Diversity-Controlled Multi-User Superposition Transmission for Uplink Cellular Networks

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***Abstract*—In this paper, we propose a diversity-controlled multi-user superposition transmission (MUST) technique for an *uplink* cellular networks, which allows multiple cell-center users to multiplex their signals with signal of a single cell-edge user. In particular, a joint maximum-likelihood (ML) receiver architecture is proposed to improve BER performance of users in uplink. Recall that a successive interference cancellation (SIC) receiver is adopted for downlink MUST techniques in general. However, it is shown through extensive computer simulations that the proposed joint ML receiver significantly outperforms the SIC receiver especially when the number of cell-center users is large.**

I. INTRODUCTION

Orthogonal multiple access (OMA) techniques have been widely used in cellular networks since the first generation cellular systems (i.e. FDMA), which simplifies a receiver structure. Recently, however, a non-orthogonal multiple access (NOMA) technique has been proposed to improve the spectral efficiency of the 5G network by allowing multiple users to utilize the same radio resources [1]–[3]. In general, advanced techniques such as multi-user detector and successive interference cancellation (SIC) are adopted in the NOMA based cellular networks.

There exist various types of NOMA techniques in literature, which include multi-user shared access (MUSA) [4], sparse code multiple access (SCMA) [5], cooperative NOMA [6], etc. In addition, the uplink NOMA techniques have been proposed [7], [8]. At each user in the downlink NOMA technique, the multiplexed signal in the downlink experiences the same fading and path-loss collectively, and it can be successfully separated with the SIC technique if a proper power allocation is adopted at the base station (BS). For the uplink NOMA techniques, in contrast, the BS receives the super-imposed signals from different users, each of which experiences independent short-term (small-scale) fading and path-loss. Recently, the NOMA concept has been applied to random access networks [9]–[12].

Multi-user superposition transmission (MUST) is a practical downlink NOMA technique that has been studied in 3GPP LTE standards [13]. The MUST techniques are divided into three categories according to adaptive power control and bit-labeling at the transmitter side. The MUST techniques, in general, assume asymmetric downlink scenarios consisting of cell-edge and cell-center users. A novel low-complexity MUST technique, called diversity-controlled MUST technique, was proposed for the downlink cellular networks, which allows multiple cell-edge users to be multiplexed with a single cell-center user [14]. In particular, the bit error rate (BER) performance was mathematically analyzed for both cell-edge user and cell-center users in [14].

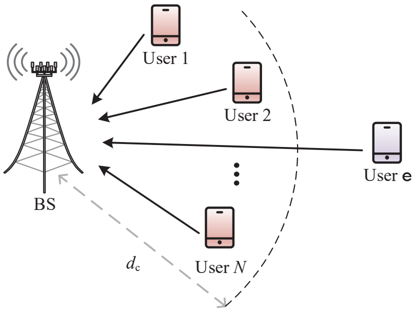

Fig. 1. System model of the proposed uplink MUST technique.

In this paper, we propose a diversity-controlled MUST technique for a uplink cellular network which consists of a single BS, multiple cell-center users, and a single cell-edge user. In the proposed diversity controlled MUST technique allows multiple cell-center users to multiplex their uplink signal with a single cell-edge user via the same radio resources. We also propose a novel joint maximum likelihood (ML) detection technique for further improving the BER performance of the proposed uplink diversity-controlled MUST technique. Through extensive computer simulations, we investigate the BER performance of the proposed uplink MUST technique especially by comparing two types of detectors: SIC and joint ML.

