Potential of Cooperative SIC for Uplink NOMA in Multi-Cell Network

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Abstract: Uplink non-orthogonal multiple access (NOMA) has attracted considerable attention as a key technology for beyond 5G/6G telecommunication. However, when adopting the uplink NOMA in multi-cell networks where an uplink signal may reach multiple base stations (BSs), the successive interference cancellation (SIC) process must be completed at every BS, resulting in smaller throughput owing to bottlenecks. To cope with this issue, we propose a novel approach called cooperative-SIC (C-SIC), where SIC processes at different BSs are mutually combined by exploiting signal transfer through backhaul links, which can prevent some signals from experiencing bottlenecks. Through performance comparison with the conventional NOMA, we reveal the significant potential of C-SIC for the uplink NOMA in a multi-cell network.

Keywords: cooperative interference cancellation, C-SIC, NOMA, power allocation, SIC, signal transfer, uplink.

Classification: Wireless communication technologies

References

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1 Introduction

Resource allocation in uplink non-orthogonal multiple access (NOMA) is performed by controlling the transmit power of user equipments (UEs). The
transmit power of each UE is calculated from the propagation attenuation of the UEs’ signals and the signal-to-interference-plus-noise ratio (SINR) required to meet the target throughput [1]. In the case of uplink NOMA, where the UEs’ signals can reach multiple base stations (BSs), the throughput is dominated by the BS with the lowest SINR. This is because successive interference cancellation (SIC) at each BS must decode the signals of the UEs. Throughput bottlenecks can be prevented by transferring the signal from the BS with the best SINR to other BSs with lower SINRs. Signal transfer allows SIC to be performed without decoding at the other BSs [2].

In this study, we aim to reveal the potential performance of the uplink NOMA employing cooperative-SIC (C-SIC), which exploits the signal transferred between BSs. First, we clarify the mechanism of the throughput bottleneck occurring in uplink NOMA. Then, the advantage of mutually combined SIC processes in C-SIC is demonstrated, and the derivation method of transmit power allocation is provided. Finally, we demonstrate the performance of C-SIC through numerical analysis and compare it to the conventional approaches.

2 Cooperative SIC for uplink NOMA

2.1 Communication capacities under inter-cell interference

In this study, we use the parameters achieved through standardization of the 3.7 GHz band [3], and the channel model is assumed to be a propagation model that integrates theoretical and experimental models for standardization [4]. This model is based on the two-wave model for line-of-sight communications over $R_s$ [m] to 1000m. In an urban environment with low antenna height and heavy traffic, the propagation attenuation breakpoint disappears due to the unstable reception of the reflected wave. In real-world communications, attenuation varies with time due to fading, but in this study, we use the median value as the propagation attenuation, ignoring the effects of fading and thermal noise in the transmitter and receiver. We assume that the interference power from outside the cell is constant. We considered the uplink communication between two BSs and four UEs, i.e., UE1 and UE2, and UE3 and UE4, corresponding to BS1 and BS2, respectively, and the cells are defined as in Fig. 1(a). A backhaul link with sufficient bandwidth connects BS1 and BS2, and both BSs can receive the channel response of all the UEs. Assume that UE$i$ transmits signals in the $F$[MHz] band with the $B$[MHz] bandwidth and the transmit power $p_i$[dBm] less than or equal to the maximum transmit power $p_{max}$[dBm]. The average interference power arriving at a BS from outside both the cells is $\sigma^2$[dBm/MHz]. The propagation attenuation from UE$i$ to BS$j$, $L_{i,j}$, is given by Eq. (1), where $d_{i,j}$[m], $\lambda$[m], and $R_s$[m] denote the distance from UE$i$ to BS$j$, carrier wavelength, and a parameter of the reference distance, respectively [4].

$$L_{i,j}(dB) = -20\log_{10}\left(\frac{\lambda}{2\pi R_s}\right) - 30\log_{10}\left(\frac{d_{i,j}}{R_s}\right) - 6. \tag{1}$$
The communication capacity from UE\(_i\) to BS\(_j\), \(C_{i,j}\) [Mbps], is defined based on the SINR observed at BS\(_j\) from UE\(_i\), \(\text{SINR}_{i,j}\), as formulated in Eq. (2), where \(K_{i,j}\) represents a set of indices of UEs with lower received power levels than that of the UE\(_i\) at BS\(_j\).

\[
\begin{align}
C_{i,j} &= B \log_2(1 + \text{SINR}_{i,j}), \\
\text{SINR}_{i,j} &= \frac{L_{i,j}p_i}{B\sigma^2 + \sum_{k \in K_{i,j}} L_{k,j}p_k}.
\end{align}
\]

### 2.2 Cooperative SIC to tackle the bottleneck issue

Using the example of power allocation and coordinates presented in Fig. 1(b), the SIC process and the order of the received signal strength (the received order) in each BS can be summarized as shown in Fig. 1(c). For all the signals to be decoded without error, the rates of UEs must be less than the capacity for decoding. Therefore, in the processes shown in Fig. 1(c), UE\(_i\)’s achievable throughput, \(R_i\), is calculated as Eq. (3). Even if the SINR at the corresponding BS is sufficiently large, throughput bottlenecks still occur because of the low SINR at another BS.

