The Throughput Optimization for Multi-hop MIMO Networks Based on Joint IA and SIC

Peng Zhang[1,2], Xu Ding[1,2], Jing Wang[1,2], Zengwei Lyu[1], and Lei Shi[1(✉)]

[1] School of Computer Science and Information Engineering,
Hefei University of Technology, Hefei, China
`shilei@hfut.edu.cn`

[2] Institute of Industry and Equipment Technology, Hefei University of Technology,
Hefei, China

Abstract. MIMO researches penetrate the network community due to recent advances in MIMO degree-of-freedom (DoF) frameworks. Independent from MIMO, Successive Interference Cancellation (SIC) is a powerful multi-user detection technology in physical layer, and Interference Alignment (IA) is a powerful technique for handling interference. Based on the understanding of the strengths and weaknesses of SIC and DoF, we propose mutual assistance by joint IA, SIC and DoF-based Interference Cancellation (DoF IC) to (*i*) conserve precious DoF resources through IA and SIC; (*ii*) meet strict SINR threshold criteria through IC and IA. In this paper, we develop the mathematical model to achieve the two ideas in a multi-hop MIMO network. Combined with scheduling and routing constraints, we developed a cross-layer optimization framework to the throughput maximization problem with joint IA and SIC for MIMO networks. Simulation results show that the join of IA and SIC can significantly conserve DoFs for IC and thereby improve the throughput.

Keywords: IA · SIC · DoF · IC · MIMO · Multi-hop

1 Introduction

MIMO has been extensively researched and applied, due to its ability of spatial multiplexing (SM) gain and interference cancellation (IC) [1,2]. The concept of degree-of-freedom (DoF) was originally defined to represent the multiplexing gain of a MIMO channel. Now, the concept of DoF was extended to characterize nodes spatial freedom provided by its multiple antennas, and the basic idea of the DoF model is assigning DoF resources for SM or IC to nodes. Thus, DoFs are precious resources. Especially, when IC is used, it will reduce the remaining

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DoFs for SM. Hence, it is necessary to reduce the consumption of DoFs for IC, so that maximizes the available number of DoFs for SM.

Interference Alignment (IA) [4] offers a new direction to handle mutual interference among multi-user. The basic idea is to construct signals at transmitters so that these interference signals overlap at their unintended receivers. For multi-hop networks, IA is not advanced enough, since the interference models are much more complicated. Zeng et al. [3] studied OFDM-based IA in multi-hop cellular networks, but their work were limited to single-antenna networks. Li et al. [4] made the first attempt to explore IA in a multi-hop MIMO network, but the basic idea of IA (constructing signals) was not involved into their formulation.

SIC is a powerful multi-user detection technique used in physical layer [5,6]. Independent from MIMO, the receiver can iteratively decode out the required signals from multiple signals though using SIC [7]. The strongest signal can be decoded successfully, if it meets the SINR threshold. Research on exploiting SIC for nodes with single-antenna in a wireless network can be found in [8]. However, SIC does have its limitation that as long as one of the steps of the SINR can not be met, the subsequent procedures cannot be continued.

The main contributions of this paper are as follows:

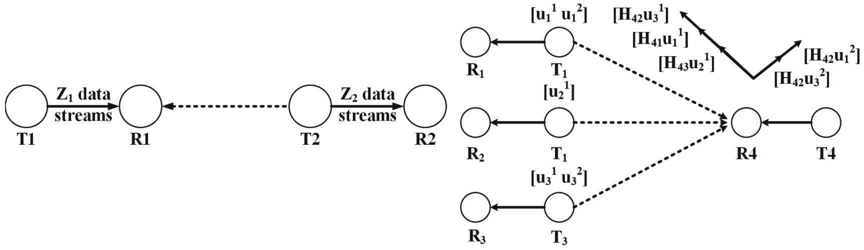
- We develop an IM model with joint IA and SIC for multi-hop MIMO networks. We show that DoFs can be conserved if it satisfies the constraints in our IM model. Our model consists of (i) constraints at transmitters to determine the subset of interference streams for IA and (ii) constraints at receivers to determine the IA and SIC pattern of the interference streams.
- In multi-hop MIMO networks, coupling of both routing and scheduling with IM and DoF allocation is a nontrivial issue. We propose a scheme that addresses the flow routing and scheduling problem. On the one hand, IA and DoF IC can eliminate the barrier signals for SIC. On the other hand, DoF resources can be conserved through joint SIC and IA. Based on this scheme, the throughput will significantly increase in the multi-hop MIMO network.

