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On Lossless Interval of Low-Correlated Superposition Coding NOMA toward 6G URLLC

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Abstract

Recently, a lossless non-successive interference cancellation (SIC) non-orthogonal multiple access (NOMA) implementation has been proposed. Such lossless NOMA without SIC is achieved via correlated superposition coding (SC), in comparison with conventional independent SC. However, only high-correlated SC was investigated in the lossless non-SIC NOMA implementation. Thus, this paper investigates low-correlated SC, especially a lossless interval, owing to low-correlation between signals.

First, for the low-correlated SC scheme, we derive the closed-form expressions for the two roots with which the lossless interval is defined. Then, simulations demonstrate that the lossless interval of low-correlated SC NOMA is enlarged, with a degraded middle interval, compared to that of high-correlated SC NOMA. Moreover, we also show that such tendency becomes stronger as the value of the correlation coefficient varies.

As a result, the proposed low-correlated SC scheme could be considered as a promising correlated SC scheme, with the enlarged lossless interval in NOMA toward the future sixth-generation (6G) ultra-reliable low-latency communications (URLLC).

Keywords: *NOMA, 6G, URLLC, Superposition coding, Successive interference cancellation, Power allocation.*

1. Introduction

One of key communication scenarios to be serviced by the future sixth-generation (6G) mobile network [1] is ultra-reliable low-latency communications (URLLC). As the number of mobile devices has been increasing rapidly from the fourth-generation (4G) network [2, 3] to the fifth-generation (5G) and beyond 5G (B5G) network, i.e., more than 10^7 devices/km^2, non-orthogonal multiple access (NOMA) [4-6] has tackled the spectral efficiency. In NOMA, successive interference cancellation (SIC) is a decoding latency factor [7, 8]. To reduce latency, NOMA without SIC was investigated in discrete-input lattice-based NOMA [9-12]. Impacts of correlation on superposition coding (SC) have been investigated [13]. Channel estimation errors were also studied [14]. Unipodal binary pulse amplitude modulation (2PAM) was proposed in NOMA [15]. In addition, a non-SIC NOMA scheme has been investigated for correlated information sources [16]. Asymmetric 2PAM non-SIC NOMA was proposed in [17].

Recently, a lossless NOMA without SIC has been proposed [18]. This lossless non-SIC NOMA was

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achieved via correlated superposition coding (SC), in contrast to conventional independent SC. However, only the achievable data rates for high-correlated SC NOMA were investigated in [18]. Thus, this paper investigates low- correlated SC, especially a lossless interval, owing to low-correlation between signals.

First, for a low-correlated SC scheme, we derive the closed-form expressions for the two roots with which the lossless interval is defined. Then, simulations demonstrate that the lossless interval of low-correlated SC NOMA is enlarged, with a degraded middle interval, compared to that of high-correlated SC NOMA.

The remainder of this paper is organized as follows. In Section 2, the system and channel model are described. Lossless intervals of low-correlated SC are derived in Section 3. The numerical results are presented and discussed in Section 4. Finally, the conclusions are presented in Section 5.

The main contributions of this paper are summarized as follows:

- We propose a low-correlated SC NOMA scheme, in contrast to a conventional high-correlated SC NOMA scheme.
- Then, we derive the power allocation range to be achieved by the proposed low-correlated SC scheme, namely lossless interval.
- It is shown that the lossless interval of low-correlated SC is enlarged, with degraded middle interval, compared to that of high-correlated SC.
- Moreover, we also show that such tendency becomes stronger as the value of the correlation coefficient varies.

2. System and Channel Model

Consider a cellular downlink NOMA network with one base station and two users. The complex channel coefficient between the *m*th user and base station is denoted by h_m, $m = 1,2$. The channels are sorted as $|h_1| \geq |h_2|$. The base station sends the superimposed signal $x = \sqrt{Pa_1}s_1 + \sqrt{Pa_2}s_2$, where P is the average power of x, s_m is the signal for the *m*th user with the average unit power, and a_m is the power allocation coefficient, with $a_1 + a_2 = 1$. Note that $r_{1,2} = E\left[s_1 s_2^*\right] = 0$, in conventional NOMA schemes. The received signal r_m at the *m*th user is expressed as follows:

