1}(y_1 \mid b_1=0)\,dy_1,
\end{aligned}
\tag{15}
$$

where we use the translation property of the differential entropy:

$$\int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 | b_1 = 0)\log_2 p_{Y_1|B_1}(y_1 | b_1 = 0)dy_1 = \int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 | b_1 = 1)\log_2 p_{Y_1|B_1}(y_1 | b_1 = 1)dy_1. \tag{16}$$

Thus the achievable data rate R_1 is given by

$$\begin{aligned} R_1 &= -\int_{-\infty}^{\infty} p_{Y_1}(y_1)\log_2 p_{Y_1}(y_1)dy_1 + \int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 | b_1 = 0)\log_2 p_{Y_1|B_1}(y_1 | b_1 = 0)dy_1 \\ &= -\int_{-\infty}^{\infty} \left(p_{Y_1|B_1}(y_1 | b_1 = 0)p_{B_1}(b_1 = 0) + p_{Y_1|B_1}(y_1 | b_1 = 1)p_{B_1}(b_1 = 1)\right)\log_2 p_{Y_1|}(y_1)dy_1 \\ &+ \int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 | b_1 = 0)\log_2 p_{Y_1|B_1}(y_1 | b_1 = 0)dy_1, \end{aligned} \tag{17}$$

where we use the total probability theorem:

$$p_{Y_1|}(y_1) = p_{Y_1|B_1}(y_1 | b_1 = 0)p_{B_1}(b_1 = 0) + p_{Y_1|B_1}(y_1 | b_1 = 1)p_{B_1}(b_1 = 1). \tag{18}$$

Hence the achievable data rate $R_1^{(\text{non-SIC})}$ is expressed by

$$\begin{aligned} R_1 &= -\int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 | b_1 = 0)\log_2 p_{Y_1|}(y_1)dy_1 + \int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 | b_1 = 0)\log_2 p_{Y_1|B_1}(y_1 | b_1 = 0)dy_1 \\ &= \int_{-\infty}^{\infty} p_{Y_1|B_1}(y_1 | b_1 = 0)\log_2 \frac{p_{Y_1|B_1}(y_1 | b_1 = 0)}{p_{Y_1|}(y_1)}dy_1. \end{aligned} \tag{19}$$

It should be noted that the above-mentioned equation has a similar form to the equation (7) for the non-SIC user in the standard 2PAM NOMA, because we do not perform SIC on the first user for the unipodal 2PAM NOMA.

Similarly, for the second user, the achievable data rate R_2 is expressed by

$$R_2 = -\int_{-\infty}^{\infty} p_{Y_2}(y_2)\log_2 p_{Y_2}(y_2)dy_1 + \sum_{b_2=0}^{1} P(b_2)\int_{-\infty}^{\infty} p_{Y_2|B_2}(y_2 | b_2)\log_2 p_{Y_2|B_2}(y_2 | b_2)dy_2, \tag{20}$$

where the PDF $p_{Y_2|}(y_2)$ of y_2 is represented by

$$\begin{aligned} &p_{Y_2}(y_2) = \\ &\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{\left(y_2-|h_2|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=0)+\sqrt{(1-\alpha)}c_2(b_2=0|b_1=0)\right)\right)^2}{2N_0/2}} + \frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{\left(y_2-|h_2|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=0)+\sqrt{(1-\alpha)}c_2(b_2=1|b_1=0)\right)\right)^2}{2N_0/2}} \\ &+\frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{\left(y_2-|h_2|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=1)+\sqrt{(1-\alpha)}c_2(b_2=0|b_1=1)\right)\right)^2}{2N_0/2}} + \frac{1}{4}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{\left(y_2-|h_2|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=1)+\sqrt{(1-\alpha)}c_2(b_2=1|b_1=1)\right)\right)^2}{2N_0/2}}. \end{aligned} \tag{21}$$

and the conditional PDF $p_{Y_2|B_2}(y_2 | b_2)$ of y_2 conditioned on b_2 is represented by

$$p_{Y_2|B_2}(y_2 | b_2) = \frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2 - |h_2|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=0) + \sqrt{(1-\alpha)}c_2(b_2|b_1=0)\right)\right)^2}{2N_0/2}} + \frac{1}{2}\frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{\left(y_2 - |h_2|\sqrt{P_A}\left(\sqrt{\alpha}c_1(b_1=1) + \sqrt{(1-\alpha)}c_2(b_2|b_1=1)\right)\right)^2}{2N_0/2}}. \tag{22}$$