II. SYSTEM MODEL

We consider an uplink cellular network system consisting of a single base station (BS), N cell-center users, and a single cell-edge user. We assume that all users and the BS have a single transmit/receive antenna, and quadrature phase shift keying (QPSK) modulation is used. As shown in Fig 1, the cell-center users are denoted by users $1, 2, \ldots, N$, and they are closer to the BS than the cell-*edge* user e. d_c represents the boundary distance among the cell-center users and the cell-edge user. Each signal of all cell-center users is transmitted

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over a different frequency band (sub-carrier), while the signal of the cell-edge user is sent over N frequency bands (sub-carriers). In addition, we assume that the total transmit power of the cell-edge user is uniformly divided over N sub-carriers. When the cell-center user $i \in \{1, 2, \ldots, N\}$ transmits the signal via the i-th sub-carrier, the superposed signal between the i-th cell-center user and the cell-edge user is given by

$$\begin{aligned} s_i &= h_i \sqrt{\mathcal{E} d_i^{-\alpha}} x_i + h_{\mathsf{e},i} \sqrt{\tfrac{\mathcal{E}}{N} d_{\mathsf{e}}^{-\alpha}} x_{\mathsf{e}}, \\ y_i &= s_i + n_i, \end{aligned} \tag{1}$$

where s_i and y_i indicate the superposed signal and the received signal at the BS via the i-th sub-carrier, respectively. And, h_i and $h_{\mathsf{e},i}$ represent the channel coefficients of the i-th cell-center user and the cell-edge user, respectively. All channels are identically and independently distributed, and follow the complex-valued Gaussian distribution with zero mean and unit variance. Furthermore, x_i and x_{e} represent the QPSK symbols of the i-th cell-center user and the cell-edge user, $\mathcal{E}$ denotes the fixed transmit power of each user, and d_i and d_{e} denote the distance of the i-th cell-center user and the cell-edge user to the BS, respectively. α is the path-loss exponent, and n_i represents the additive white Gaussian noise (AWGN) on the i-th sub-carrier, i.e. $n_i \sim \mathcal{CN}(0, \sigma_n^2)$, where σ_n is the standard deviation of the Gaussian noise.

III. PROPOSED UPLINK DIVERSITY-CONTROLLED MUST

In this section, we consider two types of detectors at the BS: successive interference cancellation (SIC) detector and joint ML detector in order to detect the signal of the cell-edge user, while the signal of each cell-center user is detected only by the joint ML detector.

A. SIC detection for cell-edge user

The BS performs the SIC detection by assuming that the channel gain of the cell-center user is always larger than the cell-edge user, even though the channel gain of the cell-edge user can be greater than the channel gain of the cell-center user with the probability of $1/(1 + d_{r,i}^{-\alpha}/N)$, where $d_{r,i} := d_i/d_{\mathsf{e}}$. We also assume that the BS knows the channel state information and distances of all users. First, the BS calculates the log-likelihood ratio (LLR) value for the received signal of the i-th cell-center user as follow:

$$\begin{aligned} \mathcal{L}_{k,i} &= \log \frac{\Pr\{y_i \mid b_{k,i} = 0\}}{\Pr\{y_i \mid b_{k,i} = 1\}} \\ &= \log \frac{\sum\limits_{s_0 \in \{s_i \mid b_{k,i}=0\}} \Pr\{y_i \mid s_0\}}{\sum\limits_{s_1 \in \{s_i \mid b_{k,i}=1\}} \Pr\{y_i \mid s_1\}} \\ &= \log \frac{\sum\limits_{s_0 \in \{s_i \mid b_{k,i}=0\}} \exp\left(-\frac{|y_i - s_0|^2}{\sigma_n^2}\right)}{\sum\limits_{s_1 \in \{s_i \mid b_{k,i}=1\}} \exp\left(-\frac{|y_i - s_1|^2}{\sigma_n^2}\right)}, \end{aligned} \tag{2}$$

where $\mathcal{L}_{k,i}$ and $b_{k,i}$ denote the LLR value of the k-th bit and the k-th bit value of the cell-center user i, respectively. For the QPSK modulation, $k \in \{1, 2\}$. Then, according to $\mathcal{L}_{k,i}$, the k-th bit of the cell-center user i is determined as follows:

$$\hat{b}_{k,i} = \begin{cases} 0, & \text{if } \mathcal{L}_{k,i} \geq 0 \\ 1, & \text{if } \mathcal{L}_{k,i} < 0 \end{cases}. \tag{3}$$