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

where $n_m \sim CN(0, s^2)$ is a complex additive white Gaussian noise (AWGN) term. On the other hand, the base station can also send the *correlated* superimposed signal $z = \sqrt{P_A b_1}c_1 + \sqrt{P_A b_2}c_2$, where the average *allocated* total power P_A of c_1 and c_2 is given by

$$P_A = \frac{P}{\sum_{i=1}^{2}\sum_{j=1}^{2} r_{i,j}\sqrt{b_i b_j}}, \tag{2}$$

where $r_{1,2} = E\left[c_1 c_2^*\right]$ is the correlation coefficient of the messages' signals, which stands for the similarity between the two signals. c_m is the signal for the *m*th user with the average unit power. b_m is the power allocation coefficient, with $b_1 + b_2 = 1$. The received signal y_m at the *m*th user is expressed as follows:

$$y_m = h_m z + n_m. \tag{3}$$

3. Derivation of Lossless Interval of Low-Correlated Superposition Coding NOMA

Before the derivation, we summarize the *conditional* achievable sum rate given $|h_1|$ and $|h_2|$ in conventional NOMA schemes, as follows:

$$R_{sum\,|\,|h_1|,|h_2|} = R_{1\,|\,|h_1|} + R_{2\,|\,|h_2|}, \tag{4}$$

where

$$R_{1\,|\,|h_1|} = \log_2\left(1 + \frac{|h_1|^2 P\alpha_1}{\sigma^2}\right) \tag{5}$$

and

$$R_{2\,|\,|h_2|} = \log_2\left(1 + \frac{|h_2|^2 P\alpha_2}{|h_2|^2 P\alpha_1 + \sigma^2}\right). \tag{6}$$

In addition, the *conditional* achievable sum rate given $|h_1|$ and $|h_2|$ in correlated SC (CSC)/SIC NOMA schemes is given by [18]:

$$R^{(\text{CSC/SIC})}_{sum\,|\,|h_1|,|h_2|} = R^{(\text{CSC/SIC})}_{1\,|\,|h_1|,\,(\text{SIC})} + R^{(\text{CSC/SIC})}_{2\,|\,|h_2|,\,(\text{non-SIC})}. \tag{7}$$

where

$$R^{(\text{CSC/SIC})}_{1\,|\,|h_1|,\,(\text{SIC})} = \log_2\left(1 + \frac{|h_1|^2 P_A b_1 (1 - r_{1,2}^2)}{s_2}\right) \tag{8}$$

and

$$R^{(\text{CSC/SIC})}_{2\,|\,|h_2|,\,(\text{non-SIC})} = \log_2\left(\frac{|h_2|^2 P + \sigma^2}{|h_2|^2 P_A \beta_1 (1 - \rho_{1,2}^2) + \sigma^2}\right). \tag{9}$$

where $R^{(\text{CSC/SIC})}_{2||h_2|,(\text{non-SIC})}$ of the high-correlated SC scheme, i.e., $\rho_{1,2} \geq \rho^{\text{C}}_{1,2}$, is larger than $R^{(\text{CSC/SIC})}_{2||h_2|,(\text{non-SIC})}$ of the low-correlated SC scheme, i.e., $\rho_{1,2} < \rho^{\text{C}}_{1,2}$.

For CSC/non-SIC NOMA schemes, the *conditional* achievable sum rate given $|h_1|$ and $|h_2|$ is as follows [18]:

$$R^{(\text{CSC/non-SIC})}_{sum||h_1|,|h_2|} = R^{(\text{CSC/non-SIC})}_{1||h_1|,(\text{non-SIC})} + R^{(\text{CSC/non-SIC})}_{2||h_2|,(\text{non-SIC})}, \tag{10}$$

where

$$R^{(\text{CSC/non-SIC})}_{1||h_1|,(\text{non-SIC})} = \log_2\left(\frac{|h_1|^2 P + \sigma^2}{|h_1|^2 P_A \beta_2\left(1-\rho^2_{2,1}\right)+\sigma^2}\right) \tag{11}$$

and

$$R^{(\text{CSC/non-SIC})}_{2||h_2|,(\text{non-SIC})} = R^{(\text{CSC/SIC})}_{2||h_2|,(\text{non-SIC})}. \tag{12}$$

Remark that in the CSC/non-SIC NOMA scheme, the first user also does not perform SIC, whereas the second user always does not perform SIC, both in the CSC/non-SIC NOMA and in the conventional SIC NOMA, because the second user is the weakest channel gain user.