Remark that the above-derived equation is not as compact as the equations for the standard 2PAM NOMA, because the translation property does not hold.

4. Numerical Results and Discussions

It is assumed that $|h_1| = \sqrt{1.5}$ and $|h_2| = \sqrt{0.5}$, for the unequal channel gains, and $|h_1| = |h_2| = 1$, for the equal channel gains. We consider the average total transmitted signal power to noise power ratio (SNR) $P / N_0 = 15$. We also assume that $\alpha_1 = \alpha$ and $\alpha_2 = 1 - \alpha$. In addition, we also use the the unipolarity factor, $u = 0.005$, based on the numerical experiments in Table 1.

Table 1. Optimization of unipolarity factor u with $\alpha_1 = \alpha = 0.1$

Sum Rate $R_1 + R_2$	*Unipolarity factor* u
1.878	0.0001
1.888	0.001
1.899	0.005
1.877	0.05
1.835	0.1

For the first user, the achievable data rates of the unipodal 2PAM NOMA without SIC and the standard 2PAM NOMA with SIC are shown in Fig. 1, for the unipolarity factor, $u = 0.005$.

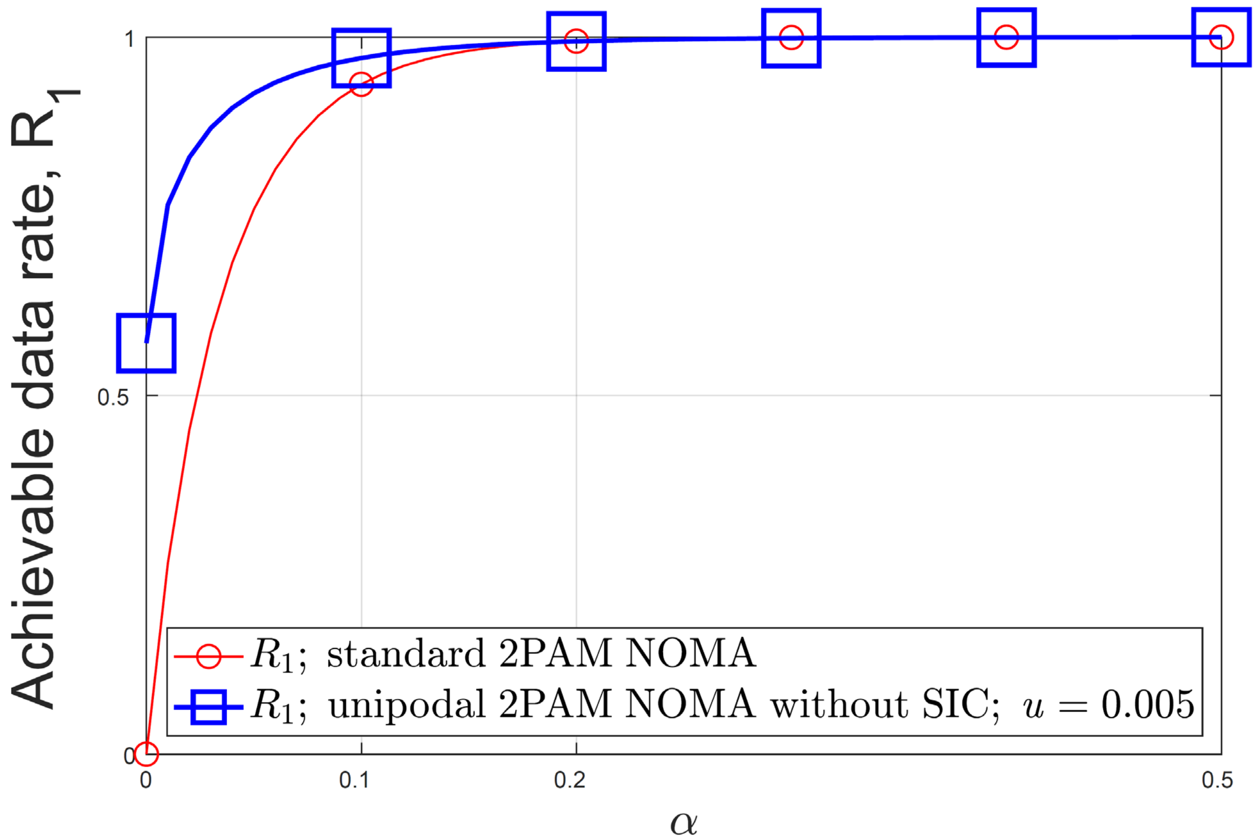

Figure 1. Comparison of achievable data rates for standard/unipodal 2PAM NOMA with/without SIC for first user.

As shown in Fig. 1, It is observed that for the first user, the achievable data rate of the unipodal 2PAM NOMA without SIC increases, compared to that of the standard 2PAM NOMA with SIC, for the designed unipodal factor $u = 0.005$.

Then, for the second user, the achievable data rates of the unipodal 2PAM NOMA without SIC and the standard 2PAM NOMA with SIC are shown in Fig. 2.