In contrast, Fig. 2 shows the combined SIC process when C-SIC is applied to the scenario depicted in Fig. 1(c). In this case, a throughput bottleneck occurs only at UE4. Because the communication capacity in each decoding step is obtained from Eq. (2), the achievable throughput is calculated as
Eq. (4).

\[
\begin{align*}
R_1 &= \min (C_{1,1}, C_{1,2}), \\
R_2 &= C_{2,1}, \\
R_3 &= \min (C_{3,1}, C_{3,2}), \\
R_4 &= \min (C_{4,1}, C_{4,2}).
\end{align*}
\]  

\[(3)\]

\[
\begin{align*}
R_1 &= C_{1,1}, \\
R_2 &= C_{2,1}, \\
R_3 &= C_{3,2}, \\
R_4 &= \min (C_{4,1}, C_{4,2}).
\end{align*}
\]  

\[(4)\]

2.3 Optimized transmit power allocation

Equation (4) shows the achievable UE throughputs, and the smallest among \(R_1\) to \(R_4\) could be varied by adjusting the transmit power allocation. In other words, the maximized UE’s minimum rate and the transmit power allocation vector achieving it can be obtained by solving the maximin optimization problem as shown in Eq. (5). It is evident from Eqs. (3)-(5) that the presence of bottlenecks affects the optimal solution.

\[
\begin{align*}
\text{maximize} \quad & p \min_i R_i, \\
\text{subject to} \quad & p \in \mathbb{P} = \{p|p_1, p_2, p_3, p_4 \leq p_{\text{max}}\}.
\end{align*}
\]  

\[(5)\]

3 Numerical analysis of Cooperative SIC

3.1 The assumed combined SIC process and optimization method

The combined SIC process depicted in Fig. 2 is an example of the possible methods of exploiting signal transfer in C-SIC. Although an alternative process can be adopted, we adopt the following strategy to design the combined SIC process for simplicity in this study. When both the BSs need to cancel a signal that is not of the corresponding UE, the BS1 preferentially decodes the UE, and the process proceeds to the next stage. For example, as shown in the second stage of the combined process in Fig. 2, the BS1 decodes the UE4,
and the process proceeds to the next stage; accordingly, the BS2 generates a replica of the UE1’s signal based on the transferred signal.

For deriving the optimized transmit power allocation by solving the optimization problem in Eq. (5), we employ the following parallelization technique to determine the global solution using the fminimax in MATLAB quickly. The objective function in Eq. (5) is discontinuous at the points where the received order changes; there are 576 possible combinations of the received order in the scenario involving two BSs and four UEs. Therefore, we divide the optimization problem according to the received order, and add Eq. (6) as a constraint, which allows us to determine a solution in each received order relatively easily because of the reduced number of local solutions in each search space. Note in Eq. (6) that $s_{(n,j)}$ shows an index of the UE with the $n$-th largest received signal strength at BS $j$. The global optimal solution can be quickly determined by choosing the solution with the largest objective function from all obtained solutions.

$$L_{s_{(n,j)}j} \times p_{s_{(n,j)}} \leq L_{s_{(n+1,j)}j} \times p_{s_{(n+1,j)}}, \quad \forall n = 1, 2, 3, \forall j = 1, 2. \quad (6)$$

### 3.2 Minimum rate comparison

We compared the minimum UE rate achieved by NOMA with C-SIC, namely the proposed NOMA, and conventional methods in the same environment. In the conventional NOMA, the UEs in the same cell share a spectrum, and each cell uses a different frequency of the same bandwidth. In OMA, all the UEs transmit signals with the same transmit power, $p_{\max}$, using the frequency bandwidth allocated to each UE. The parameters are shown in Fig. 3(a), where $h_1$ and $h_2$ represent the heights of the BS and UE, respectively. The analysis is based on 1000 samples obtained through simulations by randomly changing the distribution of the UEs. The performance ratio is calculated by normalizing the minimum rate of the proposed and conventional NOMA based on the minimum rate of the OMA in each sample. The cumulative distribution function (CDF) is plotted as shown in Fig. 3(b), where a ratio smaller than one indicates a lower performance than that of the OMA, and a ratio greater than one implies that the method outperforms the OMA. In the CDF, we removed four samples where UEs are distributed within 20m of each BS, because the domain of definition in Eq.(1) is $d_{i,j} \geq R_s = 20$. The average, minimum, and maximum performance ratios are shown in Fig. 3(b). These results show that the proposed NOMA outperforms the OMA in 81.53% of the samples.

### 3.3 Interference power comparison

Under the same environment and parameters as in the previous subsection, we compare out-of-cell interference. We calculated the average interference power density at a point $x[m]$ away from the center point between the two BSs and plotted the average over 996 samples, as shown in Fig. 3(c). In the proposed NOMA, all the UEs transmit signals using the full bandwidth; therefore, the interference power density is constant throughout the band.
In conventional NOMA and OMA, each UE transmits using different frequencies; therefore, the interference power densities differ depending on the frequency. In Fig. 3(c), the conventional NOMA and OMA are plotted as the mean of the interference power density averaged over the frequencies. The interference power density from outside both the cells assumed in this environment is represented by a dotted line. This result shows that the proposed NOMA exhibits lower out-of-cell interference than that of the other methods.

4 Conclusion

In this study, we revealed the potential performance of C-SIC for uplink NOMA in adjacent cells. We described a method for preventing throughput bottlenecks via signal transfer using a backhaul link between BSs, and a method for solving the optimization problem considering the combined SIC process. Through numerical analyses, we demonstrated that the proposed method achieved higher minimum rates than conventional methods in more samples, while displaying less out-of-cell interference. Thus, the throughput can be improved by reusing the spectrum more efficiently. The uplink NOMA with C-SIC has significant room for further improvement in performance and feasibility by revisiting the scheduling strategy in C-SIC, the optimization technique for transmit power control, the highly efficient backhaul utilization method. This work was supported in part by Japan Society for the Promotion of Science KAKENHI Grant Number JP20K11785.