2 The Background and Motivation

2.1 The Principles of the Three Technologies

Consider a MIMO network consisting of a set of nodes $\mathcal{N}$ with $N = |\mathcal{N}|$. Assume that each node have M antennas, and there are L possible links in the network. Denote $Tx(l)$ and $Rx(l)$ as the transmit and receive nodes of link l. We consider a time-slotted scheduling strategy, where a time frame consists of T time slots.

The number of DoFs represents the total available resources that can be used for SM and IC. SM refers to use DoFs for data streams transmission and reception, with each DoF being responsible for one data stream. IC refers to use DoFs to cancel interference, with each DoF corresponding to one interfering stream. IC can be used either at a transmitter or a receiver. For example, like the two links in Fig. 1(a), both nodes T_1 and R_1 consume z_1 DoFs for SM to



(a)An illustration of IC and SM in MIMO

(b)An illustration of IA

Fig. 1. The illustration of IC, SM and IA.

transmit z_1 data streams. For IC, if R_1 cancels this interference, it needs to consume z_2 DoFs. Or if T_2 cancels this interference, it needs z_1 DoFs.

IA refers to a construction of data streams at transmitters so that they align at the unintended receivers and remain resolvable at the intended receivers. Since the interfering streams are overlapped at a receiver, it can use fewer DoFs to cancel these interfering streams. As a result, the DoF resources will be conserved and used to transfer data. As shown in Fig. 1(b), without IA, R_4 needs to consume 5 DoFs to cancel the interference signals for IC. However, with IA, the 5 interfering can be aligned streams into 2 dimensions.

SIC allows a receiver to take multiple signals from different transmitters and decode each of them iteratively. For the composite received signal, the receiver attempts to iteratively decode the strongest signal and considers all other signals as noise. The process continues until all intended signals are successfully decoded, or the SINR threshold cannot be met at a certain stage.

2.2 Motivation and Basic Idea

After discussing the background, we find that the three technologies can help each other. *(i) DoF IC to remove barrier signal in SIC.* SIC will fail to continue, if the SINR threshold is no longer satisfied at any stage. Fortunately, we could use one DoF to cancel a particular interference for IC. After removing this signal, SIC can decode the remaining signals in the aggregate signal. *(ii) IA and SIC to conserve DoFs in IC.* Before we expend precious DoFs for IC, we exploit SIC and IA to its fullest extent at the receiver.

3 A Joint Design for Multi-hop MIMO Networks

We assume that a node cannot transmit or receive in one time slot. Denote $x_i[t]$ as a binary variable to indicate whether node i is a transmitter in time slot t, i.e., $x_i[t] = 1$ if node i is a transmitter in time slot t and 0 otherwise. Similarly, denote $y_i[t]$ as a binary variable to indicate whether node i is a receiver in time slot t. Then the half duplex constraints can be written as:

$$x_i[t] + y_i[t] \leq 1, (i \in \mathcal{N}, 1 \leq t \leq T). \tag{1}$$

Denote $z_l[t]$ as the number of data streams on link l in time slot t. If node i is a transmitter, we have $1 \leq \sum_{l \in \mathcal{L}_i^{out}} z_l[t] \leq M$, otherwise $\sum_{l \in \mathcal{L}_i^{out}} z_l[t] = 0$. Combining the two cases, the node activity constraints as follows:

$$x_i[t] \leq \sum_{l \in \mathcal{L}_i^{out}} z_l[t] \leq N_A \cdot x_i[t], (i \in \mathcal{N}, 1 \leq t \leq T), \tag{2}$$

$$y_i[t] \leq \sum_{l \in \mathcal{L}_i^{in}} z_l[t] \leq N_A \cdot y_i[t], (i \in \mathcal{N}, 1 \leq t \leq T). \tag{3}$$

3.1 IA in MIMO

Denote $\mathcal{A}_{ij}$ as the set of interfering streams from node i to node j, with $\alpha_{ij} = |\mathcal{A}_{ij}|$. Denote $\mathcal{B}_{ij}$ as the subset of interfering streams that are aligned to the other interfering streams at receiver j, with $\beta_{ij} = |\mathcal{B}_{ij}|$. For node i, $\mathcal{B}_{ij} \subseteq \mathcal{A}_{ij}$, e.g., $\beta_{ij}[t] \leq \alpha_{ij}[t]$, where $\mathcal{I}_i$ is the set of nodes within the interfering range of i.