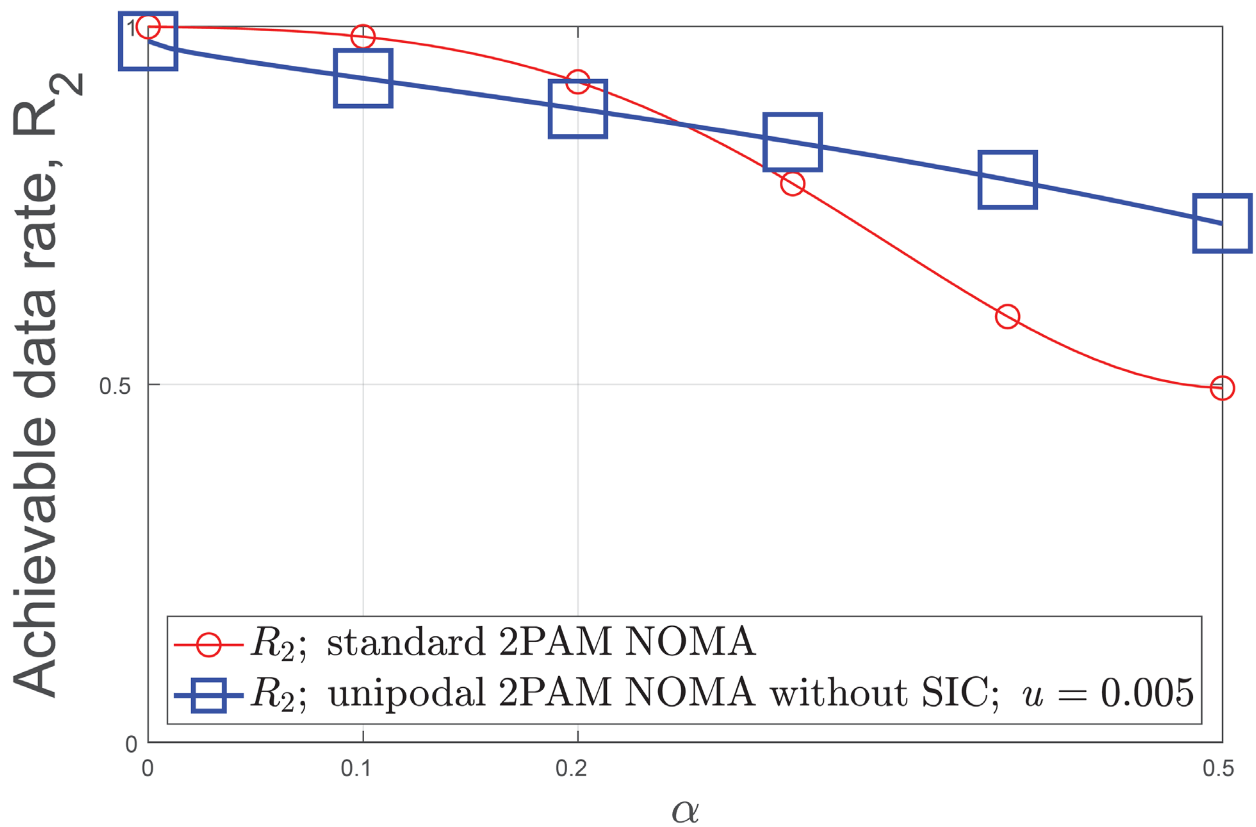

Figure 2. Comparison of achievable data rates for standard/unipodal 2PAM NOMA with/without SIC for second user.

As shown in Fig. 2, however, for the second user, the achievable data rate of the unipodal 2PAM NOMA decreases, compared to that of the standard 2PAM NOMA, for $u = 0.005$, up to the power allocation factor less than $\alpha \simeq 0.25$. It should be noted that as $\alpha_1 = \alpha$ increases, $\alpha_2 = 1 - \alpha$ decreases; thus as $\alpha_1 = \alpha$ increases, the achievable data rate R_2 also decreases.

In order to investigate the total impact of the unipodal 2PAM on the achievable data rate, we depict the sum rate of two users in Fig. 3.

