# Optimal User Grouping and Resource Allocation for Downlink Non-Orthogonal Multiple Access Systems

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**Abstract.** Non-orthogonal multiple access (NOMA) with successive interference cancellation (SIC) has recently been considered as a key enabling technique for 5G cellular networks to satisfy future users' network needs, such as ultra-high transmission rate, ultra-high throughput, ultra-low latency and ultra-high density connections. A group of users is allowed to share the same spectrum and multiplex the power domain to transmit data. In this paper, we investigate the optimization of bandwidth allocation and user grouping under the conditions of transmission power limit, bandwidth allocation limit, and user traffic requirements, so that the total resource consumption is minimized. The key idea to solve the problem is to use the layer structure of the problem and divide the problem into the optimization grouping problem and the bandwidth allocation problem. We propose a simulated annealing algorithm to solve the optimization grouping problem.

**Keywords:** Bandwidth allocation · Power allocation
Non-orthogonal multiple access (NOMA)
Successive interference cancellation (SIC)

## 1 Introduction

Non-Orthogonal Multiple Access (NOMA) [1] is considered to be the most likely user access scheme for 5th generation cellular networks [2]. The key idea of NOMA is to actively introduce interference among users and use the same bandwidth resources to serve multiple users to improve spectrum utilization. Compared with conventional orthogonal multiple access (OMA), NOMA allows multiple message information of multiple users to be superimposed in the power domain. At the receiving end, SIC is used according to the size of the user's channel power gain to eliminate interference and decode each user's information signal, the users' throughput can be improved. Due to these advantages of NOMA, relevant researchers have developed a strong interest in this area.


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In [3], Benjebbour *et al.* studied the obvious advantages of NOMA compared with traditional orthogonal access (OMA) in terms of power allocation and high mobility in practical application scenarios. In [4], Wu *et al.* proposed an optimal power allocation and scheduling for NOMA relay-assisted networks. In [5], Di *et al.* studied a joint sub-channel assignment and multi-user power allocation for downlink NOMA to keep balance between the number of served users and the total throughput maximization. In [6], Lei *et al.* proposed a joint channel and multi-user power allocation for downlink NOMA to maximizing the sum-rate utility. In [7], the authors proposed fixed and opportunistic two-user pairing schemes by statically power allocation for 5G NOMA downlink transmissions. In [8], the authors proposed power allocation on the fairness of downlink NOMA which considered perfect channel state information (CSI) feedback as well as average CSI feedback. In [9], an energy-efficient NOMA-enabled traffic offloading through small-cell networks has been proposed. In [10], the authors proposed a cooperative NOMA scheme to achieve the outage probability, diversity order and user pairing approach to reduce system complexity. In [11], the authors investigated the cooperative traffic offloading among mobiles devices, they are focus on receiving a common content from a cellular base station (BS). Considering the fast vehicle mobility and varying communication environment in vehicular communications, Qian *et al.* introduced the NOMA with SIC to the vehicle-to-small-cell networks to achieve dynamically allocate small-cell base stations and transmit power to vehicular users in [12].

Although there have been many studies on the performance of NOMA access solutions in the past, some papers have studied the allocation of channel bandwidth and power of users in a single cluster. Some papers have investigated the user clusters and power allocation (or bandwidth allocation) of multiple users under the condition of fixed bandwidth allocation (or power allocation). In this paper, based on our previous work [13], we consider the optimal multi-user grouping method, bandwidth allocation and power allocation in the downlink, and achieve the optimal total system resource consumption. Our main contributions are summarized below:

- In the downlink NOMA, we propose a method of joint bandwidth and power allocation within multi-user cluster so that the total bandwidth and power resource consumption in the cluster is minimized when the user traffic demand is satisfied.
- A feasible algorithm is provided to optimize the grouping of users to be served in the coverage of the base station (BS) to improve spectrum utilization.

## 2 System Model and Problem Formulation

### 2.1 System Model

We consider a cellular system with one Base Station (BS), and there exists $I$ mobile users (MUs) served by this BS. It is notable that the overall MUs are able to divide into $K$ $(1 \leq K \leq I)$ user-cluster(s), which denoted by $\mathcal{K} =$

$\{1, .., k, .., K\}$. Figure 1 plots an illustrative model comprised of one BS, seven MUs and four user-clusters.