Next, we require to obtain the QPSK symbol $\hat{x}_i$ from the QPSK constellation of $(\hat{b}_{1,i}\hat{b}_{2,i})$ in order to perform the following symbol-level SIC:

$$\bar{y}_i = y_i - h_i \sqrt{\mathcal{E} d_i^{-\alpha}} \hat{x}_i. \tag{4}$$

Finally, the LLR value of the k-th bit of the cell-edge user is calculated with $\bar{y}_i$ as follows:

$$\mathcal{L}_{k,\mathsf{e}} = \log \frac{\sum\limits_{x_0 \in \{x_{\mathsf{e}} \mid b_{k,\mathsf{e}}=0\}} \exp\left(-\frac{|\bar{y}_i - x_0|^2}{\sigma_n^2}\right)}{\sum\limits_{x_1 \in \{x_{\mathsf{e}} \mid b_{k,\mathsf{e}}=1\}} \exp\left(-\frac{|\bar{y}_i - x_1|^2}{\sigma_n^2}\right)}, \tag{5}$$

where $b_{k,\mathsf{e}}$ denotes the k-th bit of the cell-edge user. Then, the k-th bit of the cell-edge user is determined as follows:

$$\hat{b}_{k,\mathsf{e}} = \begin{cases} 0, & \text{if } \mathcal{L}_{k,\mathsf{e}} \geq 0 \\ 1, & \text{if } \mathcal{L}_{k,\mathsf{e}} < 0 \end{cases}. \tag{6}$$

B. Joint ML detection for cell-edge user

For the cell-edge user, the BS performs joint ML detection from N received signals as follows:

$$\mathcal{L}_{k,\mathsf{e}} = \sum_{i=1}^{N} \log \frac{\sum\limits_{s_0 \in \{s_i \mid b_{k,\mathsf{e}}=0\}} \exp\left(-\frac{|y_i - s_0|^2}{\sigma_n^2}\right)}{\sum\limits_{s_1 \in \{s_i \mid b_{k,\mathsf{e}}=1\}} \exp\left(-\frac{|y_i - s_1|^2}{\sigma_n^2}\right)}. \tag{7}$$

Eq. (7) indicates that the BS combines all LLR values of x_{e} in order to perform the joint ML detection for the cell-edge user. According to $\mathcal{L}_{k,\mathsf{e}}$, the bit of the cell-edge user is determined by the Eq. (6).

IV. SIMULATION RESULTS

In this section, we show the performance of the proposed uplink MUST technique by extensive computer simulations. Specifically, the average bit error rate (BER) curves of the cell-center/edge users are shown according to the number of cell-center users based on two types of detection methods. We assume that all cell-center users are located with the same distance to the BS. Note that the SNR (dB) of the cell-center user is used in x axis in all simulations.

Fig. 2 shows the BER performance of the proposed uplink MUST technique based on the SIC detection method for varying SNR values when $\alpha = 3$, $d_{r,i} = 2$ and $N = 1, 2, 4, 6$. In the SNR range of 0 to 25 dB, as N increases, the BER performance of the cell-center users is slightly improved by the reduced interference of the cell-edge user. The BER performance of the cell-edge user improves as N (diversity order) increases.

Fig. 3 shows the BER performance of the proposed uplink MUST technique based on joint ML detection method for varying SNR values when $\alpha = 3$, $d_{r,i} = 2$, and $N = 1, 2, 4, 6$.