Each data stream corresponds to one precoding vector. Since each outgoing stream interferes with all the unintended receivers within the interference range of node i, the corresponding precoding vector determines the direction of one interfering stream for those receivers. For instance, precoding vector u_i^1 determines the directions of the outgoing stream at k receivers, only one of which is the intended receiver. Among the $k-1$ interfering streams, only one of them can be aligned to a particular direction by u_i^1. Since there are $\sum_{l \in L_i^{out}} z_l[t]$ precoding vectors at transmitter i, at most $\sum_{l \in L_i^{out}} z_l[t]$ interfering streams can be utilized by IA at their receivers. Then, we have: $\sum_{j \in \mathcal{I}_i} \beta_{ij}[t] \leq \sum_{j \in \mathcal{L}_i^{out}} z_l[t]$.

For receiver i, there are three constraints that must be satisfied: (i) the interfering streams in each $\mathcal{B}_{ij}$ should not occupy independent directions at receiver j, so $\mathcal{B}_{ij}$ can only aligned to an interfering stream in $\cup_{i \in \mathcal{I}_j} (\mathcal{A}_{ij} \backslash \mathcal{B}_{ij})$; (ii) for resolvability, any interfering stream in $\mathcal{B}_{ij}$ and $\mathcal{A}_{ij}$ are linearly independent; (iii) any two interfering streams in $\mathcal{B}_{ij}$ cannot be aligned to the same interfering stream. The above conditions are all satisfied if the following constraint is satisfied: $\beta_{ij}[t] \leq \sum_{k \in I_j}^{k \neq i} (\alpha_{kj}[t] - \beta_{kj}[t])$.

Since the DoFs consumed for SM and IC cannot exceed its total DoFs, we have the following constraint: $\sum_{l \in L_j^{in}} z_l[t] + \sum_{j \in \mathcal{I}_i} (\alpha_{ji}[t] - \beta_{ji}[t]) \leq N_A \cdot y_i(t)$.

If node i is a transmitter and node j is a receiver in time slot t, we get $\alpha_{ij}[t] = \sum_{l \in L_i^{out}}^{R_X(l) \neq j} z_l[t]$, and 0 otherwise. Thus, we have:

$$\alpha_{ji}[t] = y_i[t] \cdot \sum_{l \in L_j^{out}}^{R_X(l) \neq i} z_l[t], (i \in \mathcal{I}_j, 1 \leq j \leq N, 1 \leq t \leq T). \tag{4}$$

3.2 SIC in MIMO

Consider the MIMO model, we assume that nodes are symbol synchronous and they may transmit up to M data streams. Depending on the transmit precoding vectors and receiver matrices, SINR can be calculated [9]. Assume data streams are uncorrelated, SINR for the q^{th} element in y_{ji} is: $SINR_{ji}^{q} = \frac{p_j \cdot L_{ji}^2 \left\|(v_{ji}^q)' H_{ji}' u_j^q\right\|^2}{\sum_{k \in I_i, k \neq j} p_k L_{ki}^2 \left\|(v_{ji}^q)' H_{ki}' U_k\right\|^2 + N_0}$, where N_0 is equal to $N_0 \left\|v_{ji}^q\right\|^2$, due to $\left\|v_{ji}^q\right\|^2 = 1$; L_{ji} is the path-loss factor between node j and i; H_{ji} is the channel matrix between node j and i and is normalized to mean power 1, u_{ji}^q and v_j^q define as the precoding vector and the decoding vector, respectively.

For MIMO, there are usually multiple data streams from a transmitter, so we use the worst-case aggregate SINR for the same transmitter. If the worst-case data stream from node j is decodable, all data streams from node j can be decoded. For generality, suppose that the minimum received power levels of the data streams from the q transmitters at node i are listed in non-decreasing order as $p_q L_{qi}^2 C_{qi} \geq \cdots \geq p_n L_{ni}^2 \geq \cdots \geq p_1 L_{1i}^2 C_{1i}$. With SIC, receiver i will decode the signals in the order of $q, q-1, \cdots, n$. The intended signal n is decodable, if both the intended and stronger unintended signals satisfy the SINR threshold.