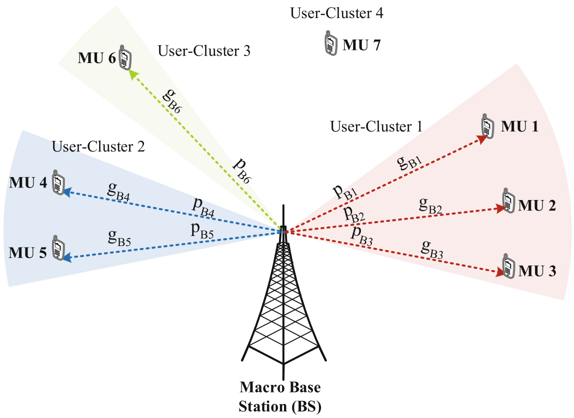


**Fig. 1.** System model comprised of one BS, 7 MUs and 4 user-clusters, with MU 1–3 are choose to access cluster 1 and MU 4–5 are in cluster 2, while cluster 3 only has one MU, which is MU 6. MU 7 is not served by BS.

In this scenario, the BS uses NOMA to send data to each user-cluster on different subchannels. Due to NOMA, the BS can use successive interference cancellation (SIC) to mitigate their intra-cluster co-channel interference when transmitting to the MU(s) in cluster $k$. Hence, the inter-cluster co-channel interference from other clusters (i.e., cluster $k'$, $k' \neq k$) can be neglected.

SIC requires an ordering of the MUs according to their channel power gains with respect to BS. Thus, we introduce the index-set $\mathcal{I}$, in which the group of MUs follow the following descending ordering, expressed as:

$$g_{B1} > g_{B2} > ... > g_{Bi} > ... > g_{BI}, \tag{1}$$

where $g_{Bi}$ denotes the channel power gain from the BS to MU $i, i \in \mathcal{I}$.

We use $a_{ki}$ to denote the $i$-th MU's access-selection to cluster $k$, namely, $a_{ki} = 1$ means that MU $i$ (i.e., the $i$-th MU in $\mathcal{I}$) chooses to access cluster $k$ (i.e., the $k$-th cluster in $\mathcal{K}$), otherwise, $a_{ki} = 0$. Hence, introducing index-set $I_k = \{a_{ki}\}_{k\in\mathcal{K}, i\in\mathcal{I}}$ to represent each cluster's access-selection.

It is reasonable to assume that each MU can only access one cluster, which corresponds to the following constraint:

$$\sum_{k\in\mathcal{K}} a_{ki} \leq 1, \forall i \in \mathcal{I}. \tag{2}$$

Besides, introducing $T_k$ to denote the number of MU(s) that choose to access cluster $k$, which means:

$$T_k = \sum_{i\in\mathcal{I}} a_{ki}, \forall k \in \mathcal{K}. \tag{3}$$

For the sake of easy presentation, we study arbitrary cluster $k$ firstly. We introducing the virtual index $\phi_k(i)$ for MUs in cluster $k$, which defined as follows:

$$\phi_k(i) < \phi_k(i'), \text{when } a_{ki}g_{Bi} > a_{ki'}g_{Bi'}, \forall k \in \mathcal{K}, \forall i, i' \in \mathcal{I}. \quad (4)$$

Similar with (1), in cluster $k$, the larger the channel power gain $g_{Bi}$ from BS to MU $i$, the smaller $\phi_k(i)$ will be. Moreover, we defined that $\phi_k(i) = 1$ when $i$ is the smallest ordering number according to (1) in cluster $k$, and $\phi_k(i) = T_k$ when $i$ is the biggest one.

Using $p_{Bki}$ to denote the transmit-power from BS to MU $i$ in cluster $k$, proposed the following constraint:

$$(1 - a_{ki})p_{Bki} = 0, \forall k \in \mathcal{K}, \forall i \in \mathcal{I}. \quad (5)$$

namely, $p_{Bki} > 0$ only when $a_{ki} = 1$, which means the MU $i$ chooses to access cluster $k$ and severed by BS. On the other side, $p_{Bki} = 0$ when $a_{ki} = 0$, which means the MU $i$ doesn't belong to cluster $k$.