First, in order to have a lossless interval, we should have

$$R^{(\text{CSC/non-SIC})}_{1||h_1|,(\text{non-SIC})} = \log_2\left(\frac{|h_1|^2 P + \sigma^2}{|h_1|^2 P_A \beta_2\left(1-|\rho_{2,1}|^2\right)+\sigma^2}\right) \geq R^{(\text{CSC/SIC})}_{1||h_1|,(\text{SIC})} = \log_2\left(\frac{|h_1|^2 P_A \beta_1\left(1-|\rho_{1,2}|^2\right)+\sigma^2}{\sigma^2}\right). \tag{13}$$

Then, after some algebraic manipulations, we obtain the lossless interval:

$$\beta_1 \leq \beta_1^{(\text{root\#1})}, \quad \beta_1^{(\text{root\#2})} \leq \beta_1, \tag{14}$$

where

$$\beta_1^{(\text{root\#1})} = \frac{1-\sqrt{1-4K}}{2}, \qquad \beta_1^{(\text{root\#2})} = \frac{1+\sqrt{1-4K}}{2}, \tag{15}$$

with

$$K = \left(\frac{2s^2 r_{1,2}\left(\left|r_{1,2}\right|^2 - 1\right) ? \sqrt{\left(2s^2 r_{1,2}\left(\left|r_{1,2}\right|^2 - 1\right)\right)^2 + 4\left(P\left|h_1\right|^2\left(1-\left|r_{1,2}\right|^2\right)\left(1-\left|r_{1,2}\right|^2\right) - s^2 2\mathrm{Re}\{r_{1,2}\} 2\mathrm{Re}\{r_{1,2}\}\right) s^2 \left|r_{1,2}\right|^2}}{2\left(P\left|h_1\right|^2\left(1-\left|r_{1,2}\right|^2\right)\left(1-\left|r_{1,2}\right|^2\right) - s^2 2\mathrm{Re}\{r_{1,2}\} 2\mathrm{Re}\{r_{1,2}\}\right)} \right)^2. \tag{16}$$

Notably, when

$$P\alpha_1 = P_A \beta_1 (1 - \rho_{1,2}^2), \tag{17}$$

we have the following equations:

$$R_{1||h_1|} = R^{(\mathrm{CSC/SIC})}_{1||h_1|,(\mathrm{SIC})}, \tag{18}$$

and

$$R_{2||h_2|} = R^{(\mathrm{CSC/SIC})}_{2||h_2|,(\mathrm{non\text{-}SIC})}. \tag{19}$$

4. Numerical Results and Discussions

First, we investigate the power allocation range to be achieved by the proposed low-correlated SC scheme, by comparing $R^{(\mathrm{CSC/non\text{-}SIC})}_{sum||h_1|,|h_2|}$ with $R_{sum||h_1|,|h_2|}$. For this, the conditionals are assumed to be $|h_1| = \sqrt{2}$ and $|h_2| = 0.1$, and the average total transmitted signal-to-noise power ratio (SNR) is $P / s^2 = 50$. It should be noted that the objective of this study is to investigate the conditional achievable rates given the channel gain realization, so that for any fading channel gain model, such as Rayleigh fading channel, the simulation results are applicable. Then, for the high-correlated SC schemes, $r_{1,2}$? $r^{\mathrm{C}}_{1,2}$ 0.819, whereas for the low-correlated SC schemes, $r_{1,2} < r^{\mathrm{C}}_{1,2} = 0.819$.

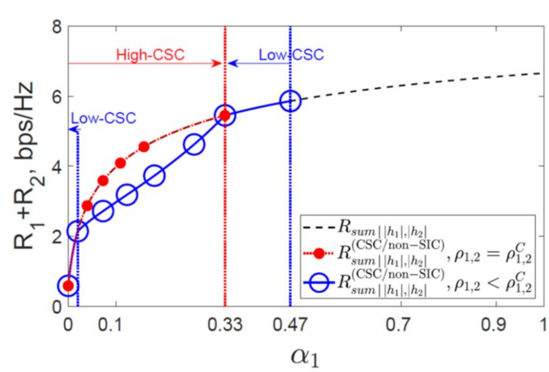

Figure 1. Comparison of achievable sum rates of conventional high-correlated SC scheme and proposed low-correlated SC scheme.