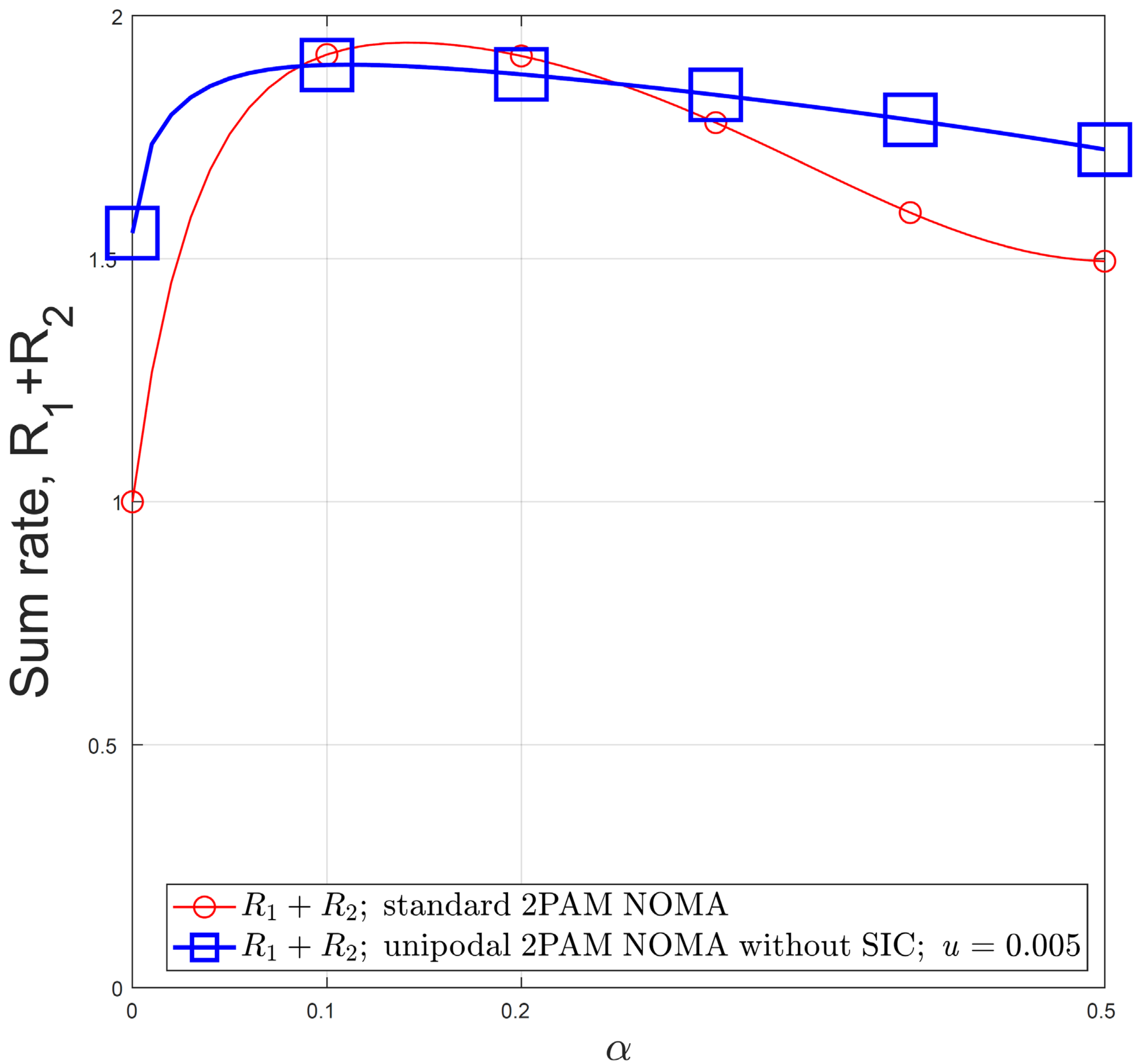

Figure 3. Comparison of sum rate for standard/unipodal 2PAM NOMA with/without SIC for unequal gain channels.

As shown in Fig. 3, the sum rate of the unipodal 2PAM NOMA without SIC is larger than that of the standard 2PAM NOMA with SIC, except the vicinity of the power allocation coefficient about $\alpha \simeq 0.15$. It should be noted that user-fairness of the main principle of NOMA recommends that the power allocation coefficient should be less than about $\alpha \simeq 0.1$. It should be noted that for about $\alpha_1 = \alpha > 0.2$, the achievable data rate R_1 is almost one, whereas the achievable data rate R_2 decreases; thus as $\alpha_1 = \alpha$ increases, the sum rate $R_1 + R_2$ also decreases.

Also, in order to investigate the impact of the unipodal 2PAM NOMA without SIC on the achievable sum rate, especially when the channel gains are equal, i.e., $|h_1| = |h_2| = 1$, we depict the sum rate of two users in Fig. 4.