While $a_{ki}g_{Bi} > 0$, according to virtual index $\phi_k(i)$, the MU $\phi_k(i)$ in the cluster $k$ and MU $i$ on the coverage of BS are the same one, then we use $g_{Bk\phi_k(i)}$ to represent $g_{Bi}$ in the following paper.

Based on NOMA, the BS broadcasts the superposition of signals to all the MU(s) within cluster $k$ via power domain division. For MU $\phi_k(i)$ (i.e., MU $i$), it decodes the message of MU $\phi_k(i')$ (i.e., MU $i'$, and $\phi_k(i') > \phi_k(i)$) and then removes the decoded message from the received signal. Meanwhile, for MU $\phi_k(i)$, it treats the message of MU $\phi_k(i')$ (with $\phi_k(i') < \phi_k(i)$) as noise. According to the above decoding scheme, the throughput from the BS to MU $\phi_k(i)$ (i.e., MU $i$) $R_{Bki}$ can be given by:

$$R_{Bki} = W_k \log_2(1 + \frac{g_{B\phi_k(i)}p_{Bki}}{g_{B\phi_k(i)} \sum_{\phi_k(i') < \phi_k(i)} p_{Bki'} + W_k n_0}), \forall i \in \mathcal{I}, \forall k \in \mathcal{K}. \quad (6)$$

where $W_k$ denotes the BS's bandwidth allocation for serving MUs in cluster $k$. Parameter $n_0$ denotes the background noise.

## 2.2 Problem Formulation

Our objective is to minimize the BS system-wise resource consumption cost comprised of the power consumption and the bandwidth usage, while it is necessary to satisfy all MUs' traffic demands. Above all, formulating the following Multi-Cluster Consumption Minimization (MCM) Problem:

$$\textbf{(MCM):} \ \min \alpha \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{I}} p_{Bki} + \beta \sum_{k \in \mathcal{K}} W_k$$

$$\text{Subject to: } \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{I}} p_{Bki} \le P_B^{tot}, \quad (7)$$

$$\sum_{k \in \mathcal{K}} W_k \le W_B^{tot}, \quad (8)$$

$$R_{Bki} \ge R_i^{req}, \quad (9)$$

Constraints (2) , (5) and (6),

Variables: $\{a_{ki} = \{1, 0\}\}_{k \in \mathcal{K}, i \in \mathcal{I}}$, $\{p_{Bki}\}_{k \in \mathcal{K}, i \in \mathcal{I}}$ and $\{W_k\}_{k \in \mathcal{K}}$.

In Problem (MCM), in the objective function, $\alpha$ and $\beta$ denote the unit-prices announced by power and bandwidth, respectively. Constraint (7) means that the BS's total power consumption cannot exceed the capacity $P_B^{tot}$. (8) imposed to ensure that total bandwidth budget $W_B^{tot}$ will not be exceeded. Then we use parameter $R_i^{req}$ in (9) to denote MU's traffic demands which must be satisfied. Recalling that due to (2) and (5) only one element in $\{p_{Bki}\}_{k\in\mathcal{K}}$ is positive. (6) is the expression of throughput from BS to MU $i$.

## 3 Propose Algorithms to Solve Problem

### 3.1 Decomposed Structure of Problem (MCM)

Problem (MCM) is very difficult to solve, since it is a mixed binary non-convex optimization problem. To tackle with this difficulty, we separate the impact of binary variables $\{a_{ki} = \{1, 0\}\}$. Thus, we vertically decompose Problem (MCM) into top-problem and sub-problem.

The top-problem optimizes the access-selection of overall the MUs, which expressed as:

$$\begin{aligned} (\textbf{MCM-top}):&\ \min V(\{a_{ki}\}_{k\in\mathcal{K},i\in\mathcal{I}}) \\ \text{Subject to:}&\ \text{Constraints (2),} \\ \text{Variables:}&\ \{a_{ki} = \{1,0\}\}_{k\in\mathcal{K},i\in\mathcal{I}}. \end{aligned}$$

Specially, given $\{a_{ki}\}$ (i.e., $I_k$ is given), the value of $V(\{a_{ki}\})$ is given by the minimum objective function value of sub-problem, then the expression of sub-problem (MCM-sub) given by:

$$\begin{aligned} (\textbf{MCM-sub}):&\ V(\{a_{ki}\}) = \\ &\ \min \alpha \sum_{k\in\mathcal{K}} \sum_{i\in I_k} p_{Bki} + \beta \sum_{k\in\mathcal{K}} W_k \\ \text{Subject to:}&\ \text{Constraints (6), (7), (8), and (9),} \\ \text{Variables:}&\ \{p_{Bki}\}_{k\in\mathcal{K},i\in I_k} \text{ and } \{W_k\}_{k\in\mathcal{K}}. \end{aligned}$$

We then focus on solving sub-problem (MCM-sub) firstly and then solving top-problem (MCM-top).