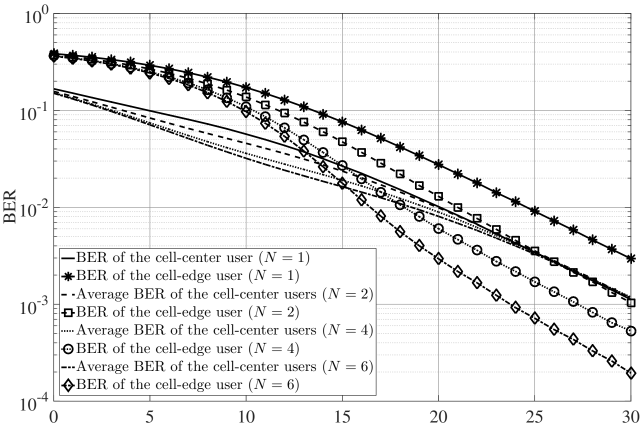

Fig. 2. BER performance of the proposed uplink MUST technique based on the SIC detection when α=3, $d_{r,i}=2$ and $N=1,2,4,6$.

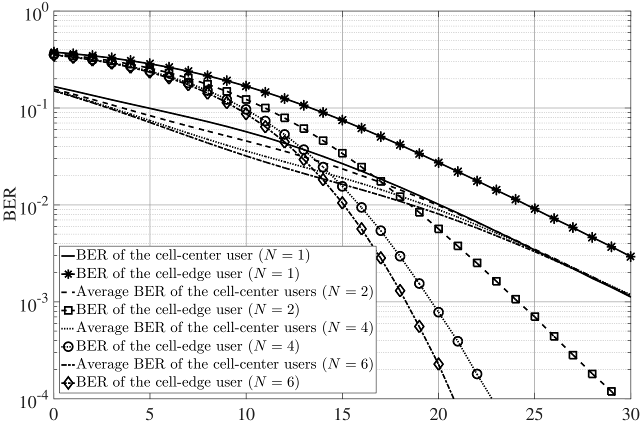

Fig. 3. BER performance of the proposed uplink MUST technique based on the joint ML detection method when α=3, $d_{r,i}=2$ and $N=1,2,4,6$.

The performance of the cell-edge user is more improved by the frequency diversity proportional to N especially in a high SNR range, compared to that of the SIC detection in Fig. 2.

Fig. 4 shows the BER performance of the proposed uplink MUST technique based on the joint ML detection for varying $d_{r,i} := d_i/d_{\mathsf{e}}$ when $\alpha=3$, $N=2$. As $d_{r,i}$ increases (the cell-edge user is farther away from the cell-center users), the BER performance of the cell-edge user decreases, while the average BER performance of the cell-center user increases due to the reduced interference by the cell-edge user.

V. CONCLUSION

In this paper, we proposed a diversity-controlled uplink MUST technique that allows multiple cell-center users to multiplex their uplink signals with the signal of the cell-edge user. We considered two types of detectors at the BS, which includes the SIC and the joint ML. Extensive computer simulation results showed that the BER performance of the cell-edge user with the joint ML detection outperforms that of the SIC detection as the number of cell-center users multiplexed increases.

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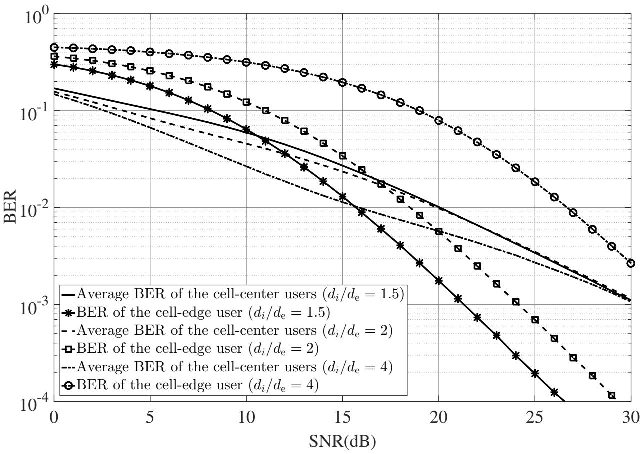

Fig. 4. BER performance of the proposed uplink MUST technique based on the joint ML detection method when α=3, $N=2$, $d_{r,i}=1.5,2,4$.

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