Define the so-called residual SINR (rSINR) [9] as the mathematical program as follow: $rSINR_{ji}[t] = \frac{p_j \cdot L_{ji}^2 \cdot C_{ji}}{\sum_{Q=1}^{Q-1} p_q \cdot L_{qi}^2 \cdot D_{jqi} + N_0}$, where the summation in the denominator includes all transmit nodes q with weaker received signals than node j, $C_{ji} = min_q \left\|(v_{ji}^q)' H_{ji}' u_j^q\right\|^2$, $D_{jki} = max_q \left\|(v_{ji}^q)' H_{ki}' U_k\right\|^2$. For intended node n, $C_{ni} = 1$ due to the SM requirements.

3.3 SIC-IA Based MIMO DoF Model

In general, a receiver may receive a aggregate signal from both the intended and unintended transmitters, receiver i divides the signals from they into five sets.

Set 1. Unintended signals are canceled by DoFs at the transmitters. ***Set 2.*** Unintended signals are canceled by DoFs or IA at the receiver. ***Set 3.*** Unintended signals are decoded and subtracted from the composite received signals by SIC (i.e., the received powers from these transmitters are greater than the powers from the intended transmitter n). ***Set 4.*** Intended signals from intended node n. ***Set 5.*** Unintended signals are treated as noise for SIC (i.e., the received powers from these transmitters are less than the powers from intended node n).

For the unintended signals, the question of which sets (1, 2, 3 and 5) the signals belong to will be solved by an optimization problem. Now we describes the process of SIC scheme. First, *set*1 signals are canceled by IC and a part of *set*2 are canceled by IA. Then, the remaining composite signals are received at node i. A receiver has one reconfigurable receive matrix, which is updated iteratively during SIC. In each SIC iteration, the receiver first tries to use SIC to decode the signal. If the decoding is unsuccessful, it then tries to use IC to eliminate the interference; and if there are enough freedom resources, the signal will be eliminated and continues SIC decoding, otherwise the subsequent signals can not be decoded and will be decoded in the next time slice.

Now, we show how the joint IA and SIC model and DoF IC model can be coupled together. For the 5 sets of signals, we define three binary indicator variables $\gamma_{ji}[t]$ (for sets 1 and 2), $\eta_{ij}[t]$ (for sets 3 and 5) and $\lambda_{ji}[t]$ (for set 4).

$\gamma_{ji}[t] = 1$ if the interference from transmitter j to receiver i is canceled by DoF (either at node j or i), and 0 otherwise. When $\gamma_{ji}[t] = 1$, it does not determine which node does the IC (node j or i). Thus, we need the value of $\theta_{ji}[t]$ [9]. This sufficient condition can be modeled as follow: $x_j[t], y_i[t] \geq \gamma_{ji}[t]$.

$\eta_{ji}[t] = 1$ if the interference from unintended transmitter j to receiver i is canceled by SIC, and 0 otherwise. Similarly, we have: $x_j[t], y_i[t] \geq \eta_{ji}[t]$.

$\lambda_{ji}[t] = 1$ if intended transmitter j transmits data streams to node i via SM, and 0 otherwise. For SM, we have: $\lambda_{ji}[t] \leq z_l[t] \leq N_A \cdot \lambda_{ji}[t]$.

Now, we introduce the details about the MIMO DoF model with joint IA and SIC. With the above definitions for $\gamma_{ji}[t]$, $\eta_{ji}[t]$ and $\lambda_{ji}[t]$, the DoF consumption constraints in (2) and (3) can be extended by taking into account SIC. When node i is a transmit node, then the DoF consumption at this node must satisfy:

$$\begin{aligned}&\sum_{l \in L_i^{out}} z_{(l)}[t] + \sum_{j \in \mathcal{I}_i} \theta_{ji}[t]\gamma_{ij}[t] \sum_{k \in \mathcal{I}_j^{in}}^{Tx(k) \neq i} z_{(k)}[t] \\ &\leq N_A \cdot x_i[t] + (1 - x_i[t])B_i, (i \in \mathcal{N}, 1 \leq t \leq T),\end{aligned} \tag{5}$$

where B_i is no small than the number of inference signal, we set $B_i = N_A \cdot |\mathcal{I}_i|$.