### 3.2 Solving Problem (MCM-sub)

Although we have separated the impact of binary variables, it is difficult to solve Problem (MCM-sub) directly. Then we aim at minimizing the total resource consumption of all the MU(s) in cluster $k$, which means we take a single cluster into consideration:

$$
\begin{aligned}
(\textbf{MCM-sub-single}):\ & F(\{a_{ki}\}_{i\in I_k}) = \\
& \min \alpha \sum_{i\in I_k} p_{Bki} + \beta W_k \\
\text{Subject to:}\ & W_k \le W_B^{tot}, && (10)\\
& \sum_{i\in I_k} p_{Bki} \le P_B^{tot}, && (11)\\
& \text{Constraints (6) and (9)},\\
\text{Variables:}\ & \{p_{Bki}\}_{i\in I_k} \text{ and } W_k.
\end{aligned}
$$

Where we imposing constraint (10) to ensure that total bandwidth $W_B^{tot}$ will not be exceed. Constraint (11) means that the BS's total power consumption cannot exceed the capacity $P_B^{tot}$.

After solving the Problem (MCM-sub-single) and driving $F(\{a_{ki}\}_{i\in I_k})$ according to the given $\{a_{ki}\}$, we are able to further solve the multi-clusters problem:

$$
\begin{aligned}
(\textbf{MCM-sub-multiple}):\ & V(\{a_{ki}\}) = \sum_{k\in\mathcal{K}} F(\{a_{ki}\}_{i\in I_k})\\
\text{Subject to:}\ & \text{Constraints (7) and (8)}.
\end{aligned}
$$

Problem (MCM-sub-single) has been resolved in [13], so we can derive the optimal bandwidth allocation $W_k^*$ of Problem (MCM-sub-single). Furthermore, we can recursively derive the optimal transmit-power allocation for the MU $i$ in given cluster $k$ as follows

$$
p_{Bki}^* = (2^{x^* R_i^{req}} - 1)\Big(\sum_{\phi_k(i')<\phi_k(i)} p_{Bki'}^* + \frac{n_0}{g_{B\phi_k(i)}}\frac{1}{x^*}\Big). \tag{12}
$$

Then, we finish solving the Problem (MCM-sub-single) and obtain the minimum total resource consumption cost $F^*(\{a_{ki}\}_{i\in I_k})$ of the cluster $k$.

After solving Problem (MCM-sub-single), we continue to solve Problem (MCM-sub-multiple). With the help of $F^*(\{a_{ki}\}_{i\in I_k})$, $W_k^*$ and $p_{Bki}^*$, transforming Problem (MCM-sub-multiple) as follows:

$$
\begin{aligned}
(\textbf{MCM-sub-multiple}):\ & V(\{a_{ki}\}) = \sum_{k\in\mathcal{K}} F^*(\{a_{ki}\}_{i\in I_k})\\
\text{Subject to:}\ & \sum_{k\in\mathcal{K}}\sum_{i\in I_k} p_{Bki}^* \le P_B^{tot},\\
& \sum_{k\in\mathcal{K}} W_k^* \le W_B^{tot}.
\end{aligned}
$$

The meaning of Problem (MCM-sub-multiple) is further optimizes the overall minimum total resource consumption cost under the given access-selection $\{a_{ki}\}$. Specially, we propose the following algorithm (i.e., Algorithm (sol-multiple)) to solve Problem (MCM-sub-multiple).

Then, we drive the solution of Problem (MCM-sub-multiple) under the given $\{a_{ki}\}$, i.e., $V(\{a_{ki}\})$. Thus, we finish solving the Problem (MCM-sub) completely.