As shown in Fig. 1, the power allocation range achieved by the proposed low-correlated SC scheme with $r_{1,2} = 0.75 < r_{1,2}^{C} = 0.819$ is given numerically as $0 ? \alpha_1 \quad 0.02$ or $0.33 ? \alpha_1 \quad 0.47$, whereas the power allocation range achieved by the conventional high-correlated SC scheme with $r_{1,2} = r_{1,2}^{C} = 0.819$ is given numerically as $0 ? \alpha_1 \quad 0.33$. Notably, the power allocation range achieved by the proposed low-correlated SC scheme with $r_{1,2} = 0.75 < r_{1,2}^{C} = 0.819$ is much larger than that of the conventional high-correlated SC scheme with $r_{1,2} = r_{1,2}^{C} = 0.819$, although the proposed low-correlated SC scheme is slightly inferior to the conventional high-correlated SC scheme over $0.02 ? \alpha_1 \quad 0.33$. It should be noted that the smaller the correlation coefficient $\rho_{1,2}$ is, the larger the power allocation range $0 ? \alpha_1 \quad (1 - \rho_{1,2}^{2})$ in equation (17) becomes.

Second, in order to investigate the power allocation ranges to be achieved by the proposed low-correlated SC schemes and the conventional high-correlated SC schemes with varying $\rho_{1,2}$, we depict the lossless intervals in Fig. 2, where $0 ? \alpha_1 \quad (1 - \rho_{1,2}^{2})$ is for the conventional high-correlated SC schemes, and $0 ? \alpha_1 \quad \beta_1^{(\text{root}\#1)}$ or $\beta_1^{(\text{root}\#2)} ? \alpha_1 \quad (1 - \rho_{1,2}^{2})$ are for the proposed low-correlated SC schemes.

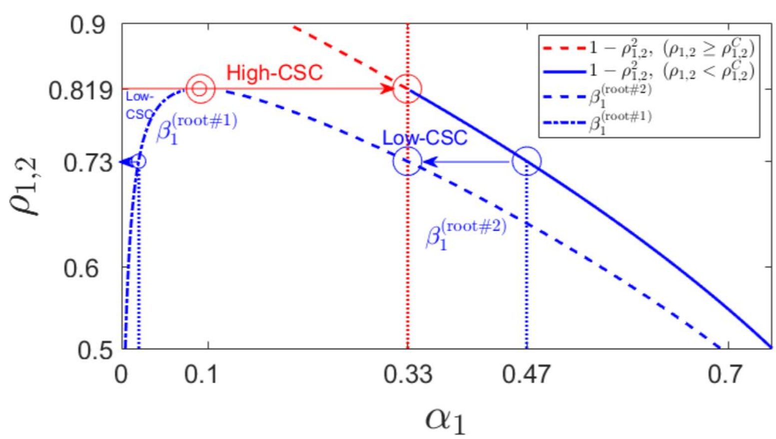

Figure 2. Comparison of lossless intervals to be achieved by proposed low-CSC and conventional high-CSC.

As shown in Fig. 2, the power allocation ranges to be achieved by the proposed low-correlated SC schemes increase greatly, as $\rho_{1,2}$ decreases, whereas the power allocation ranges to be achieved by the conventional high-correlated SC schemes decrease, as $\rho_{1,2}$ increases. Notably, based on the upper limit $\alpha_1 < (1 - \rho_{1,2}^{2})$ of the power allocation range, for the smaller correlation coefficient, the upper limit $\alpha_1 < (1 - \rho_{1,2}^{2})$ increases, whereas for the larger correlation coefficient, the upper limit $\alpha_1 < (1 - \rho_{1,2}^{2})$ decreases.

5. Conclusion

In this paper, we proposed a low- correlated SC, especially by low-correlation between signals, which was designed by the base station or the communication systems.

First, for the low-correlated SC scheme, we derived the closed-form expressions for the two roots with which the lossless interval was defined. Then, simulations demonstrated that the lossless interval of low-correlated SC NOMA is enlarged, with a degraded middle interval, compared to that of high-correlated SC NOMA. Moreover, we also showed that such tendency becomes stronger with the varying value of the correlation coefficient.

As a result, the proposed low-correlated SC scheme could be considered as a promising correlated SC scheme, with the enlarged lossless interval in NOMA toward the future 6G URLLC.

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