Similarly, the DoF consumption at node i must satisfy:

$$\begin{aligned}&\sum_{l \in L_i^{in}} z_{(k)}[t] + \sum_{j \in I_i} \theta_{ji}[t]\gamma_{ji}[t] \sum_{l \in L_j^{out}}^{Rx(l) \neq i} [\alpha_{kj}[t] - \beta_{kj}[t]] \\ &\leq N_A \cdot y_i[t] + (1 - y_i[t])B_i, (i \in \mathcal{N}, 1 \leq t \leq T).\end{aligned} \tag{6}$$

With DoF IC, the barrier signals can be removed and SIC can continue to work. We incorporate DoF IC into the rSINR definition through the $\eta_{ji}[t]$ and $\lambda_{ji}[t]$ variables, which allows us to account for only those interference signals handled by SIC. Thus, $rSINR_{ji}[t]$ can be re-defined as: $rSINR_{ji}[t] = \frac{p_j \cdot L_{ji}^2 \cdot C_{ji}}{\sum_{k \in I_i, k \neq j, \eta_{ki}[t]=1 or \lambda_{ki}[t]=1}^{p_k L_{ki}^2 \cdot C_{ki} \leq p_j L_{ji}^2 \cdot C_{ji}} p_k L_{ki}^2 D_{jki} + N_0}$, if node j is the intended node, $C_{ji} = 1$.

Note that if $\lambda_{ni}[t] = 1$ (i.e., intended signals send from transmitter n to receiver i), we must have: (i) The $rSINR_{ji}[t]$ of all stronger received signals from unintended transmitters j with $\eta_{ji}[t] = 1$ are no less than the SINR threshold β; (ii) $rSINR_{ni}[t]$ is no less than β. If $\lambda_{ni}[t] = 1$, we have:

$$SINR_{ji}[t] \geq \beta, \quad (i \in \mathcal{N}, j \in \mathcal{I}_i, \eta_{ji}[t] = 1 \text{ } or \text{ } \lambda_{ji} = 1, 1 \leq t \leq T). \tag{7}$$

4 Performance Evaluation

4.1 A Throughput Maximization Problem

Suppose there is a set of active sessions $\mathcal{F}$. Denote $r(f)$ as the rate of session f and r_{min} as the minimum session rate among all sessions $\mathcal{F}$, i.e., $r_{min} \leq r(f)$ $(f \in \mathcal{F})$. Our objective is to maximize r_{min}.

Denote $r_l(f)$ as the amount of data rate on link l for session f. Denote $s(f)$ as the source nodes of session f, we have the flow routing constraint as follow:

$$\sum_{l \in L_i^{out}} r_l(f) = r(f). \tag{8}$$

At the intermediate relay node, we have the flow routing constraint as follow:

$$\sum_{l \in L_i^{in}} r_l(f) = \sum_{l \in L_i^{out}} r_l(f). \tag{9}$$

It can be verified that if (8) and (9) are satisfied, the constraint of destination node is also satisfied. So it is sufficient to have (8) and (9).

Since the aggregate data rate on link l cannot exceed the links average rate, we have the link capacity constraints as follow:

$$\sum_{f=1}^{F} r_l(f) \le \frac{1}{T} \sum_{t=1}^{T} z_{(l)}[t]. \tag{10}$$

Putting all the constraints together, we have the following formulation for the throughput maximization problem.

OPT max r_{min}

s.t. $r_{min} \le r(f), \ (f \in F)$;

Half duplex constraint: (1);

Node activity constraints: (2), (3);

DoF consumption with joint IA and SIC: (5), (6);

Sequential SIC with IC: (7);

Flow balance and link capacity constraints: (8), (9), (10);

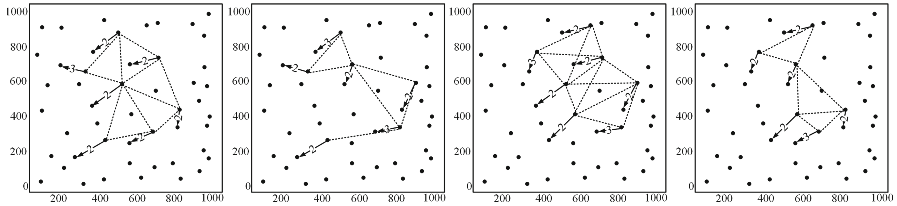
Variables: $x_i[t], y_i[t], z_{(l)}[t], \pi_i[t], \theta_{ji}[t], \eta_{ji}[t], \gamma_{ji}[t], \lambda_{ji}[t], r_l(f), r(f)$;