**Algorithm (sol-multiple): to solve Problem (MCM-sub-multiple) and compute $V(\{a_{ki}\})$**

**Input:** $\{W_k^*\}_{k\in\mathcal{K}}$ and $\{p_{Bki}^*\}_{k\in\mathcal{K},i\in I_k}$.
Initialize the feasibility status flag $s^{flag}=1$ of the Problem (MCM-sub-multiple).
$W^*=\sum_{k\in\mathcal{K}} W_k^*$.
$p_B^*=\sum_{i\in\mathcal{I}} p_{Bki}^*$.
**if** $W^*\le W_B^{tot}$ **and** $p^*\le p_B^{tot}$ **then**
    $V(\{a_{ki}\})=\sum_{k\in\mathcal{K}} F^*(\{a_{ki}\}_{i\in I_k})$.
**else**
    Output that Problem (MCM-sub-multiple) is infeasible and $s^{flag}=0$.
**end if**
**Output:** $V(\{a_{ki}\})$ and $s^{flag}$ for Problem (MCM-sub-multiple).

## 3.3 Solving Problem (MCM-top)

Here, according to the previous section, under the each given $\{a_{ki}\}$, we are able to solve Problem (MCM-sub) completely and obtain the corresponding $V(\{a_{ki}\})$ which is the minimum total resource consumption cost for the given $\{a_{ki}\}$. We next continue to solve the Problem (MCM-top), which means finding the optimal MUs' access-selection $\{a_{ki}^*\}$ in this procedure to further minimize the total resource consumption cost globally. we exploit the Simulated Annealing (SA) algorithm to obtain the optimal solution, i.e., $V(\{a_{ki}^*\})$, since we propose the Total resource Consumption Simulated Annealing Algorithm (i.e., TCSA-Algorithm).

The output of TCSA-Algorithm, i.e., $\{a_{ki}^*\}$ and $V(\{a_{ki}^*\})$, are the optimal MUs' access-selection and the global total minimum resource consumption cost, namely, we finish solving the Problem (MCM-top). Finally, we solve the original Problem (MCM) completely.

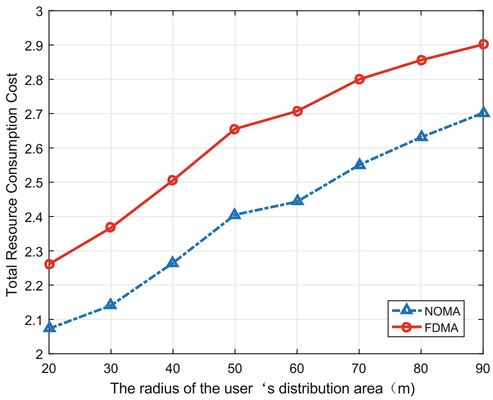


**Fig. 2.** Performance under different radius of the MUs.

**TCSA-Algorithm: solve Problem (MCM-top) to obtain $\{a^*_{ki}\}$ and $V(\{a^*_{ki}\})$**

Initialization: assign the MUs into $\{I_k\}_{k\in\mathcal{K}}$, set the iteration index $q = 1$, the initial temperature $T_{ini} = 97$, temperature decay function parameter d=0.99, the length of the Markov chain $L = I^2$ and the final temperature $T_{final} = 3$. The minimum value of resource consumption cost $V^{min}$ initial as infinite.
Given $\{I_k\}_{k\in\mathcal{K}}$, use the Algorithm (sol-multiple) to obtain $V(\{a_{ki}\})$. At time $t$, the system temperature is $T_t$.
**while** $(T_t \geq T_{final})$ **do**
  **while** $(q \leq L)$ **do**
    Randomly select two set $I_k$ and $I'_k$ with $I_k$ as a non-empty set. Randomly select one MU (let us say MU $r$) in $I_k$, and move MU $r$ from $I_k$ to $I'_k$. Denote the two updated sets as $\overline{I}_k$ and $\overline{I}'_k$, respectively, and denote the whole profile after updating as $\{\overline{a}_{ki}\}$.
    Given $\{\overline{I}_k\}$, use the Algorithm (sol-multiple) to obtain $V(\{\overline{a}_{ki}\})$.
    **if** $s^{flag} == 1$ **then**
      **if** $V(\{\overline{a}_{ki}\}) < V(\{a_{ki}\})$ **then**
        Update $\{a_{ki}\} = \{\overline{a}_{ki}\}$.
        **if** $V(\{\overline{a}_{ki}\}) < V^{\min}$ **then**
          Update $V^{\min} = V(\{\overline{a}_{ki}\})$
          Update $\{a^*_{ki}\} = \{\overline{a}_{ki}\}$
        **end if**
      **else**
        Set $\Delta = V(\{a_{ki}\}) - V(\{\overline{a}_{ki}\})$.
        With probability equal to $\exp\{\frac{\Delta}{T_t}\}$. Update $\{a_{ki}\} = \{\overline{a}_{ki}\}$.
      **end if**
    **else**
      Update $q = q - 1$.
    **end if**
    Update $q = q + 1$.
  **end while**
  Update $T_t = T_t * d$
**end while**
Output $\{a^*_{ki}\}$ and $V(\{a^*_{ki}\}) = V^{\min}, \forall i \in \mathcal{I}, k \in \mathcal{K}$.