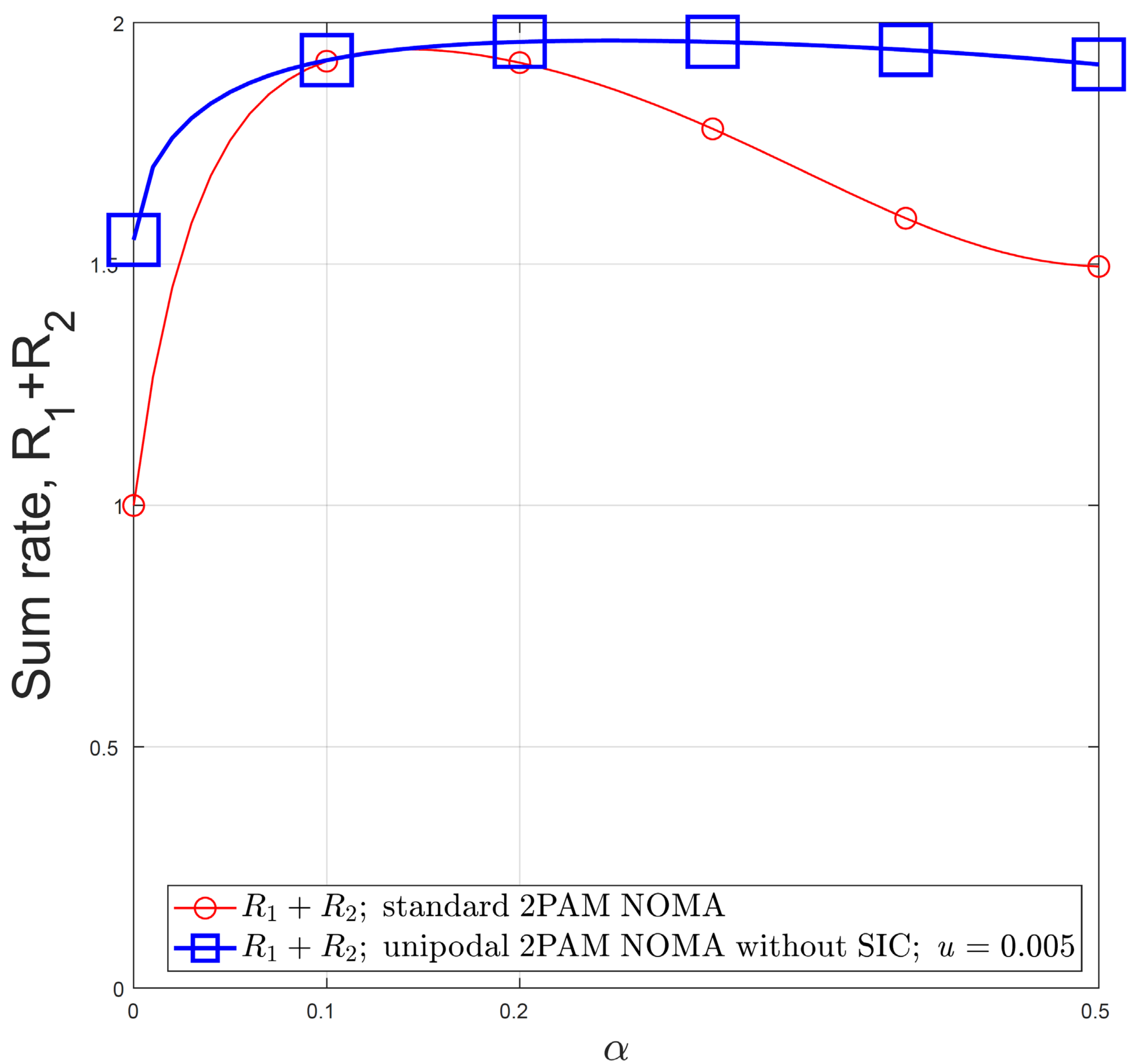

Figure 4. Comparison of sum rate for standard/unipodal 2PAM NOMA with/without SIC for equal gain channels.

As shown in Fig. 4, the sum rate of the unipodal 2PAM NOMA without SIC is larger than that of the standard 2PAM NOMA with SIC, over the entire power allocation coefficient. It should be noted that the standard NOMA is not superior to the conventional OMA, especially for the equal gain channels. However, the proposed unipodal 2PAM NOMA without SIC is superior to the conventional OMA, even for the equal gain channels.

5. Conclusion

In this paper, we proposed the unipodal 2PAM NOMA without SIC. First, we derived the analytical expressions for the achievable data rates of proposed the unipodal 2PAM NOMA without SIC. Then it was shown that for the stronger channel user, the achievable data rate of the unipodal 2PAM NOMA without SIC increases. We also showed that for the weaker channel user, the achievable data rate of the unipodal 2PAM NOMA decreases up to the power allocation factor less than $\alpha \simeq 0.25$. In addition, for unequal gain channels, the sum rate of the unipodal 2PAM NOMA without SIC is comparable to that of the standard 2PAM NOMA. Furthermore, we showed that for equal gain channels, the sum rate of the unipodal 2PAM NOMA without SIC is superior to that of the standard 2PAM NOMA. As a consequence, the unipodal 2PAM could be a promising modulation scheme for NOMA toward 6G systems, with super ultra-low latency, especially without SIC.

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