Constants :$M, N, T, B_i, p_j, L_{ji}^2, \beta, N_0, C_{ji}, D_{jki}$

Through reformulation on (4), (5), (6) and (7), OPT can be reformulated into a mixed integer linear program (MILP) [10]. There exist highly efficient heuristics to solve it. Another approach is to apply an off-the-shelf solver, like GUROBI, which can handle up to a moderate-sized network successfully. It is sufficient to demonstrate our results with moderate-sized networks, because the main goal of this paper is to explore joint IA and SIC for MIMO DoF.

4.2 A 50-Node Example

In this chapter, we will exploit this model to achieve two goals: (*i*) show how IA and SIC are performed in a network; (*ii*) make a quantitative comparison between our joint IA and SIC framework and the case without SIC.



(a) Time Slot 1 (b) Time Slot 2 (c) Time Slot 3 (d) Time Slot 4

Fig. 2. Scheduled links in each time slots.

For generality, we normalize all units for location, data rate and power with appropriate dimensions. We consider a randomly generated wireless network with 50 nodes distributed in a 1000 × 1000 area. At the network layer, minimum-hop routing is employed, and there are 4 active sessions: N_7 to N_2, N_{19} to N_{50}, N_{10} to N_{43}, and N_{47} to N_{49}. We assume $M = 4$, $\beta = 1$ and $T = 4$. The transmit power is set to 1. The path-loss factor L^2_{ji} between nodes i and j is $L^2_{ji} = d^{-\lambda}_{ji}$, where d_{ji} is the Euclidean distance between the two nodes and $\lambda = 3$ is the path-loss index. The power of ambient noise is $N_0 = 10^{-10}$. The average value of C_{ji} is 0.3460. The worst case upper bound value for D_{jki} is 7.3753. For the 50-node network, we apply GORUBI solver for the MILP formulation.

Figure 2 demonstrates the transmission/reception pattern and interference pattern in each time slot. Specifically, a solid line with arrow represents a transmission link. A dashed line represents an interference. We get $r_{min} = 2$, which is a significantly improvement compared with the case without SIC ($r_{min} = 1$). Meanwhile, we get $E_j = 63$ and $E_{IA} = 43$, where denote E_j and E_{IA} as the number of eliminated interference signals in joint scheme and the number of eliminated interference signals in IA-MIMO scheme, respectively.

4.3 Complete Results

Table 1 shows r_{min} and E under the scheme for 60 randomly generated network instances. The total average percentage increase in r_{min} under the joint scheme is 100%, while the total average percentage of eliminated interference signals increase is 44.5%. Note that if all nodes with $r_l(f) = 1$ increase their $r_l(f)$ to 2, r_{min} will increase from 1 to 2. These increases are intuitive as less interference signals will remain more DoFs to transmit data and time slots for scheduling, so alleviating the DoF resources shortage issue.

Table 1. Optimized Results

Instances	1–20		21–40		41–60	
	r_{min}	E	r_{min}	E	r_{min}	E
IA-SIC in MIMO	2	E_j:59.0	2	E_j:62.4	2	E_j:61.5
Only IA in MIMO	1	E_{IA}:39.8	2	E_{IA}:44.3	1	E_{IA}:42.5

5 Conclusions

In multi-hop MIMO networks, since interference is unavoidable, DoF is a precious resource for SM and IC. This paper proposes a strategy joint IA and SIC to maximize the throughput in the multi-hop MIMO networks. For a transmitter, we will precode signals for IA and SIC to allow that the intended node receive more data streams. For a receiver, a part of inference signals will be aligned at the antennas and multiple signals are received by SIC. We studied the mathematical model to characterize (*i*) how the SINR threshold can be satisfied by using IA and IC; (*ii*) how DoF resources can be conserved by using IA and SIC. Based on our mathematical model, we studied a throughput maximization problem and confirmed that IA, SIC and IC can achieve the benefits proposed in this paper.

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