## 4 Numerical Results

We use a scenario of five MUs are randomly distributed within the coverage of BS. Specially, the coverage of BS is a circle whose radius is $R_{MU}$, and we place the BS at the circle center. We model the channel power gain as $g_{Bi} = \frac{\varrho_{Bi}}{l^{\kappa}_{Bi}}$, where $l^{\kappa}_{Bi}$ denotes the distance between the BS and MU $i$, and $\kappa$ denotes the power-scaling factor for the path-loss (we set $\kappa$ as 2.5). Meanwhile, we set the BS's total bandwidth $W^{tot}_B = 15$ MHz and the power capacity $P^{tot}_B = 20$ W.

Figure 2 shows the performance of proposed algorithms under different radius of the MUs compared with FDMA. Specifically, we randomly distribute MUs within the coverage of BS, vary radius $R_{MU}$ (i.e., coverage of BS is a plane) as (20 m, 30 m, 40 m, 50 m, 60 m, 70 m, 80 m, 90 m).

Figure 2 shows that the average total resource consumption cost of FDMA and the proposed algorithms increases when the radius $R_{MU}$ of circle moves away from the BS. This result is reasonable. With the expansion of $R_{MU}$, the MUs move away from the BS, which causes the resource-consuming long-distance transmission. Meanwhile, compared with FDMA scheme, Fig. 2 shows that our proposed algorithm can always save much more resource consumption.

We consider that 10 MUs are randomly distributed within the coverage of the BS, and the radius $R_{MU}$ is 50 m, 70 m, and 100 m respectively. With the number of given clusters increase, the changes of the optimal total resource consumption in the case of three user distributions are shown in Fig. 3. Figure 3 shows that the total resource consumption increases with the radius of distribution. When all users are in the same cluster, the total resource consumption is always the largest, which is because the weak co-channel interference in the cluster is too large. At the same time, as the number of given user clusters increases, the total resource consumption decreases first and then increases. This also explains why the FDMA scheme is not used in 5G networks, but NOMA's multi-user grouping scheme is chosen. The difference of the optimal resource consumption under the cluster number near the optimal cluster number and the optimal resource consumption under the optimal cluster number are very small.

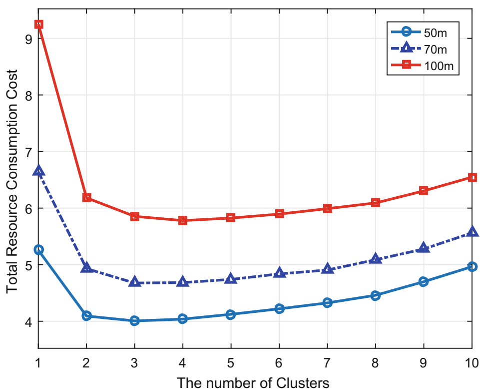


**Fig. 3.** The effect of the number of user clusters on total resource consumption.

## 5 Conclusion

In order to solve the problem of minimizing the total resource consumption of multi-user clusters formulated in this paper, we split it into the top-problem and the sub-problem. This split can make good use of the convexity of bandwidth allocation and simplify the process of the grouping optimization. From the final simulation results, our proposed algorithm can greatly reduce the system resource consumption.

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